Advances in Manufacturing Technology – XXII

Volume I

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Edited by
Professor Kai Cheng, Dr. Harris Makatsoris and Professor David Harrison

Volume I

About the Editors

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Professor David Harrison is currently Head of Design within the School of Engineering and Design, and his research interests are in sustainable design and printed electronics. Over the past decade he has lead a number of research projects inspired by the goals of environmentally sensitive design. These projects include the application of offset lithographic printing to the manufacture of electronics. New manufacturing processes arising from this project have been successfully patented and licensed. He has also worked on the development of the concept of "Active Disassembly", where by features are designed into products to permit them to disassemble at end of product life, facilitating recycling. He is a Director of a spin out company, Active Fasteners, set up to commercialise this work. Other recent projects supervised include work on ecological footprinting of products, eco innovation, and tools to calculate ecologically optimum product lifetimes.

Preface

The Consortium of UK University Manufacturing Engineering Heads (COMEH)

The Consortium is an independent body and was established at a meeting held at Loughborough University on 17 February 1978. Its main aim is to promote manufacturing engineering education, training, and research. To achieve this the Consortium maintains a close liaison with those Government Departments and other bodies concerned with the initial/continuing education and training of professional engineers, while also responding to appropriate consultative and discussion documents and other initiatives. It organizes and supports national manufacturing engineering education research conferences and symposia. COMEH is represented on the Engineering Professors' Council (EPC). The Consortium consists of heads of those university departments or sections whose first priority is to manufacturing engineering and who have a direct responsibility for running honours degree courses in the field of manufacturing engineering. Currently there are about seventy members of COMEH.

COMEH decided in 1984 that a national forum was needed in which the latest research work in the field of manufacturing engineering and manufacturing management could be disseminated and discussed. The result of this initiative was that an annual series of these national conferences on manufacturing research (NCMR) was started, the first NCMR being held at the University of Nottingham in 1985. The first ICMR (ICMR 2003) built upon the NCMR series of conferences and was held at the University of Strathclyde in 2003. The subsequent NCMR/ICMR conferences have been held as follows:

1986	Napier
1987	Nottingham
1988	Sheffield
1989	Huddersfield
1990	Strathclyde
1991	Hatfield
1992	University of Central England
1993	Bath
1994	Loughborough
1995	De Montfort
1996	Bath
1997	Glasgow Caledonian
1998	Derby
1999	Bath
2000	University of East London
2001	Cardiff
2002	Leeds Metropolitan
ICMR 2003	Strathclyde
ICMR 2004	Sheffield Hallam
ICMR 2005	Cranfield
ICMR 2006	Liverpool John Moores
ICMR 2007	De Montfort
ICMR 2008	Brunel

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Advanced Manufacturing Technologies

HIGH ENERGY MILLING OF MICRO MAGNETIC POWDER FOR FINGERPRINT DEVELOPMENT

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Abstract

Highly reflective magnetic powders have been available commercially for latent fingerprint development on dark background surfaces for a few years, however there are needs of a superior darker variety of the magnetic powder which would be ideally suitable for obtaining good contrast on light background surfaces. A novel dark magnetic powder is therefore suggested for the application in latent fingerprint development on light backgrounds. Based on a comprehensive analysis of the manufacturing techniques for the production of metallic powders and previous experiences, a series of dry milling trials were proposed using a high energy vibratory mill. In these milling trials, atomized iron powders of appropriate particle dimensions were chosen as the starting material. The starting atomized iron powders are mixed with a specific process controlling agent in cylindrical plastic pots, which are fixed on the vibratory mill. Stainless steel balls were used as the milling medium. The amount of starting iron powders and the milling time are designated so as to obtain flakes of different particle dimensions. After the designated milling process, the powders were carefully exposed to the air to avoid catching fire and separated from the steel balls. Thereafter, the samples of the powders were inspected using scan electron microscope and the result reveals that some good quality flakes with leafy characteristics and high aspect ratio were developed. The samples of the powders were also used to develop latent fingerprints on a common background at the university's forensic investigation laboratory, and the result indicates that some flakes obtained can be considered as good quality darker variety of magnetic powder for fingerprint development.

Keywords: High Energy Milling, Magnetic Iron Flakes, Fingerprint Powder.

1.0 Introduction

Metallic flake powders have been widely used for fingerprint detection. In the UK there are several varieties of fingerprint powders available from different forensic suppliers, although very few of these powders are actually manufactured solely for the purpose of fingerprint detection. Typical examples of flake powders which are used extensively for fingerprint detection are aluminum powder, brass powder and Magneta Flake (a commercial variety of magnetic flake). Highly reflective aluminum powder has been the most widely used powder for fingerprint detection in crime scenes investigation and is generally employed for bright fingerprint development on dark backgrounds (most effective on glass surface). However with the introduction of Magneta Flake in the last decade, high density magnetic flake (e.g. iron) when applied on crime scenes, has been able to overcome the problem of air-borne dust level typically associated with application of low density aluminum flake when applied with standard squirrel brush [1]. Also because of its low density, aluminum powder tends to take some time to settle during application. Furthermore, the magnetic flakes are applied on the crime scene with a magnetic applicator thereby leading to somewhat non destructive fingerprint detection. Magneta Flake thus, produced a suitable alternative and as with aluminium flake it is found to be extremely reflective and ideally suitable for dark backgrounds. Recent home office evaluation of various fingerprint powders suggest that Magneta Flake actually outperforms aluminum on lot of surfaces like painted metal, gloss painted wood and others and closely matches the performance of aluminum on glass surfaces [2]. While Magneta Flake has been successfully used for bright fingerprint development on darker backgrounds, there is not a suitable powder obtained commercially which could be as effective as Magneta Flake on lighter backgrounds. Further, Home Office report suggests that one of the black magnetic powder varieties obtained commercially is actually a mixture of two particles, one large magnetic carrier particles of iron (20-200 µm) and the other smaller non magnetic particles of iron oxide (3-12 µm) which actually develops the mark in adhering to the fingerprint residue. It is however, the least used powder in crime scenes investigations, and is not very effective on most surfaces as compared to that of aluminum powder and Magneta Flake. Previous research with different metal flakes suggests that iron flake with diameters 10-25 µm would allow print development to a quality considerably superior to that of other commercial black and magnetic black powders, when applied by a magnetic applicator on light backgrounds [3]. However, manufacturing of such powders had found little success over the years. The aim of the present study is therefore to develop a superior quality of dark iron magnetic flake fingerprint powder suited for lighter backgrounds on a wide range of surface textures. A set of initial experiments have therefore been conducted to develop the darker variety of magnetic flakes and subsequently been analyzed for its suitability as a fingerprint powder.

2.0 Factors Governing the Development of Dark Flake for Forensic Applications

Although most of the commercially available metal flakes including aluminum flakes are usually produced by rotary ball milling in tonnage quantities**,** various high energy milling devices are often utilised for rapid production of trial quantities of metal powders for experimentation. They differ mostly in terms of their design and modes of operation. However, the fundamentals of change in particle morphology of ductile metal powder during high energy milling is same for all the devices and can be attributed to a combination of phases, i.e. *micro-forging*, *fracture*, *agglomeration* and *de-agglomeration*, all of them can take place simultaneously in a mill [4]. It is therefore important that periodic samples are drawn at different stages of a milling experiment and analysed in order to identify the different milling phases.

2.1 Role of Additives as A Process Controlling Agent (PCAs)

Although a large number of solid or liquid additives are used in practice in different milling applications, stearic acid ($CH_3(CH_2)_{16}COOH$) is the most common PCA used in metal flake pigments for both laboratory purposes and industrial applications. The most important function of stearic acid as an additive is essentially to lubricate the powder particles, thereby helping the process of microforging of flakes. In absence of stearic acid, frictional forces prevent particles sliding over each other and a considerably large number of particles will be involved in the impact between the balls. With addition of stearic acid, it allows particles to flow over one another resulting in fewer particles coming under the entrapment zone. Thus fewer particles will receive the impact energy and will have a greater strain increment, thereby initiating microforging. Further, studies have indicated that milling of aluminum under oxygen without stearic acid has resulted in the powder remaining in the granular form and showed a slight increase in apparent density. With the usage of stearic acid there was a substantial fall in both in apparent density and oxygen pressure, indicating that flakes have been formed with high surface area of aluminum reacting with oxygen. This has been explained by the mechanism of interaction between stearic acid and the metal in formation of the flakes. Essentially a metal stearate is formed in which metal atom is bound in the surface and the stearate atoms are roughly oriented perpendicular to the surface. Further, layers of free stearic acid may be formed above this layer which provides resistance to cold welding of the metal particles thereby inhibiting agglomeration. Another important role of stearic acid in production of fingerprint powder is that the thin coat of stearic acid remaining on the flake surfaces helps in the adhesion of flakes to a latent fingerprint deposit. Previous studies have shown that removal of stearic acid coating by solution in a suitable solvent (usually soxhlet in hot acetone) seriously reduces the effectiveness of flakes for fingerprint development [5]. It is to be mentioned that in previous studies with fingerprint powders, a variety of alternate organic coatings have been experimented with, particularly with substances which are secreted in sweat and/or sebum present in latent fingerprint residues (e.g. tripalmitin, tristearin, squalene) [6] but none of them seemed to match the quality achieved by stearic acid.

2.2 Choice between Wet and Dry Milling

Two types of milling environment can be defined based on the formation of surface films on the metal powders, reactive and non reactive milling. In reaction milling the powder surface reacts extensively in the fluid to produce surface films which inhibits agglomeration by welding. This would result in the milled powder being extremely fine. In non reactive milling, the powder particles hardly react with the milling fluid, thereby bare metal surfaces are formed which enhances the weldment of the powder particles. Metal powders milled in organic or inorganic fluids retain small amounts of the fluid dispersed throughout each particle. Thus, hydrocarbons containing hydrogen and carbon and carbohydrates containing hydrogen, carbon, and oxygen are likely to introduce carbon and/or oxygen into the particle. In essence, in wet milling a milling liquid can interact with the metal particle and influence in the same way a gaseous medium would interact in dry grinding. Normally when the final product is dry, dry milling is preferred as in the case of producing metal flakes for most industrial applications. Wet milling of metal particles is considered only when flakes fail to form by conventional dry milling route. It is therefore suggested that dark fingerprint powder be produced by dry milling, wet milling with suitable liquid can only be considered if the dry milling route cannot yield any positive results.

2.3 Colour and Visual Quality of the Powder

One of the important criteria of developing a fingerprint powder is to understand how we can obtain the desired colour of the powder. The colour of the metal flake can be governed by two factors, the basic colour of the starting material used and the presence of surface films on the metal surface. The basis colour of the metal surfaces arises out of the interaction of the electric field of light waves with conduction electrons of the metal; the detailed phenomenon is not discussed here. Essentially it can be said that to obtain a dark fingerprint powder, the colour of the starting material should not be bright and preferably darker in appearance. However, during the milling operation the starting material may undergo variety of shape changes at different stages of milling and would therefore exhibit different colours due to either specular or diffuse reflection of light. It is expected that a relatively equiaxial particle will reflect light in a diffuse manner where as flat flakes will tend to be glossy due to the specular reflection. Further the flakes should be deposited parallel to each other (leafing)[7], if not, the flakes will scatter the light by overall diffuse reflection and specular reflection will take place over very small distances of the order of the flake diameter, which would result in the loose flakes appear to sparkle. Further, although flat parallel flake surfaces would give specular reflection, the edges/perimeter of the flake will still be radiating at different angles (diffuse reflection). Thus with decreasing flake diameter the edge effect will tend to predominate and there will be more diffused reflection. It is therefore expected that to obtain dark fingerprint powder, the flake diameter has to be small, although optimum size has to be determined based on the quality of developed fingerprints. Another important factor which governs the colour of the final product is the surface chemistry of the flakes i.e. either a presence of oxide layer, a layer of metal stearate or free stearic acid; all of which are encountered in the milling process. Thickness of the oxide layer can influence the colour of the product particularly when the milling environment is non inert, i.e. in presence of air. The level of the metal stearate and/or free stearic acid could also influence the flake colour as interference effect could be produced if the layers are thick enough.

3.0 Experimental Procedure

The choice of an appropriate starting material has been determined based on previous studies [8], where it has been observed that very fine powder like iron carbonyl when milled by standard dry grinding method, forms a solid mass by agglomeration and so wet milling in a suitable liquid had to be introduced for the formation of flakes. Since the study also suggested that small particle size of the starting powder is beneficial to the production of flakes by high energy milling, in the present study, atomized iron powder manufactured by Sigma Alldrich, of approx average particle size of 15 µm has been selected as the starting material. Also the powder selected is irregular in shape as flakes produced from irregular shaped powder tend to produce dark flakes as compared to spherical particles which produce highly reflective flakes like that of Magneta Flake. A set of experiments have been carried out with different amount of starting material in a prototype vibratory mill at 3000 rpm, 50 Hz. The starting material along with 2-4 wt% of stearic acid as process controlling agent are charged in plastic containers and milled intermittently for a length of time with the aid of 7mm stainless steel balls. The milling time, the amount of starting material varied during the dry milling process to obtain flakes of different particle dimensions. Iron flake powder of 1g during the milling was sampled and characterized, subsequently analyzed by scanning electron microscope. Remaining powder was utilised for developing latent fingerprint development. Since the quality of the print can vary depending on the level of fingerprint residue, a standard procedure was therefore adopted to obtain a set of virtually identical fingerprints. A single donor rubbed his hand to distribute sweat over his fingers before pressing all his fingers on a white piece of paper. The same process was repeated for deposition of all the prints. The fingerprints were then developed for each of the powder samples using a magnetic applicator and subsequently they were scanned directly in the university's forensic department with the aid of 'Livescan', a device used for AFIS (Automated Fingerprint Identification System) in crime scene investigation.

4.0 Results and Discussion

4.1 Milling Behavior of the Iron Powder and Feasibility of the Dry Milling Process

The milling of the powder has been carried out in a prototype vibratory mill which can generate great impact forces due to the rapid vibration of the motor thus resulting in faster and finer grinding. The starting atomized powder has been milled for a maximum of 9 hrs and it has been observed that flakes of 25-30 µm have been obtained after milling for at least 4 hrs, depending on the amount of starting material used. Fig 1 shows the scanning electron microscopic image of the starting material which during the course of milling has undergone a combination of milling phases, primarily microforging and fracture. The irregularity of the particle shape of the resultant flakes indicate that the starting irregularly shaped particles are actually compressed in a non uniform manner which has resulted in flakes with complex surface contours and jagged outlines.

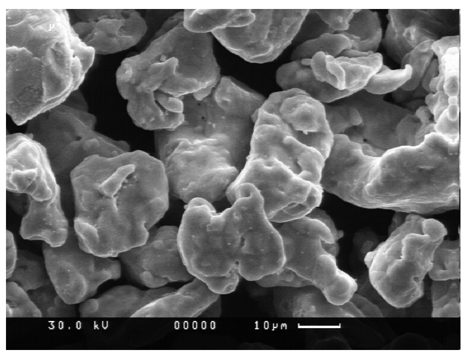


Fig. 1. Scanning Electron Microscopic image of the starting atomized iron powder manufactured by Sigma Alldrich

During the experimental study it has been observed that the dry milling process in producing flakes is feasible only when the process is carried out with some careful considerations. The powder flakes exhibited pyrophoric behavior and tend to ignite spontaneously when being exposed to atmosphere. The milling containers, made of thin plastic did not heat up substantially during the milling process and the powders only starts burning once the milling vials are opened and the flakes are being exposed to atmosphere. The burning is in the form of spatters, starting from few powder particles, then progressively spreads to other powder particles to form a lump at the end, unless they are interrupted in between and separated. However, it has been observed that with controlled exposure of powder to the atmosphere by slow bleeding of air into the milling vials at the end of the milling process and carefully separating the powder from the balls, the powder tends not to burn in atmospheric conditions. It is therefore suggested that to negate the effect of oxidation of the powder particles, dry milling should be carried out in an inert atmosphere with the addition of 2-5% of oxygen to allow careful oxidation within narrow limits. This would enable the formation of protective oxide films on the flakes thereby reducing the pyrophoric behaviour of the powder particles.

4.2 Effect of Milling Time and the Amount of Starting Material Used

Two sets of experiments were carried out with different amount of starting material; the first set of experiment with 5g of powder and the second experiment with amount varying between 15-30g. Milling time has been varied between 4-9 hrs in order to achieve flakes of different dimensions. Typically, flakes of average particle dimensions of 25-30 µm and 10 µm have been obtained as previous studies have suggested that such flake dimensions can be considered as optimum for latent fingerprint development.

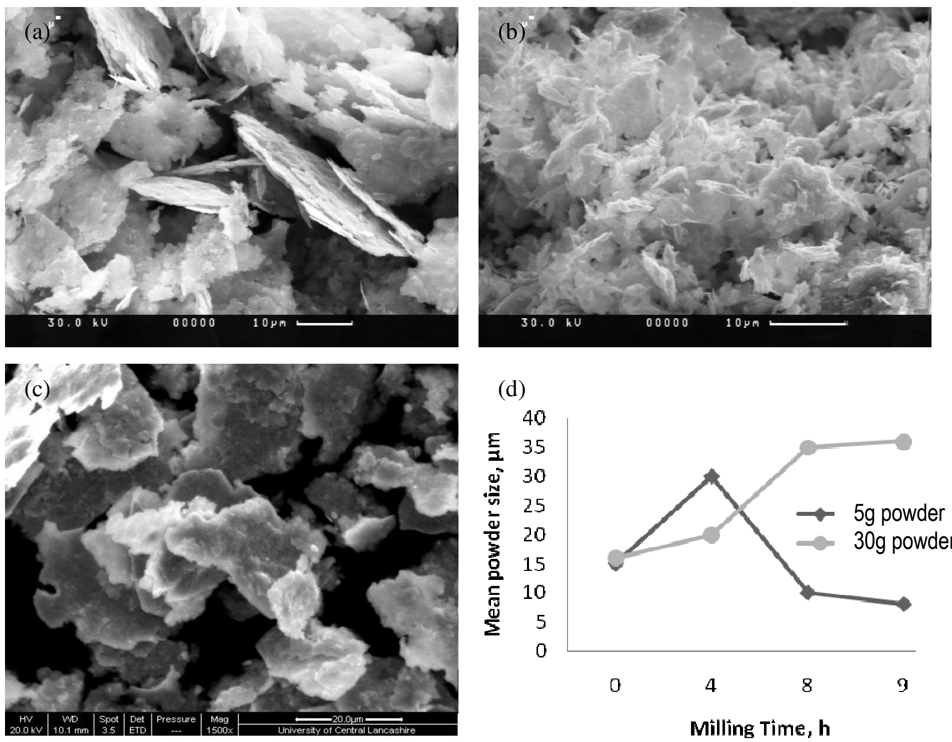


Fig. 2. Scanning Electron Microscopic image of dark iron flakes when starting material of quantity (a) 5g is milled for 4hrs (b) 5g is milled for 8 hrs and (c) 30g is milled for 8hrs and (d) graph showing the effect of milling time and the amount of starting material used (5g and 30g with similar ball to powder weight ratio) on the mean flake dimensions.

It has been observed that with 5g of starting material, dry milling for 4 hrs have resulted in flakes of average particle size of 25-30 µm. Figure 2a shows a scan electron microscopic image of a typical sample of dark powder from the 1st set of experiments, after being milled for 4 hours. The particles as observed in Scan Electron Microscope (SEM), show good flaky characteristic, but is not uniform throughout. It showed the presence of bigger particles which have not been milled properly. However, more consistent flake sizes have been obtained when a sample of the resultant flakes has undergone sieving operation and +38 µm of the fraction is being discarded. A different sample, under identical set of milling condition having undergone milling for 4 hours is being milled further for another 15mins with the aid of glass beads to achieve more uniform flakes. However, it did not show any marked difference in the surface characteristics of the flake. Further milling of powder flakes up to 8hrs has resulted in achieving flake dimensions <10 µm. Figure 2b shows a scan electron microscopic image of a typical sample of dark powder from the 1st set of experiments, having undergone milling for 8 hours. SEM analysis of the powder reveals consistent flakes have been obtained with very good leafy structures and with relatively uniform distribution.

In the initial stage of the milling process, the particles are compressed via repeated impact of the milling medium which results in a deformation (flattening) of the particle. Thus good quality flakes have been obtained of required particle dimension after milling for 4hrs. Further milling of the flakes has resulted in increased fracture of the particles due to the initiation and propagation of cracks across the particle. The cracks may occur due to work hardening, ductile rupture as the flake becomes thinner in some parts than in others, fatigue failure, fragmentation, initial defects and inclusions in particle, or a combination of these effects. This has resulted in decreasing the particle dimension to <10 µm after 8 hrs of dry milling. During the milling process, it has been observed that the amount of starting material has pronounced effect on the milling pattern. While 25-30 µm particle size has been obtained by milling 5g of powder for 4hrs, almost 8 hrs of milling was required for 30g of powder to achieve the same results. Figure 2c shows a scan electron microscopic image of a sample of dark powder from the 2nd set of experiments, where 30 g of powder has undergone 8 hrs of milling. The sample after being milled for 4 hrs did not sufficiently flatten the powders to form flakes although there has been a noticeable increase in diameter to thickness ratio. With further milling of the powder, it shows the tendency of microforging and subsequent initiation of cracks until an optimum size 25-30 µm flakes have been obtained after 8 hrs of milling. Fig 2d shows the variation in mean powder size of two samples with respect to the milling time for 5g and 30g of starting material used. Other samples with 15-25 g of powder also took much longer than 4 hrs of milling to obtain the required flake dimensions. These results clearly demonstrate that as the quantity of the starting powder charged into the milling vials are decreased, the processes of microforging, fracture and agglomeration occurred more rapidly. In all the cases, milling process was not carried out beyond 9 hours as it has been decided that total production time should not exceed 10 hours (including set up time, time for charging and discharging etc.) to make the process viable for rapid production of metal flakes on a laboratory scale. As a result, it was not possible to obtain flakes of 10 µm variety with 20-30 g of powder. It is however, expected that longer milling time up to 16 hrs would be required to obtain 10 µm variety of flakes under the present experimental set up. The overall milling time can however be reduced by changing and optimising the process parameters like increasing the efficiency of the vibratory mill, optimising the ball to powder ratio, size of the balls and quantity of the stearic acid used. The slight variation of the stearic acid level between 2-5 wt% under present experimental conditions however, had negligible effect on the milling time as well as the quality of flakes produced.

4.3 Comparative Analysis with Magneta Flake & Suitability for Latent Fingerprint Development

Samples from two set of experiments have been visually inspected and digitally photographed to compare the coloration and appearance of the powder which would be an important factor when powders are to be applied on common backgrounds to test the suitability for latent fingerprint development. It has been observed that flakes of particle dimension less than 10 µm is much darker in appearance when compared to that of 25-30 µm flakes. This can be attributed to the fact that due to the smaller average particle size of sample, edge effect is more predominant which contributed to more diffused reflection of light, as explained earlier. A sample of commercially available Magneta Flake has also been analysed in SEM and a comparative analysis has been made with the dark powder produced, as briefed in Fig 3. Elementary analysis of the powders as well as the starting material, reveals that the dark powder has got higher oxygen content compared to that of Magneta Flake, where it is almost negligible. This indicates that the dark powder has undergone slight oxidation during the course of dry milling as the starting material has found to be of pure iron without presence of any oxides. It is further corroborated from the fact that during the experiments, it was difficult to open the covers of the plastic vials indicating that there is a pressure drop inside as a result of the slight oxidation.

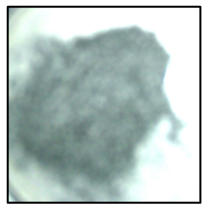
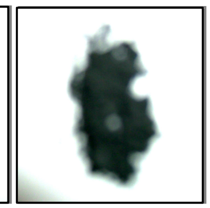
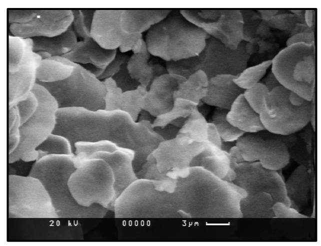
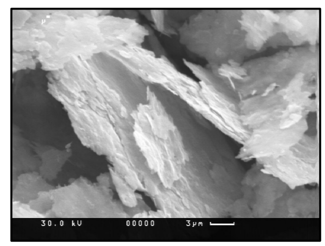
Particle	Magneta Flake	Dark Powder
Composition	Iron flake	Iron flake
Process	Wet Milling	Dry Milling
Description	Flat structure, smooth surface Highly reflective	Rough surface with jagged edges Dark appearance
Distribution	Uniform	More or less uniform
Grouping	Moderate	Moderate
Thickness	Thin	Extremely thin
Particle Diameter	10-15μm	25-35 μm, <10μm
Visual Characteristics for a lump of powder		 
Typical Scanning Electron Microscopic Image		

Fig. 3. Comparative analysis between dark flake powder and bright magnetic flakes (Magneta Flake)

A set of samples from both experiments have been utilised for developing latent fingerprints on a white background following a standard procedure to obtain identical fingerprints. Since the magnetic flakes are specifically useful for latent print development on porous surfaces such as wall, paper and polythene [9]; 80gsm A4 sized white papers have been considered for impression and development of latent fingerprints. A commercial variety of black magnetic powder has also been included in the analysis to identify the quality of fingerprint developed with respect to that achieved by the dark flakes. Analysis of the developed prints reveal that good quality of prints has been obtained using both the 25-30 μm and 10 μm variety of the flakes. Fig 4. shows the scanned images of the latent fingerprint developed by the three types of powders considered. It is evident that the best quality of developed prints has been obtained by 25-30 μm variety of the flakes with good ridge details and reasonably good contrast. It has been observed that 10 μm variety of the flakes also allowed reasonably good quality of print development with much darker appearance producing a better contrast against a white background. However, this fine flake tends to paint over the surface of the paper, thereby somewhat reducing the quality of the overall print developed. In either case, the print developed on white paper background has found to be much superior to that obtained by the commercially available magnetic powder. Further analysis by the Automated Fingerprint Identification System (AFIS) in the university's forensic department also conform the findings. It is to be mentioned that the print quality did vary slightly from sample to sample indicating that best fingerprint quality can be achieved by optimising the flake characteristics and particle dimensions. Further, it is also suggested that similar experiments can be conducted with other types of iron/steel powders as starting materials and find their potential as magnetic flakes for fingerprint development.

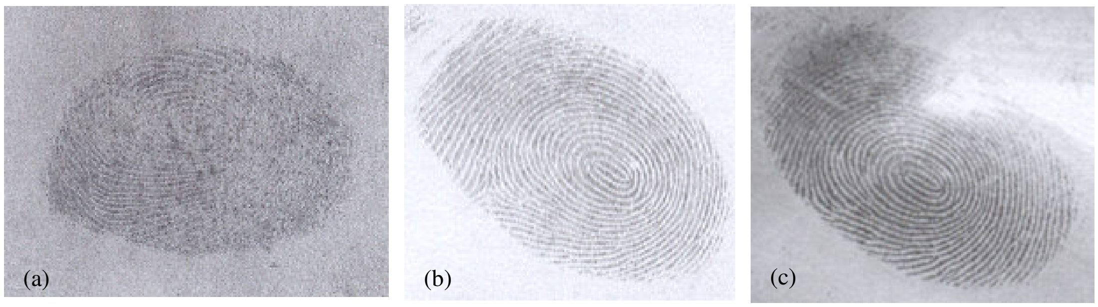


Fig. 4. Quality of fingerprints developed under identical set of conditions on a white paper using a magnetic applicator by (a) commercially available magnetic fingerprint powder (b) 25-30 µm dark iron flakes and (c) 10 µm dark iron flakes

5.0 Conclusions

High Energy Milling devices, particularly a vibratory mill can be used for rapid production of micro magnetic metal flakes which has potential applications in fingerprint technology. The magnetic properties of iron flake together with the flake characteristics achieved by dry milling can be utilised for developing a suitable darker variety of magnetic flakes for latent fingerprint development on light backgrounds. Analysis of these flakes produced from a set of initial experiments reveal that print developed can easily surpass the quality achieved by commercially available dark magnetic powders on porous surfaces. The quality of the flakes can be further enhanced by optimising the dry milling parameters including the amount of starting material, milling time and other criteria like size of milling medium, amount of process controlling agents etc. Further, other varieties of dark magnetic flakes can be produced from different starting material which can be suitable for developing latent fingerprints on a wide range of background surfaces.

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AN EVAULATION OF HEAT PARTITION MODELS IN HIGH SPEED MACHINING OF AISI/SAE 4140 STEEL

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Abstract

Temperature and heat partition at the tool rake face are significant parameters which can influence tool wear mechanisms, tool life and hence machining quality. Therefore, reducing the amount of heat flowing into the cutting tool is of particular importance. In this paper, various analytical approaches for determining the percentage of the heat flowing into the cutting tool from the secondary deformation zone are evaluated. These analytical models were either derived solely from thermal properties of the tool and workpiece materials or a combination of thermal and contact conditions. Where experimental data was required, cutting tests were performed for conventional to high speed machining of AISI/SAE 4140 high strength alloy steel at cutting speeds ranging between 100 and 880 m/min. Cutting temperatures were measured experimentally using an infrared thermal imaging camera. This predicted heat partition was then benchmarked using heat partition values available in literature. The paper elucidates on important thermal properties of the tool and workpiece, cutting process variables, and contact phenomena which should all be considered in predicting heat partition.

Keywords: Heat Partition, High Speed Machining (HSM) and Tool-Chip Contact Area.

1.0 Introduction

High Speed Machining (HSM) at significantly increased cutting speeds and feedrates can lead to a marked reduction in machining time. Therefore, HSM is now recognised as one of the key manufacturing technologies for higher productivity. Key advantages of HSM have been reported as high material removal rates, low cutting forces, the reduction in lead times and improvement in part precision and surface finish [1]. The distinction between the conventional and high speed machining depends on the workpiece material being machined, type of cutting operation and the cutting tool used [2].

The main regions where heat is generated during the orthogonal cutting process are shown in Figure 1. Firstly, heat is generated in the primary deformation zone due to plastic work done at the shear plane. Secondly, heat is generated in the secondary deformation zone due to work done in deforming the chip and in overcoming the friction at the tool-chip interface zone. Finally, heat is generated in the tertiary deformation zone, i.e. at the tool-workpiece interface, due to work done to overcome friction which occurs at the rubbing contact between the tool flank face and the newly machined surface of the workpiece.

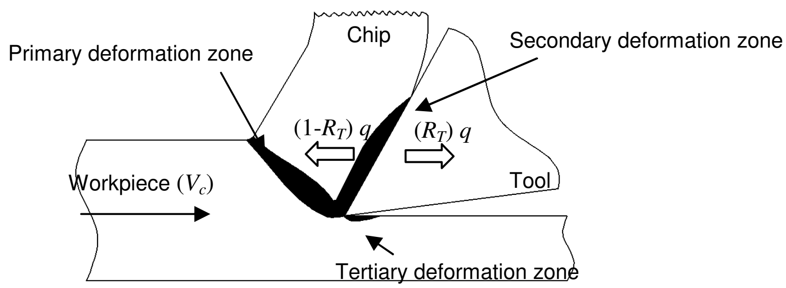

Fig. 1. Illustration of heat generation zones in orthogonal metal cutting

There are very few studies which report numerical values for heat partition, considering workpiece and cutting tool combinations, these are summarised in the Table I. Most of these, except [3], only cover uncoated tools for conventional cutting speeds. From these reported works on conventional machining, heat partition into the cutting tool (R_T) has been identified to range from 56% to 10% for machining of steels.

Table I. Reported values of heat entering the cutting tool for specified cutting velocity range and workpiece and cutting tool combination

Authors and reference	Workpiece material	Cutting tool material	Cutting velocity V_c (m/min)	Percentage of heat entering the cutting tool (R_T)
Loewen and Shaw [4]	SAE B1113 Steel	K2S carbide	30 to 182	40% down to 20 %
Takeuchi et al. [5]	Carbon steel (C = 0.55%)	P15 carbide	100	10% to 30%
Wright et al. [6]	low carbon iron	M34 high-speed steel	10-175	20% to 10%
Lo Casto et al. [7]	AISI 1040	Sintered carbide type P10	99 to 240	56% down to 24%
Grzesik and Nieslony [8]	AISI 1045	P20 uncoated carbide	50 to 210	50% down to 40%
Grzesik and Nieslony [8]	AISI 1045	Multilayer coated ($TiC/Al_2O_3/TiN$)	50 to 210	35% down to 20%
Abukhshim et al. [3]	AISI 4140	Uncoated cemented carbide	200 to 600 and 600 to 1200	46% down to 15% and 15% to 64%

This paper, presents a benchmarking of heat partition models available in literature. The reference heat partition data used which is summarised in Table I. Additionally, the tool-chip interface temperature in the secondary deformation zone is predicted. Research approaches to estimate heat partition into the cutting tool, used in this study include a machining experiment and cutting mechanics analysis. AISI/SAE 4140 steel was turned using tungsten-based uncoated carbide cutting tools and the acquired cutting forces, chip thickness, tool-chip contact area, and sticking and sliding lengths were analysed for heat source characterisation.

2.0 Analytical Models for Prediction of Heat Partition Coefficient

The fraction of heat which flows into the cutting tool (which is assumed to be stationary relative to the heat source) is based on the determination of heat partition coefficient (R_T), which defines the percentage of the heat entering the cutting tool (Figure 1). The fraction R_{ch} defines the heat energy going into the moving chip. By further manipulating heat partition models (R_T = 1- R_{ch}), the heat going into tool, R_T, can be directly computed, as summarised in Table II.

Table II. Summary of heat partition models for the determination of (R_T)

Model	Equation for the determination of (R_T)	Model	Equation for the determination of (R_T)
Loewen and Shaw [4]	$R_{L(T)} = \dfrac{\dfrac{0.377\, q\, l_{ch}}{\lambda_W \sqrt{N_p}} + \Delta\theta_s - \theta_o}{\dfrac{q\, l_{ch}\, A_a}{\lambda_T} + \dfrac{0.377\, q\, l_{ch}}{\lambda_W \sqrt{N_p}}}$	Shaw [9]	$R_{SH(T)} = \dfrac{[0.754(\lambda_T/\lambda_W)/(A_a\sqrt{N_T})]}{1+[0.754(\lambda_T/\lambda_W)/(A_a\sqrt{N_T})]}$
Reznikov [10]	$R_{R(T)} = \dfrac{[(3\lambda_T/2\lambda_W)\sqrt{(\alpha_W/\alpha_T)}]}{1+[(3\lambda_T/2\lambda_W)\sqrt{(\alpha_W/\alpha_T)}]}$	Tian and Kennedy [11]	$R_{TK(T)} = \dfrac{\dfrac{\lambda_T}{\lambda_W}\sqrt{\dfrac{1+Pe_T}{1+Pe_W}}}{1+\dfrac{\lambda_T}{\lambda_W}\sqrt{\dfrac{1+Pe_T}{1+Pe_W}}}$
Gecim and Winer [12]	$R_{GW(T)} = \dfrac{\lambda_T}{\lambda_T + 0.807\, b_W \sqrt{r_o V_{ch}}}$	Kato and Fujii [13]	$R_{KF(T)} = \dfrac{\sqrt{(C_p\rho\lambda)_T/(C_p\rho\lambda)_W}}{1+\sqrt{(C_p\rho\lambda)_T/(C_p\rho\lambda)_W}}$

2.1 Some Comments on the Existing Heat Partition Models and Their Limitations

1) Some of the heat partition models are purely based on the thermal properties of the tool and the workpiece materials (for example, Reznikov [10] and Kato and Fujii [13] heat partition models). While this methodology has been made for conventional machining its relevance to HSM has not been validated. In HSM it has been reported that tool-chip contact area increases and this widens the gap available for heat transfer [3]. Therefore, the effect of contact area needs to be taken into account.
2) These models do not account for the influence of the cutting speed and frictional heat flux on heat partition except Loewen and Shaw model [4]. Indeed, most of the studies on steel were performed only at cutting speeds less than 100 m/min with some studies at 300 m/min, which lies in the conventional cutting range where the effect of cutting speed may be neglected. Heat flux should ideally be considered for all cases.
3) The main concern about Block's procedures [14] is the universal assumption (in all cases) of a uniform distribution of heat flux over the contact region, especially when considering the existence of both sticking and sliding zones which can simultaneously occur on the tool rake face.

4) Most of these models, assume steady-state conditions when partitioning the heat generated in the primary and secondary zones. This leads to an underestimation of heat partition into the cutting tool especially in the transient regime.
5) There is a lack of consensus in the methodology for accounting of heat partition and the effect of the remote primary heat source on the rake face temperature field. In HSM, it could be argued that the low interaction time diminishes the significance of the primary heat source on rake face temperatures.

The estimated heat partition may be higher or lower than the measurements depending on how strong the factors are which discussed above. It is thus obvious that the issue of the heat partition into the cutting tool needs a more scientific study and, in particular, exploration for the HSM case. This paper investigates this aspect for the case of machining at conventional to high cutting speeds ranging from 100 to 880 m/min.

3.0 Prediction of the Tool-Chip Interface Temperature

The computation of the mean tool-chip temperature, (equation (1)), is based on dimensional analysis developed by Cook [15]. The estimated tool-chip interface temperatures were compared with the experimental data. This information was used to map the interface temperatures to cutting speeds.

$$\Delta\theta_t = 0.4 \frac{u}{\rho C_p} \left[\frac{V_c t}{\alpha_W} \right]^{1/3} \quad (1)$$

where, $\Delta\theta_t$ is the mean temperature rise at tool-chip interface, u is the total specific cutting energy, V_c is the cutting velocity, ρC_p is volumetric specific heat for the workpiece, α_W is the thermal diffusivity of the workpiece material and t is the undeformed chip thickness. Since the work material properties α_W and ρC_p depend on temperature, this equation is applied iteratively, with new material properties calculated based on successive values of $\Delta\theta_t$, until convergence is achieved. Temperature dependant thermal properties of the tool and the workpiece material are adopted from [3], [16]-[20].

4.0 Experimental Investigations

4.1 Experimental Details

The cutting tests were performed on a Dean Smith and Grace Lathe machine. A Kistler cutting force dynamometer model 9121 was used to measure the cutting forces. The inserts used were tungsten based uncoated cemented carbide, Sandvik gray that have geometry designated as TCMW 16T304 5015 (ISO specification) [Triangular shape insert with 0.4 mm nose radius, 3.97 mm thickness and 7^{o} clearance angle]. The tool holder used was Sandvik STGCR/L 2020K 16. The pre-bored workpiece used was AISI/SAE 4140 high tensile alloy steel with an external diameter of 200 mm and 2.5 mm tube thickness. The cutting tests were performed at eight different cutting speeds of 100, 197, 314, 395, 565, 628, 785, and 880 m/min. These cutting speeds were set by the available RPM on the conventional lathe. New cutting edge was used for every cutting speed. The feedrate (f) and depth of cut (a_p) were kept constant at 0.1 mm/rev and 2.5 mm respectively. The length of cut was limited to 5 mm.

4.2 Temperature Measurements

In the current work, temperatures were measured using an infrared thermal imager FLIR ThermaCAM SC3000. This system allows extensive analysis of highly dynamic objects and events typically found in metal machining research applications. The infrared thermal imaging camera was mounted near the machine turret and placed directly over the tool rake face (at 30 cm stand off distance) during cutting tests. The cutting tool temperatures were measured at the "flying line" on the tool rake face. This line was appropriately selected at prominent observable locations on the rake face of the cutting tool. When recalled on the stored image the 'flying line' gave the temperature value at the required tool-chip interface.

5.0 Results and Discussion

5.1 Tool-Chip Interface Temperature

Cutting tool temperatures along the tool-chip interface were measured from the IR images. The estimated experimental tool-chip interface temperature is presented in Figure 2 and shows a good agreement with the model developed by Cook [15] within the conventional speed region. But in the HSM region increasing deviation from the experimentally measured temperature is observed. It must be noted that Cook's equation uses the cutting velocity instead of the chip velocity, this leads to an under-estimation of the velocity effect in the high cutting speed region. Furthermore, it utilises the undeformed chip thickness and hence the heat source is considered to be purely in the shear zone and the model appears to neglect the secondary deformation zone frictional heating. However, the results are in good general agreement and only represent a small percentage deviation. To quantify the discrepancy between the experimental and predicted results, the percentage error (e) was used. The chart in Figure 3 compare the predicted average tool-chip interface temperatures to the measured results for all cutting tool inserts tested and eight different cutting speeds applied. The results are nevertheless in good general agreement.

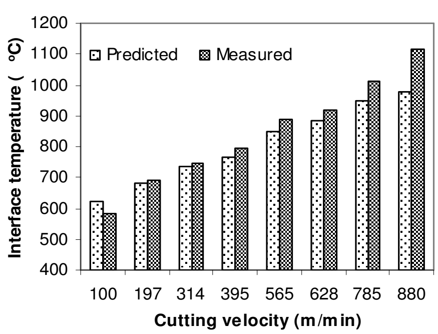

Fig. 2. Variation of the tool-chip interface temperature with the cutting speed

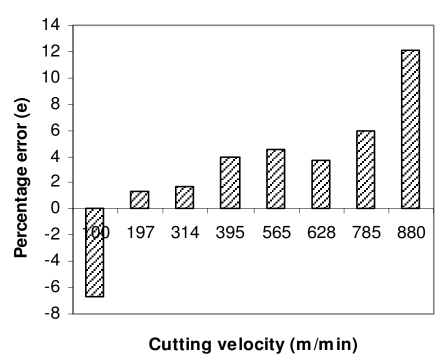

Fig. 3. Percentage error of calculated versus experimentally measured tool-chip interface temperature

5.2 Cutting Forces

The cutting and feed forces versus cutting speed relationship for the various cutting tests are shown in Figure 4. It is observed, that the cutting force decreases when the cutting speed is increased from low to medium 100 to 395 m/min, marginally increases with the cutting speed up to 565 m/min, and subsequently decreases in the high speed cutting region. The feed force also decreases gradually when the cutting speed is increased in all the cutting tests. These results generally agree with the accepted effect of cutting speed in cutting forces.

5.3 Chip Compression Ratio and Shear Angle

Figure 5 shows the variations in the chip compression ratio λ_h and shear angle ϕ with cutting speed. It is observed, that the chip compression ratio decreases while the shear angle increases when the cutting speed is increased from 100 to 565 m/min. When cutting increased up to 800 m/min, the chip compression ratio increases because of an increase in the deformed chip thickness, whereas the shear angle decreases. Consistently, the chip thickness increases along the cutting edge but the shear angle decreases. The increase in the shear angle reduces the area of the shear plane and consequently reduces the cutting force.

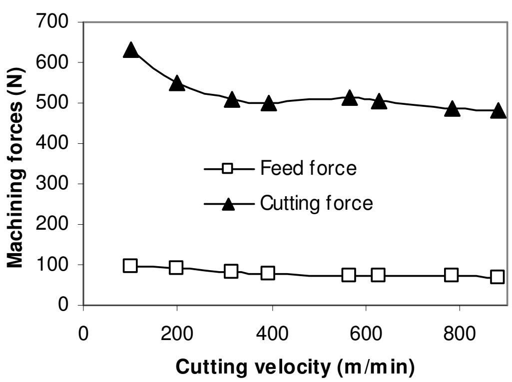

Fig. 4. Variation of the machining forces with the cutting speed

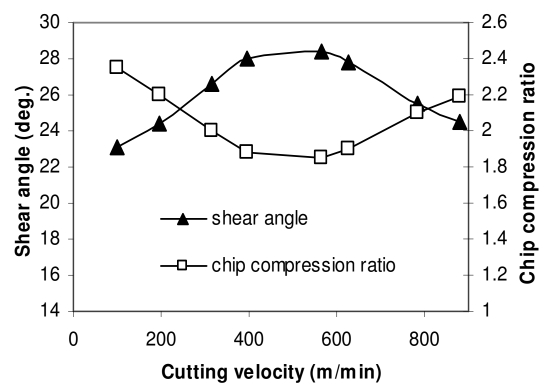

Fig. 5. Variations in the chip compression ratio and shear angle with the cutting speed

5.4 Tool-Chip Contact Area

The nature of contact between the chip and tool rake face has a major influence on the mechanics of machining, heat generation, and heat partition into the cutting tool. The tool-chip contact area of the worn carbide inserts were obtained at different cutting speeds from a Polyvar optical microscope equipped with image-processing software. Figure 6 presents the calculated tool-chip contact area obtained from the optical microscope images. From Figure 6, it is observed that the contact area is significantly affected by the cutting speed. There is a decrease in the contact area when the cutting speed is increased from 100 to 395 m/min. Beyond 395 m/min, the contact area increases with the cutting speed. This trend is in good agreement with the reduction in contact area for lower cutting speeds and also agrees with more recent findings [3] in HSM.

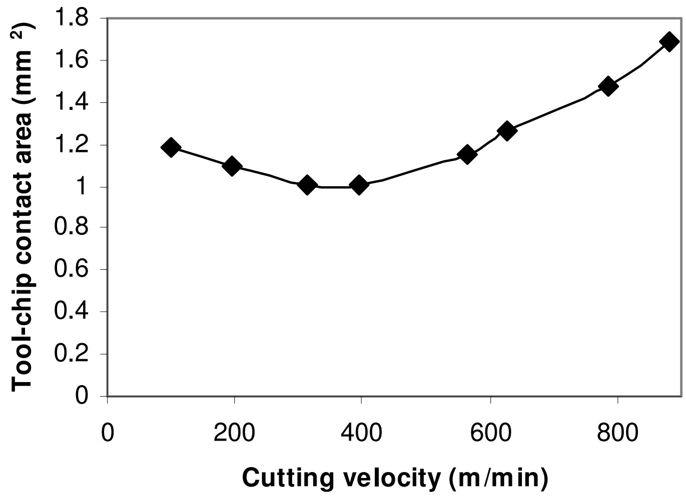

Fig. 6. Variation of the tool-chip contact area with the cutting speed

5.5 Heat Partition into the Cutting Tool

From Figure 7, it can be seen that predicted heat partition coefficients by Kato and Fujii (R_{KF}) and Reznikov (R_R), increase with the cutting speed with the maximum heat going into the tool being 63% and 72% respectively. These two models depend purely on the thermal properties of the tool and the workpiece materials, and do not take into account the contact process parameters. The Tian and Kennedy model (R_{TK}), which takes into account the influence of Peclet numbers for both the tool and the workpiece, provides values of the heat partition coefficient closer to Reznikov (R_R). On the other hand, Loewen and Shaw model (R_L) shows that the heat partition coefficient decreases with an increase in the cutting speed. It is observed that at cutting speed of 100 m/min the heat partition coefficient is 59.6% dropping to 11% at the maximum cutting speed of 880 m/min. In this case, the heat partition coefficient is modelled as a function of chip velocity, depth of cut, tool-chip contact length and most importantly, the frictional heat flux. Shaw's model (R_{SH}) predicts heat partition to be in between 13.6% down to 6% which represents the lowest amount of heat going into the tool of all the models. The values of the heat partition into the tool by Gecim and Winer (R_{GW}) range from 33% down to 15%. From Figure 7, Gecim and Winer (R_{GW}) and Loewen and Shaw (R_L) appear to be the best models for estimating the heat partition values for a wide range of cutting speeds by Abukhshim et al. [3] (Table I). It appears from this comparison that the additional information contained in the more accurate models are the variables of frictional heat flux, contact area, chip velocity, shear plane temperature, area shape factor and the triple product of ($C_p \lambda \rho$).

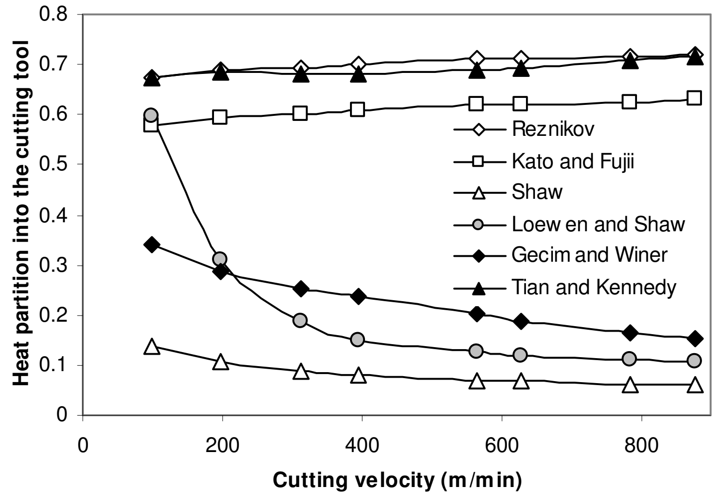

Fig. 7. Variation of heat partition with the cutting speed

6.0 Conclusions

- The results show that the contact phenomenon in addition to thermal properties influences the heat partition coefficient. In conventional machining, contact area decreases with increasing cutting speed, but in high speed region, increasing the cutting speed increases the contact area.

- Cook's model provides a reasonable estimate of the tool-chip interface temperature within the conventional machining region but slightly underestimates the tool-chip interface temperature in HSM region. This could be attributable to the use of the cutting velocity instead of the chip velocity and neglecting the heat flux. The measured cutting temperature increases with the cutting speed.

- The analytical methods by Kato and Fujii, and, Reznikov which are based solely on the thermal properties of the tool and the workpiece, appear to overestimate the percentage of heat that goes into the tool at most cutting speeds except the lowest. Kato and Fujii's model is similar to Reznikov's model but incorporates a scaling factor. Tian and Kennedy despite additionally considering the Peclet number follows the same trend as Kato and Fujii, and, Reznikov. For low cutting speeds the model developed by the Loewen and Shaw, and, Gecim and Winer that contain contact phenomena and chip velocity in their formulations, appear to be closer in agreement for estimating the heat partition. However, Loewen and Shaw model neglects the increase of heat going into the tool in the HSM region. Shaw follows similar trend but with lowering magnitude.

- Existing analytical heat partition models do not provide accurate quantitative estimates of the fraction of heat from the secondary deformation zone flowing into the cutting tool.

- Inferring from the best models, it can be concluded that the area shape factor, mean temperature rise due to plastic deformation in the primary deformation zone (shear plane temperature), frictional heat flux and contact area in addition to the usual thermal properties of the tool and the workpiece materials should all be used in developing a more accurate heat partition model.

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DRY GRINDING OF SOFT STEEL WITH USE OF ULTRASONIC VIBRATIONS

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Abstract

Compared to other machining processes, grinding involves high specific energy. A major part of this energy is transformed into heat which has a detrimental effect on surface integrity and grinding wheel wear. In conventional dry grinding, as there are no cutting fluids to transfer the heat from the contact zone, minimizing the grinding energy and grinding forces are the matters of importance. To make a step forward to pure dry grinding a new technique, called ultrasonic assisted grinding has been developed. The advantages of ultrasonic assisted grinding were proved mostly for the brittle material. Our investigations show the improvement on the surface roughness, considerable reduction of the grinding forces and thermal damage in case of using ultrasonic assisted dry grinding (UADG) comparing to conventional dry grinding (CDG) for a soft material of 42CrMo4. A decrease of up to 60-70% of normal grinding forces and up to 30-50% of tangential grinding forces has been achieved.

Keywords: Dry grinding, Ultrasonic assisted dry grinding, Grinding forces, Surface Roughness, Cutting fluids.

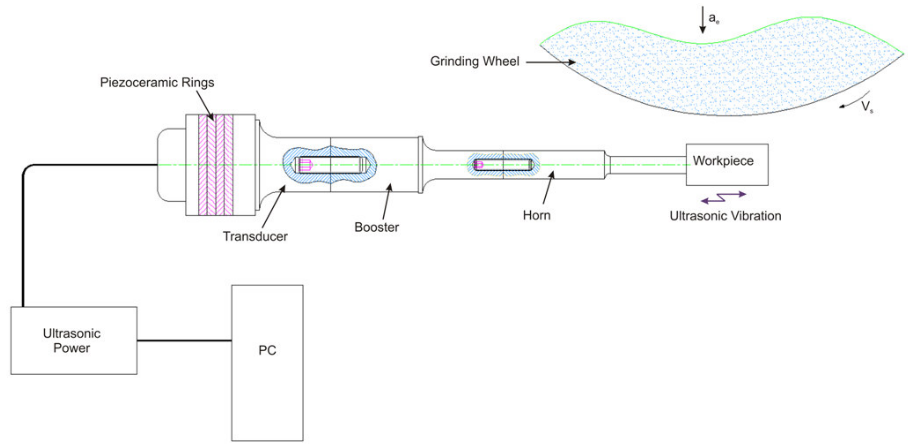
1.0 Introduction

The cutting fluids are mainly used in metal removal processes due to their effect on transmitting generated heat in the contact zone, reduction of friction in the tool-workpiece contact zone and chip transportation from the cutting area. On the other hand cutting fluids have serious disadvantages, such as health hazards and the explosiveness of oil vapor, environmental pollution, wear of the elements of the machine tool and increasing manufacturing cost. In order to decrease the negative environmental impact of the cutting fluids and reducing manufacturing costs, new machining techniques such as dry machining [1][2] are used. During grinding many of the super abrasive grits which are in contact with the workpiece do not perform real cutting, but instead generate heat by rubbing and plowing the workpiece surface in the contact zone. The high heat generation associated with a high negative rake angle and with a great contact length in grinding processes, can greatly increase the temperature in the contact zone. Without sufficient cooling and lubrication, this can cause thermal damage on the workpiece surface [3]. That is why cutting fluid is necessary in most grinding applications, and the methods of minimum grinding fluid or dry grinding have not yet been fully successful in industrial applications [4][5]. Generally in conventional dry grinding (CDG), as there is no cutting fluid to transfer the heat from the contact zone, problems frequently occur in terms of thermal damage on the workpiece surface, increasing the grinding energy and grinding forces, wear of grinding wheel, low material removal rate (regarding relatively low depth of cuts) as well as poor surface integrity compared to conventional grinding with cutting fluids. A recent and promising technique to overcome these technological constraints is known as ultrasonic assisted dry grinding (UADG). The principle of this technique is to superimpose high frequency (16–40 kHz) and low peak-to-peak (pk-pk) vibration amplitude (2–30 µm) in the feed or crossfeed direction to the tool or the workpiece. UADG is a hybrid process of CDG and ultrasonic oscillation. It is applicable to both ductile and brittle materials. By using ultrasonic assisted machining significant improvements in thrust force, burr size, material removal rate, tool wear, heat generation, noise reduction and surface finish have been reported. Zhang et al. [6] have both theoretically and experimentally concluded that there exists an optimal vibration condition such that the thrust force and torque are minimized. Takeyama and Kato [7] found that the mean thrust force in drilling can be greatly reduced under ultrasonic vibrations. Drilling chips are thinner and can be removed more easily from the drilled hole. Burr formation at the entrance and the exit sides is greatly reduced with the low cutting forces. Thus, the overall drilling quality is improved with the employment of UAD. Azarhoushang and Akbari [8] have achieved significant improvements in the circularity, cylindricity, surface roughness and hole oversize by applying ultrasonic vibration to the tool with out using any cutting fluids. Prabhakar [9] has experimentally demonstrated that the material removal rate obtained from ultrasonic assisted grinding is nearly 6-10 times higher than that from a conventional grinding process under similar conditions. Uhlmann [10] found that for ceramic materials, ultrasonic assisted grinding can be applied as an efficient production technology and the ultrasonic assisted creep feed grinding provides enormously reduced normal forces at slightly increased wheel wear and surface roughness. Tawakoli et al [11] demonstrated that in ultrasonic assisted dressing of CBN grinding wheels, considerable reduction in grinding forces and dresser wear is achievable.

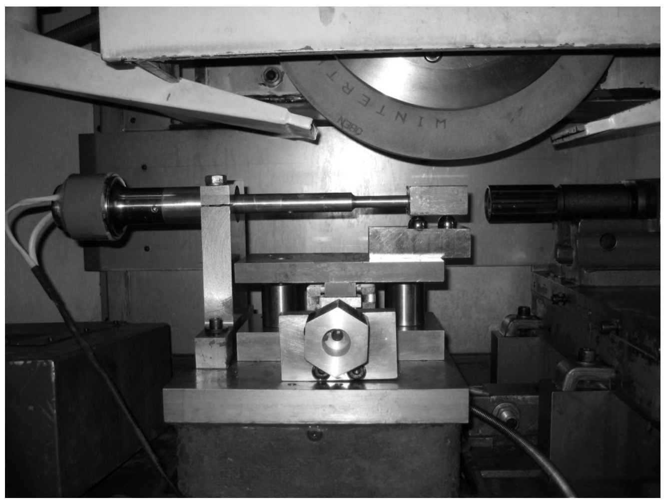
In this investigation, a UADG system has been designed, fabricated and tested. Improvements in the R_z and R_a (parameters of surface roughness) of the ground surfaces, reduction of the grinding forces and thermal damages on the ground surface due to superimposing of ultrasonic vibration in the dry grinding of 42CrMo4 have been achieved. The effect of vibration amplitude, feed speed and depth of cut on surface roughness and the grinding forces have been investigated.

2.0 Experimental Setup and Procedures

Fig. 1a illustrates schematically the experimental set-up. The workpiece holder consists of a piezoelectric transducer, a booster, a horn and a special fixture. The ultrasonic power supply converts 50 Hz electrical supply to high-frequency electrical impulses. These high frequency electrical impulses are fed to a piezoelectric transducer and transformed into mechanical vibrations of ultrasonic frequency (23 kHz), due to the piezoelectric effect. The vibration amplitude is then amplified by the booster and the horn and transmitted to the workpiece attached to the horn. The resultant vibration of the workpiece fixed in the tool holder reaches 10 µm (i.e. 20 µm peak to peak) at a frequency of about 23 kHz. Vibration is applied to the workpiece in the feed direction of the grinding wheel. The amplitude of the ultrasonic vibration can be adjusted by changing the setting on the power supply. The experimental set-up used to study UADG is shown in Fig. 1b.



(a)



(b)

Fig. 1. (a) Scheme of the experimental set-up. (b) Experimental set-up for ultrasonic assisted dry grinding.

The experimental equipment consists of the following:

- Machine tool: Elb Micro-Cut AC8 CNC universal surface grinding machine
- Ultrasonic Vibration Generator: Mastersonic MMM generator-MSG.1200.IX
- Eddy current displacement measurement system: Micro epsilon eddyNCDT 3300, to measure the amplitude of vibration.
- Surface roughness tester: Hommel-Werke, model T-8000
- Dynamometer: Kistler piezoelectric dynamometer model 9255B

3.0 Experiments

The settings of main machining parameters for the present study are summarized in Table 1.

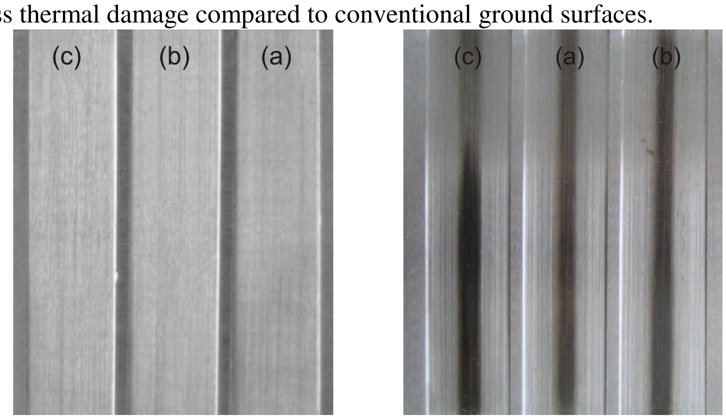
Table 1. Major machining parameters

Grinding wheel	Vitrified bond Al_2O_3 grinding wheel, Grain Size 120
Workpiece	42CrMo4, Hardness 85 HRB, Dimensions 60*55*30 mm*mm*mm
Grinding conditions	Feed speed v_{ft}= 500-1000-1500-2000 mm/min; Cutting speed v_c= 60 m/s; Depth of cut a_e= 0.010- 0.030 mm; No Coolant (Dry grinding)
Grinding process	Dry surface grinding
Dressing conditions	Wheel speed v_{cd}= 60m/s, Depth of dressing a_{ed}= 50 µm, Overlapping ratio U_d = 2, Total depth of dressing a_{ed}-total= 100 µm
Dressing tool	Diamond single point dresser width b_d =2 mm
Direction of ultrasonic vibration	Feed direction
Ultrasonic vibration conditions	Frequency f=23 KHz, Amplitude A=10µm

The tests were carried out for both UADG and CDG with the same instrument. However, during the CDG the ultrasonic generator was switched off. Every workpiece was divided into three different sections (Fig2).

4.0 Experimental Results and Discussion

Almost all of CDGs were unsuccessful due to the thermal damage on the ground workpiece surface. As there were no cutting fluids to transfer the high heat from the contact zone this result had been expected. Fig. 2 shows photographs of the ground surfaces. It is apparent that ultrasonically assisted ground surfaces have experienced much less thermal damage compared to conventional ground surfaces.



(UADG A=10 µm F=23 KHz) (CDG)

Fig. 2. The ground surfaces, v_c=60 m/s a_e=20µm a) v_{ft}=1000 mm/min b) v_{ft}=1500 mm/min c) v_{ft}=2000 mm/min.

The effect of vibration amplitude, feed speed and depth of cut on surface roughness and grinding forces were studied. In order to achieve reliable data each test was repeated 3 times. In all the figures, lines were formed by calculating the least-squares fit through the data points for a second-order polynomial equation. Fig. 3 shows the relationship between vibration amplitude and normal grinding force. The amplitude zero in this figure represents results of conventional dry grinding. The experimental results show significant improvement for UADG compared to CDG in different vibration amplitudes. Apparently, the reason for these improvements is the change of the nature of the cutting process, which is transformed into a process with a multiple-impact interaction between the abrasive grits and the formed chip.

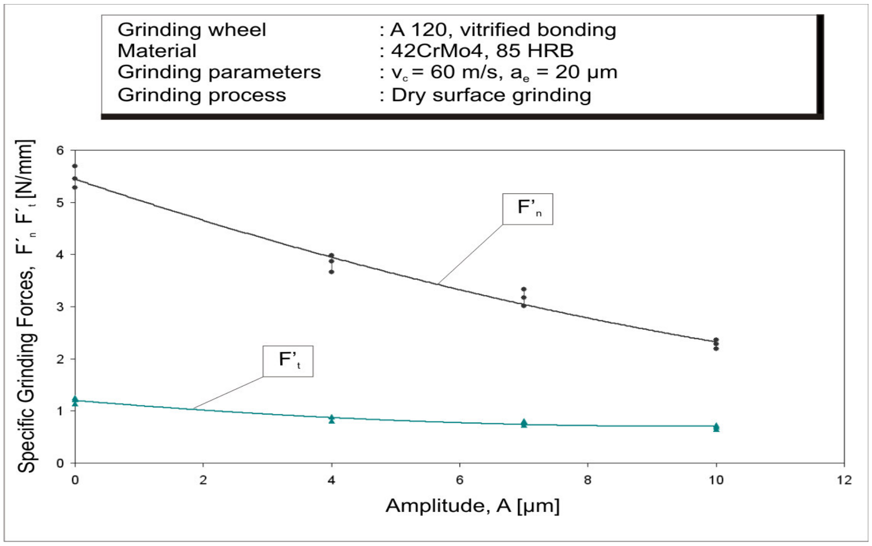


Fig. 3. Specific Grinding forces vs. Vibration Amplitude (a_e=20µm, f=23 kHz).

Figs. 4–7 compare the grinding forces and surface roughness produced by UADG with CDG under different depth of cuts and feed speeds. Experiments were carried out at v_c=60 m/s , f=23 kHz, A=10 µm. Based on the results from previous stages, it is believed that UADG performs enhanced under these conditions. These conditions are not essentially the optimal ones. For depths of cuts more than 10 µm in CDG thermal damages of the ground surfaces were observed. This phenomenon is shown with a fire symbol in the figures 4 and 5. It should be noted that the scatter in the measured surface roughness and grinding forces obtained through UADG is much less compared to CDG. It means that using UADG increases the repeatability of the process.

The maximum oscillating velocities (up to 87 m/min) and accelerations (up to 208,840 m/s^2) are generated at the amplitude of 10 µm and a frequency value of 23 kHz. The larger the vibration amplitude, the greater the material removal rate per active grain and the higher the kinetic energy with which the grits strike the work surface. Due to the high frequency interaction of active grains on the workpiece, the cutting process in UADG becomes discontinuous and ultrasonic impact action occurs, thus causing the material to begin to rollover more easily as well as more micro cracking propagation in the cutting zone which both make an effective interaction between grits and workpiece surface. Therefore the grinding forces and frictional effects are decreased, so that less plastic deformation occurs.

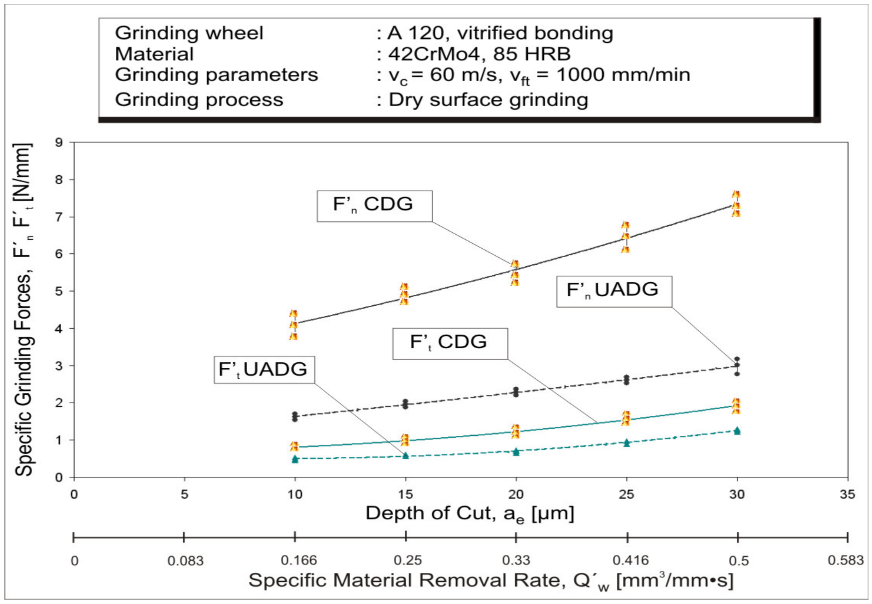


Fig. 4. Specific Grinding forces vs. Depth of Cut, v_{ft}=1000 mm/min (UADG: A=10µm, f=23 kHz).

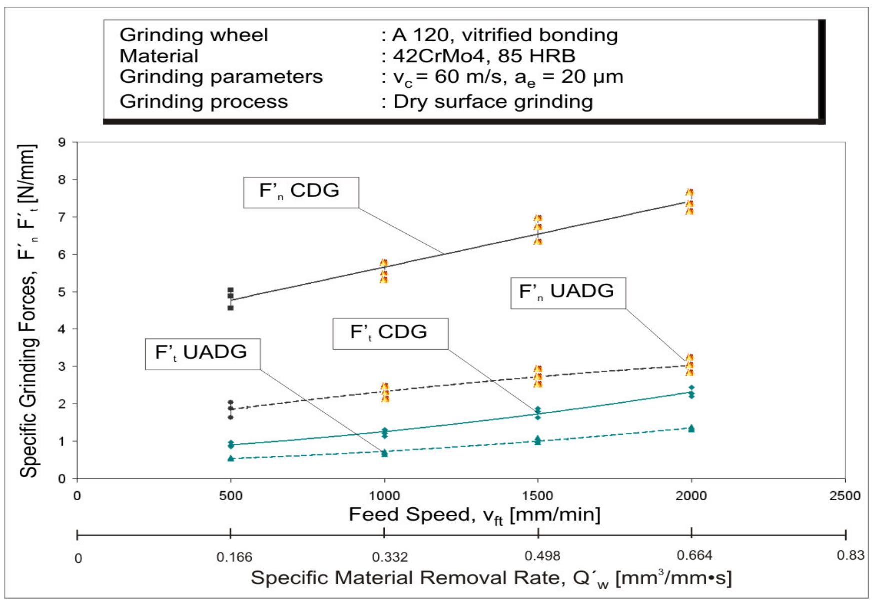


Fig. 5. Grinding normal force vs. Feed Speed, a_e=20 µm (UADG: A=10µm, f=23 kHz).

It has already been proven that deformation processes for ultrasonic assisted machining are restricted in the vicinity of the cutting edge along the surface of the workpiece and are not observed underneath the cutter, in contrast to the conventional machining process [12]. Plastic deformation of the machined surface in case of using ultrasonic oscillation is less than that in conventional machining. In addition the coefficient of friction in grinding decreases with an increase in sliding speed between the grit and the material. As the sliding speed in UADG due to ultrasonic vibration is higher than sliding speed in CDG, the coefficient of friction reduces. This suggests that in UADG a fewer number of strong bonds between the grit and the material are formed. Authors assume that by oscillation of the workpiece in feed direction, the rubbing and plowing regimes which cause the major part of plastic deformation are reduced so that the grinding specific energy is also reduced and the thermal damage on the ground surface is significantly decreased.

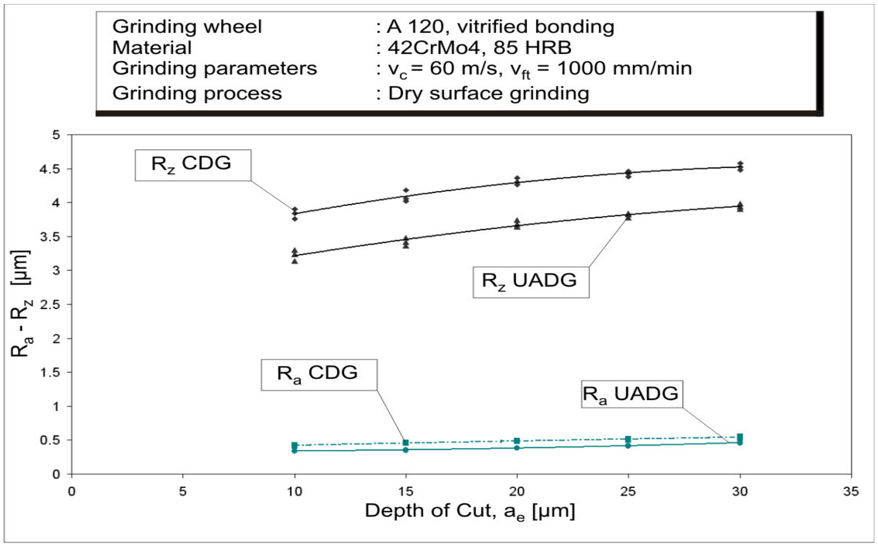


Fig. 6. R_a and R_z vs. Depth of Cut, v_{ft}=1000 mm/min (UADG: A=10µm, f=23 kHz).

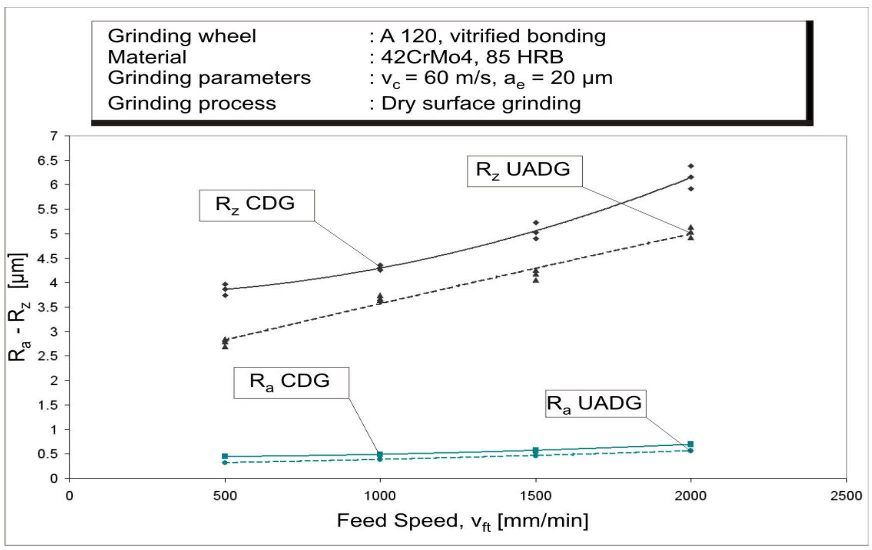


Fig. 7. R_a and R_z vs. Feed Speed, a_e=20 µm (UADG: A=10µm, f=23 kHz).

Reduction in plowing and rubbing regimes is also lead to reduction of the distance between peaks and valleys and consequently decreasing R_z. Due to feed ultrasonic oscillation (sinusoidal movement of the workpiece in feed direction) the possibility of the interaction between the grit and the workpiece surface in each contact length will be increased. It is thought that the grit will have more chance to cut the peak of the surface and therefore the R_z parameter of the surface roughness will be improved.

5.0 Conclusion

- Comparative experiments of the grinding forces demonstrated up to 70% reduction in normal grinding force and up to 50% in tangential grinding forces for the workpieces machined with superimposed ultrasonic vibration. Most of CDGs were unsuccessful due to the thermal damage on the ground workpiece surface. The reason for this phenomenon was due to the absence of cutting fluids in the process and consequently the generation of high heat in the contact zone. These improvements are subjected to the change of the nature of the cutting process in UAD, which is transformed into a process with a multiple-impact interaction between the tool and the formed chip resulting in interrupted cutting and reducing the grinding forces, frictional effect and plastic deformation zone.

- It was also found that using UADG leads to significant improvements on the R_z and R_a parameter. It is assumed that the improvement in these parameters is due to the fact that the grit in UADG has a higher chance to cut the peak of the surface due to the feed ultrasonic oscillation and increasing the possibility of the interaction of the grit and the workpiece surface in each contact length.

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EXPERIMENTAL INVESTIGATION OF DAMAGES ON MACHINED SURFACES OF GFRP PIPES

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Abstract

Composite materials play a vital role in various applications in industries such as aerospace, automobile and machine tool industry. The main reason for the significant application of composite materials is due to their excellent properties such as high specific strength, high specific stiffness, high damping, low thermal expansion and good dimensional stability. Glass Fiber Reinforced Plastic (GFRP) is an advanced composite material, which is considered to be an alternative to heavy exotic materials. It is widely used in a variety of applications which includes aircraft, robots and machine tools. Most of these applications require high quality machined surfaces with high dimensional accuracy and good surface integrity. Machining parameters, which are not carefully adjusted to the task of cutting GFRP's may lead to severe damage of work material as well as machine tool. Machining operations of cured GFRP pipes are mainly finishing operations and hence the quality achieved is of great interest. Such GFRP pipes are finding application in transportation of corrosive fluid industries. The quality of cutting results is very often carried out by visual inspection method. This work mainly focuses on the damages of the machined surfaces of hand lay up GFRP pipes. Experiments were conducted based on Taguchi's technique and the results are also tabulated and presented in this paper. Apart from visual inspection the machined surfaces are also subjected to SEM analysis for microstructural studies.

Keywords: GFRP, Machining, Taguchi, Surface Roughness, Damages

1.0 Introduction

Composite materials play a vital role in various applications in industries such as aerospace, automobile, machine tool industry [1]. The main reason for the significant application of composite materials is due to their excellent properties such as high specific strength, high specific stiffness, high damping, low thermal expansion and good dimensional stability [2]. Glass Fibre Reinforced Plastics (GFRP) have gained great importance among the composites since glass fibre reinforced polyster emerged in the early thirties. Enlarging the field of technical applications mainly for light weight components, which are mechanically highly loaded, finally resulted in the development of more efficient reinforcing materials [3]. Demand for machining GFRP materials has always existed [4] and thus the study on machining plays great importance in composite industry. Machining parameters, which are not carefully adjusted to the task of cutting GFRP's may also lead to severe damage of machine tools. Glass fibres, which are highly abrasive by nature may cause premature rounding of cutting edges. Distinct differences in hardness between fibre and matrix combined with the high cutting resistance fibres result in edge chipping. Since machining operations for cured laminates are mainly finishing operations the quality achieved is of some interest [5]. De-lamination, fiber pull-out, fibre-fragmentation, burning and fuzzing are some of the damages caused by machining on GFRP as reported by Wang & Zhang [6].

For the machining of GFRP the content of the notion "quality" has to be enlarged as compared to metal working. The material damage caused by the machining process made it evident that beyond the evaluation of surface shape and roughness a description of material affection has to take place. At present, commonly accepted standards of measurement techniques and characteristic indices do not exist. Moreover, the classification of cutting results is very often carried out by visual inspection. All these difficulties of quality description and measurement made it necessary to use GFRP of well known and equal composition for all of the tests and to carry out measurement on the same instruments, applying the same method. For this reason no other cutting data, even though available, have been used for the comparison of cutting techniques. Many authors have published cutting results of GFRP, but since in many cases the material damage and surface quality are not completely described and also they are not always comparable. This paper, therefore, is intended to give a general survey of the damages on machined surface by visual inspection method and SEM analysis.

2.0 Experimental Details

2.1 Materials and Processes

GFRP pipes were made using the resin composition of Isophthalic (50%) and Vinylester (50%). The volume fraction of the materials is 65:35 (Resin: Glass). The fiber orientation angle of the specimen used for the tests is 90^0. The hand lay up pipe composite specimens were of 75mm length, 30mm and 55mm of inner and outer diameters respectively. A CNC lathe (FANUC) with 7.5KW spindle power and maximum speed of 4500rpm was used to perform the machining operation. The force measurement was carried out by using a Kistler dynamometer. The data acquisition was carried out by appropriate software called *Dynaware kistler*.

Coated Carbide tool inserts (K_{20} grade) were used for machining. The cutting tool inserts used for the machining are of readily available Kennametal make. The geometry of the cutting tool insert is as follows: rake angle -7^0 (negative), 7^0 clearance angle, 80^0 edge major tool cutting, 0^0 cutting edge inclination angle and nose radius of 0.8mm. Tool wear was measured using Passing and Reflection type Tool Maker's microscope having a least count of 0.5micron. Flank wear was measured by the width of wearland on the flank below the cutting edge. The crater wear was measured by the depth of cup in the rake face. The surface roughness was evaluated using a surface roughness measuring instrument of Kosaka Lab, Japan. The cut off length of the instrument is 0.80 mm. A digital camera of Pentax (optio 50) make with a focal length of 5.4mm to 16.2 mm and 5.0 mega pixels of clarity was used to obtain the image of the machined surface. The machined surfaces are studied through images obtained from digital camera and SEM.

2.2 Taguchi Method

Robust design is an engineering methodology for obtaining product and process conditions, which are minimally sensitive to the various causes of variation to produce high quality products with low development and manufacturing costs [7]. Taguchi's parameter design is an important tool for robust design. It offers a simple and systematic approach to optimize design for performance, quality and cost. Taguchi methods which combine the experiment design theory and the quality loss function have been applied to the robust design of products and process and have solved even complex problems in manufacturing. Taguchi method uses a special design of orthogonal arrays to study the entire parameter space with a small number of experiments. The experimental results are then transformed in to a Signal-to-Noise (S/N) ratio. Taguchi recommends the use of S/N ratio to measure the quality characteristics deviating from the desired value. The S/N ratio for each level of process parameters is computed based on the S/N analysis. Regardless of the category of the quality characteristic, a greater S/N ratio corresponds to better quality characteristics [8].

2.3 Plan of Experiments

The methodology of Taguchi for three factors at three levels was used for the implementation of the plan of experiments. The orthogonal array L_{18} is selected which has 18 rows corresponding to the number of tests with the required columns. The plan of experiments comprises of eighteen tests where cutting velocity (V), feed rate (f) and depth of cut (d) are considered as different factors and their corresponding levels are chosen as shown in Table I. The composite pipe specimens were machined by using L_{18} orthogonal array separately with the same machining parameters for each of the eighteen test conditions. The quality responses to be observed are machining force, flank wear, crater wear and surface roughness. The experimentally collected data are then optimized using S/N ratio values calculated for each test conditions separately. The machined surfaces are also viewed and images are obtained with a high zoom digital camera to check the quality of the machined surfaces. The machined surfaces are also subjected to SEM analysis for confirmation of quality.

3.0 Results and Discussion

In order to describe the cutting results with respect to surface quality and material damage, two different measured values are used as follows,

i. Averaged roughness
ii. Width of the damaged zone

For the interpretation of these values some important remarks should be kept in mind. First of all the measurement of roughness in FRP is less dependable than in metals, Because protruding fibre tips may lead to incorrect results or at least to large variations of the reading. Additional errors may result from hooking of the fibres to the stylus. Therefore only glass and carbon fibre composites are accessable to roughness measurement. In this case, since it is a glass fibre reinforced plastic the measurement on roughness is possible on machined surfaces. The result of the roughness measurement is to a great extent dependent on the stylus path with respect to the fibre direction. Since the main direction of fibres may change from layer to layer, care has to be taken to keep the stylus path either in one layer or to get a good average of all different layers. For this reason maximum or single values of roughness like peak to valley roughness (Rt) are less suitable than integral values like averaged roughness (Ra). For the same reason the roughness has been measured atleast several times and then again been averaged. The evaluation of materials damage by microscopic inspection, of course, bears the uncertainty, whether or not all materials defects – especially those beneath the surface – have been detected. In addition to this, damage first occurs as single spots of delamination rather than as complete margin, which is typically for a high intensity of damage. From the structural – mechanic's point of view an integrated value, containing the damaged area or, an averaged width might be a more precise description of the damage situation. At present no sufficient data about the engineering strength of damaged FRP are known, which could decide whether the maximum damage, the averaged damage or the size and shape of damage should be measured. The criteria of visible appearance may in many cases be as important as the performance of the work piece. Hence, in this work the damages are first observed under visual inspection method by considering width of the damage and later confirmed through SEM images.

Also the machinability in this work was evaluated by the parameters such as surface roughness (R_a), machining forces and tool wear. The results obtained through experiments are presented in Table I. Taguchi's Design of Experiments techniques were used for conducting experiments. Also these techniques are effectively used for optimization of parameters. By considering the cutting velocity, feed rate and depth of cut and their interactions, the number of experimental trials required was determined as 18 and the experiments were conducted with different cutting inserts of the same specification to obtain more data.

Machining of GFRP is continued with the same insert up to a maximum material removal of 30 cm^3. For such constant volume of material removal, the tool wear, machining force and surface finish are measured under different machining conditions. The Taguchi's approach to experiment design consists of the following steps. The first step in Taguchi method is to determine the quality characteristic which is to be optimized. The output or response variable which influence effectively on the quality of the product is known as quality characteristic. In this study, the tool wear, machining force and surface roughness are the quality characteristics. In the second step, the control parameters or test parameters which have significant effects on the quality characteristic are identified with the required number of levels. In the third step, the appropriate orthogonal array for the control parameters is selected after calculating the minimum number of experiments required to be conducted by considering the interactive effects. In the Taguchi method of optimization, the signal-to-noise ratio is used as the quality characteristic of choice.

Smaller the better characteristic: $$S/N = -10\log\frac{1}{n}\sum \bar{y}^{2} \qquad (1)$$

where,

$\bar{y}$ - Average of observed values, n-Number of observations

In this study, "the smaller the better" characteristic is applied to determine the S/N ratio for tool wear, machining force and surface roughness, since all these parameters are to be minimized.

Table I: Machining parameters and its responses

Test Condition Number	Speed (m/min)	Feed rate (mm/rev)	Depth of Cut (mm)	Flank Wear (mm)	Crater Wear (mm)	R_a (micron)	F_m (N)	S/N ratio of 100% Combined Objective
1	100	0.05	0.5	0.023	0.018	3.95	17.50	28.20
2	100	0.1	1	0.018	0.048	8.21	47.50	27.51
3	100	0.2	2	0.028	0.018	6.22	17.50	30.00
4	150	0.05	0.5	0.017	0.018	4.25	17.70	27.25
5	150	0.1	1	0.048	0.015	8.52	15.00	28.83
6	150	0.2	2	0.025	0.015	5.03	15.00	33.38
7	200	0.05	1	0.018	0.008	6.07	07.50	30.82
8	200	0.1	2	0.018	0.013	6.07	12.50	30.30
9	200	0.2	0.5	0.023	0.012	6.34	11.50	29.60
10	100	0.05	2	0.025	0.013	4.73	12.80	27.86
11	100	0.1	0.5	0.020	0.030	6.14	30.00	28.38
12	100	0.2	1	0.020	0.023	7.51	22.50	26.81
13	150	0.05	1	0.025	0.025	3.81	25.00	31.38
14	**150**	**0.1**	**2**	**0.016**	**0.013**	**4.03**	**12.50**	**33.89**
15	150	0.2	0.5	0.015	0.008	3.73	07.50	32.88
16	200	0.05	2	0.023	0.008	4.41	08.00	27.51
17	200	0.1	0.5	0.028	0.018	8.12	17.50	30.30
18	200	0.2	1	0.023	0.012	5.08	12.00	28.20

Optimal combinations of parameters are determined based on assumed weightage of 1: 2: 3: 4 for crater wear, flank wear, machining force and surface roughness respectively. The weightage of parameters was assumed on the basis of physical significance of each parameter during machining. Surface roughness plays an important role in many areas and is a factor of greater importance in the evaluation of machining accuracy [12], and hence it is given maximum weightage. Machining force plays the next prominent role after surface roughness [2], and therefore the next best weightage was assumed to it. Apart from surface roughness and machining force, tool wear also contributes significantly in determining the optimum machining characteristics. Mostly flank wear is considered, since it largely affects the stability of the cutting wedge and consequently the dimensional tolerance of the machined work surface [9]. And hence the weightage for flank wear is assumed as the third best, while the weightage for crater wear was assumed to be the least. The S/N ratios of combined objective with flank wear, crater wear, machining force and surface roughness are calculated and presented in Table I.

3.1 Visual Inspection Method

As discussed earlier the machined surfaces are zoomed and observed using a 5.0 mega pixel digital camera. The surface of the GFRP pipe before machining is shown in figure 1. The roughness of the unmachined surface was found to be around 80 microns. Figures 2 and 3 are the images corresponding to test condition numbers 5 and 2 respectively. The measured average roughnesses of these surfaces are found to be 8.52 microns and 8.21 microns respectively. These two test conditions produced the maximum roughness in terms of numerical value. And it is clearly confirmed by the images presented in figures 2 and 3. Not only have the two test conditions produced poor finish but also through visual inspection method maximum damages are observed. If the cutting parameters of these two test conditions are analyzed, it is observed that in these two cases minimum feed rate was not there. Hence it is clearly inferred that feed rate is the most significant parameter which influences the quality of the machined surface. Therefore the feed rate should be minimum to get good quality of machined surfaces on machining hand lay up GFRP pipes.

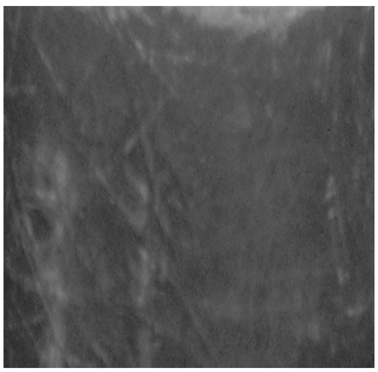


Fig. 1. Unmachined Surface

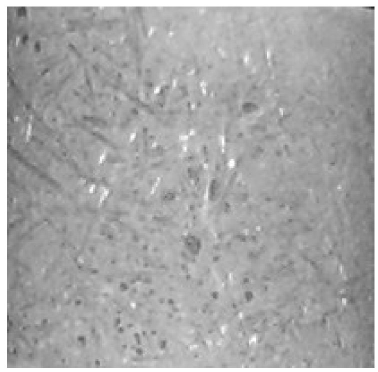


Fig. 2. Machined surface of TCN 5

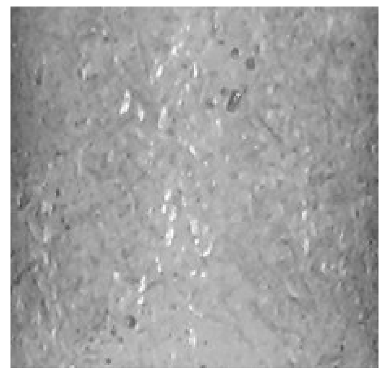


Fig. 3. Machined surface of TCN 2

Figures 4 and 5 are the images corresponding to test condition numbers 13 and 15 respectively. The measured average roughnesses of these surfaces are found to be 3.81 and 3.73 microns respectively. These two test conditions produced the minimum roughness in terms of numerical value. And it is clearly confirmed by the images presented in figures 4 and 5. The damages on the machined surfaces of figures 4 and 5 are found to be very minimum as compared to the surfaces presented in figures 2 and 3. If the cutting parameters of these two test conditions are analyzed, it is observed that in most of these cases the feed rate was found to be minimum. Hence again this study reiterates that the feed rate is the most significant parameter which influences the quality of the machined surface.

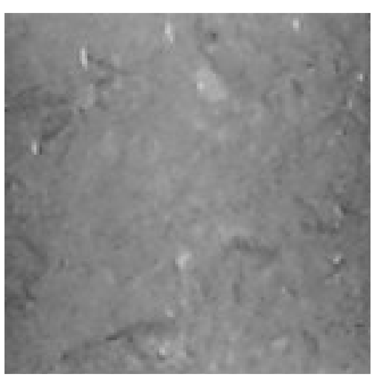


Fig. 4. Machined surface of TCN 13

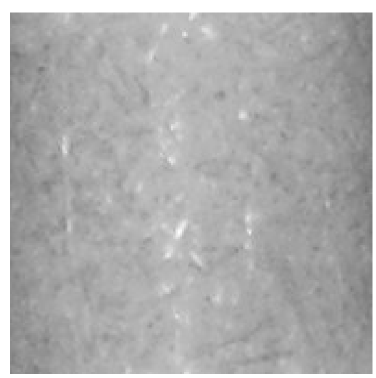
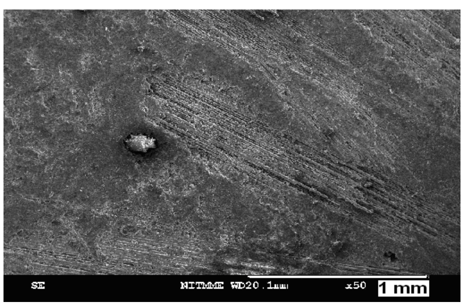


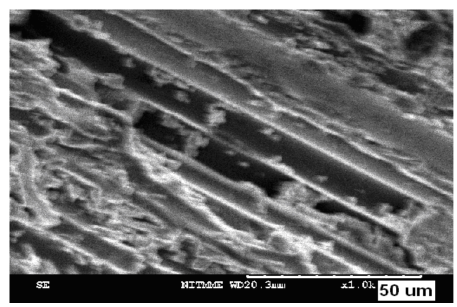
Fig. 5. Machined surface of TCN 15

3.2 SEM Analysis of Machined Surfaces

In order to confirm the results obtained from visual inspection method, the machined surfaces are subjected to SEM analysis. Figure 6 (a) & (b) represents the microstructure obtained on lower and higher magnifications respectively of machined surface for test condition number 5 (poor cutting conditions). The surface roughness of these surfaces was found to be 8.52 microns. The increased surface roughness is due to the poor selection of machining parameters. And also the damage on the surface is also found to be severe. Figure 7 (a) & (b) represents the microstructure obtained on lower and higher magnifications respectively of machined surface for test condition number 15 (good cutting conditions). The surface roughness of these surfaces was found to be 3.73 microns. The minimum surface roughness is due to the proper selection of machining parameters. And also the damage on the surface is also found to be minimum. Figure 8 (a) & (b) represents the microstructure obtained on lower and higher magnifications respectively of machined surface for test condition number 14 (optimal cutting conditions). The surface roughness of these surfaces was found to be 4.03 microns. Test condition number 14 is considered to be the optimal cutting condition since the S/N ratio of the combined objective is maximum as presented in Table I. Under some specific cutting conditions the surface of machined specimens are damage free as shown in figures 7(a) and 7(b). But under some other specific cutting conditions, debonding and fiber breakage takes place easily as shown in figures 6(a) and 6(b). More number of porous sites and damaged zones are observed in the case of hand laid up composite tubes. The average surface roughness of the machined hand lay up composite tubes is comparatively of larger order due to inherent pores during manufacture and induced damages during machining. From all these studies, it is confirmed that the results obtained are identical in all the three investigation methods namely, Taguchi's optimization technique, Visual Inspection method and SEM analysis.

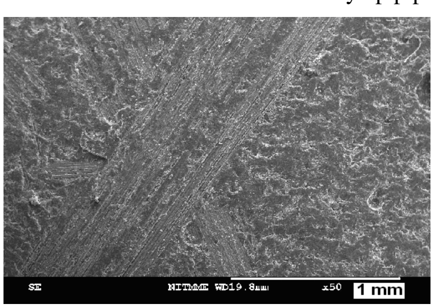


(a)

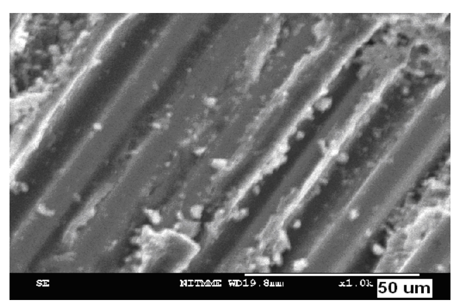


(b)

Fig. 6. Machined surface of Hand Lay up pipes - poor surface finish (TCN 5)

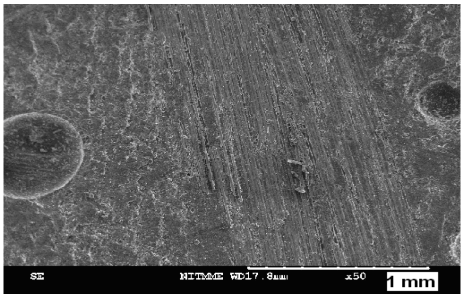


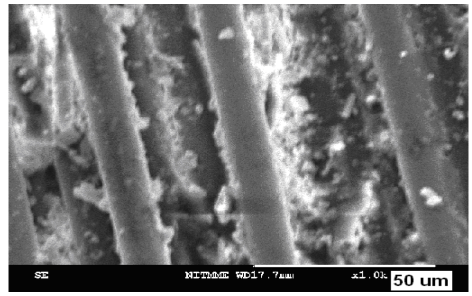
(a)



(b)

Fig. 7. Machined surface of Hand Lay up pipes - best surface finish (TCN 15)





(a) (b)

Fig. 8. Machined surface of Hand Lay up pipes – optimal test condition (TCN 14)

4.0 Conclusion

In this work, the quality of the machined surfaces of GFRP pipes made by hand lay up process is thoroughly analyzed. From this study, it is observed that the feed rate is the significant machining parameter which affects most the quality of the machined surfaces. The visual inspection method which was carried out in this work is found to be a useful tool to check the damages of the machined surface. It also gives identical result as that of results obtained from any numerical optimization technique or by SEM analysis. Debonding and fiber breakage often takes place in the case of conventional cutting conditions. More number of porous sites and damaged zones are observed on the machined surfaces of hand lay up composite tubes. To get damage free surfaces, optimized machining parameters have to be used. The SEM analysis of the machined surface confirms that these optimized parameters not only reduces the tool wear but, also reduces the damages and failures on the machined surface.

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A COMPARISON BETWEEN PROCESS 3D TOLERANCE STACK-UP AND TOLERANCE CHART

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Abstract

Tolerance allocation and manufacturing operations selection in process planning are two essential factors governing the product cost in manufacturing. For this reasons, the development of more efficient approaches has become an inescapable necessity in order to solve the tolerance allocation and the manufacturing operations selection problems during process planning. In the DFM/CE (Design for Manufacturing/Concurrent Engineering) context, a dimension of the product is often subjected to modifications, once a dimension of the product is changed the impact on the manufacturing side has to be considered. The process plan has to be changed without delay, the process designer has to take rapidly a correct decision. In order to solve this practical DFM/CE problem the tolerance chart method is used. When manufacturing a product with routed operations over a series of machining cuts, process engineers face with a tolerance stack-up problem. To handle the tolerance stack-up problem in manufacturing, the most effective way is to use a tolerance chart. The tolerance chart is a graphic tool which ensures an accurate development of the mean working dimensions and the required tolerances by the manufacturing process. The most essential task of tolerance charting is the tolerance-chain identification. Nowadays, several computer aided systems are available, they are able to carry out a statistical analysis of dimensional variations, in these software tools tolerance and attributes are interactively extracted from CAD models, feature attributes are varied within the specified tolerance range, and user-defined statistical distributions are used in simulation runs to determine: the contributors, the extent of contribution, and statistical distribution of the analyzed part dimensions. The present work suggests a new approach using the Computer Aided Tolerance tools (CAT) implementing a tolerance chain in this environment and finally comparing the obtained results with two traditional tolerance chart methods: Surface Chain Model, and Digraphic Method.

Keywords: Tolerance charting, Process planning, Tolerance allocation, 3D Stack-up.

1.0 Introduction

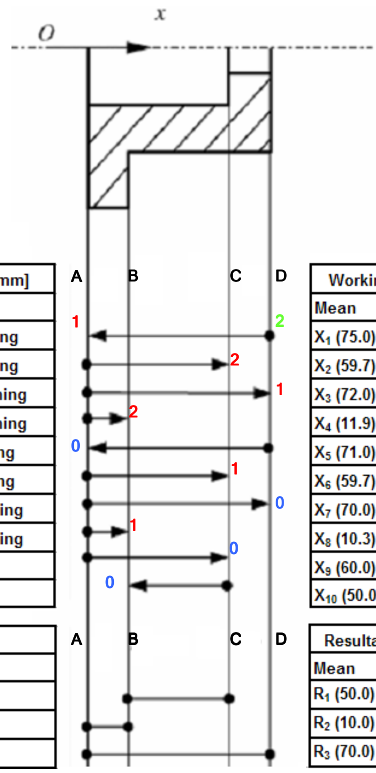
During a metal cutting process planning, process engineers should be able to assign the right tolerance to every machining cut operation, this is a tolerance stack-up problem. To handle the tolerance stack-up problem in manufacturing the most effective way is to use a tolerance chart thanks to which it is possible to ensure an accurate development of the mean working dimensions and the tolerance required by the manufacturing process. In the past the tolerance chart analysis was carried out manually [1]-[2]-[3], but since 1980s some researchers have developed computer aided tolerance-charting tools in order to automatically proceed to the tolerances allocation [4]-[5]-[6]. Subsequently other methods have been proposed and actually, the process tolerance chain is carried out through the usage of manual methods (i.e. Digraphic Method [6] e Surface Chain Model [7]). Other authors have developed appropriate methods in order to manage the correct sequence of manufacturing operations and their respective tolerances [8]-[9]-[10]-[11]-[12] but in any case they are not able to manage review requests coming from the manufacturing processes analysis (DFM/CE approach). The authors' aim in the present work is therefore to determine the tolerance for each sequenced manufacturing operation. This philosophy leads to minimize the manufacturing cost for each geometric feature. In order to reach these objectives the authors extend the usage of a traditional computer aided tolerance tool (VisVSA®) to solve a practical DFM/CE problem [7]. The obtained results, thanks to the usage of a CAT tool, have been compared with the ones obtained through the application of manual methods.

2.0 Proposed Methodology and Test Case Setup

A test case has been considered as reference for the application of the proposed methodology with its original tolerance chart [7] (Fig. 1).

If tolerance allocation phase is performed by traditional "One Dimension" (1D) approach like Digraphic Method or Surface Chain Model two key aspects are taken into consideration: tolerance control and tolerance planning. Tolerance control is performed by a continuous control on the real process in order to consider its real capabilities (usually defined SPC - *Statistical Process Capabilities*) while, tolerance planning is carried out thanks to the adoption of proper: tolerance charts and tolerance chain calculations.

Tolerance Chart needs, as shown in Fig. 1, the following input data: Design dimensions – "Blueprint Dimensions" (B_i and $\pm b_i$); Operations (*Opi*) and their sequence; Reference datum planes selection; Process Capability (C_p) of each machining operation ($\pm x_i$); Stocks Removal (Y_i). From a graphical point of view, in the tolerance chart the selected datum plane is indicated with a black ball while, the machined surface by the *Opi* is indicated by a black arrow. To each machined surface is assigned a letter, while to each machining operation is assigned a progressive number starting from 0 (last operation in the sequence) and increasing it for every other cut applied to the machined surface.



	Operation Description [mm]	
S	Op.	Name
1	10	Rough Boring
2	10	Rough Boring
3	20	Rough Turning
4	20	Rough Turning
5	30	Finish Boring
6	30	Finish Boring
7	40	Finish Turning
8	40	Finish Turning
9	50	Grinding
10	60	Grinding

Working Dimension [mm]		Stock Removal [mm]		
Mean	± Tol - SPC	Mean	± Tol	Chain
X_1 (75.0)	x_1 (.150)	Y_1 (Solid)	y_1	
X_2 (59.7)	x_2 (.150)	Y_2 (Solid)	y_2	
X_3 (72.0)	x_3 (.150)	Y_3 (3.0)	y_3 (.300)	-3,1
X_4 (11.9)	x_4 (.100)	Y_4 (Solid)	y_4	
X_5 (71.0)	x_5 (.100)	Y_5 (1.0)	y_5 (.250)	-5,3
X_6 (59.7)	x_6 (.100)	Y_6 (1.0)	y_6 (.500)	6,-5,3,-2
X_7 (70.0)	x_7 (.050)	Y_7 (1.0)	y_7 (.150)	-7,5
X_8 (10.3)	x_8 (.050)	Y_8 (0.6)	y_8 (.400)	-8,5,4,-3
X_9 (60.0)	x_9 (.050)	Y_9 (0.3)	y_9 (.150)	9,-6
X_{10} (50.0)	x_{10} (.025)	Y_{10} (0.3)	y_{10} (.125)	10,-9,8

	Blueprint Dimension [mm]	
	Mean	± Tol
1	B_1 (50.0)	b_1 (.025)
2	B_2 (10.0)	b_2 (.075)
3	B_3 (70.0)	b_3 (.050)

Resultant Dimension [mm]				Chain
Mean	± Tol			
R_1 (50.0)	r_1 (.025)			10
R_2 (10.0)	r_2 (.075)			-10,9
R_3 (70.0)	r_3 (.050)			7

Fig. 1. Tolerance chart for the considered reference case [7]

Tolerance Chain gives as output data: Mean of working dimensions (X_i); Stock removal tolerances ($\pm y_i$); Mean and tolerance of Resultant Dimension (R_i and $\pm r_i$). In this treatment is reported uniquely the tolerance chart and the tolerance chain results without explanation about the usage of the tolerance chain methods. As previously said the considered methods are Digraphic Method and Surface Chain Model, both methods provide the same results summarized in Fig. 1, and afterwards compared with achieved results of this work.

In the studied reference case the "1D" method used to evaluate the tolerance chain is replaced with a "3D" tolerance chain calculation carried out directly within a computer aided tolerance environment (Fig. 2).

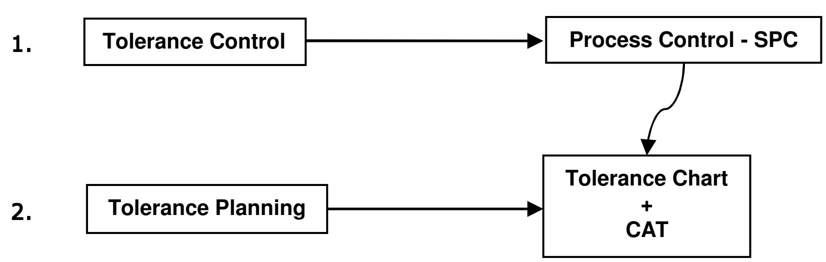


Fig. 2. Proposed methodology: "3D" approach to allocate the tolerances during process planning

In the present work the authors have applied the proposed methodology to the test case shown in Fig. 1 to demonstrate the effectiveness of the obtained results and the improved flexibility. The operative steps adopted (Fig. 3) in order to setup the numerical model are:

1. 3D Model creation within CAD environment (UG-NX® 4.0.4.2);
2. Model import within CAT environment;
3. Numerical model setup (modeling and characterization of features plane);
4. Measurements definition;
5. Simulation setting and execution;
6. Results analysis and comparison with Blueprint Dimensions.

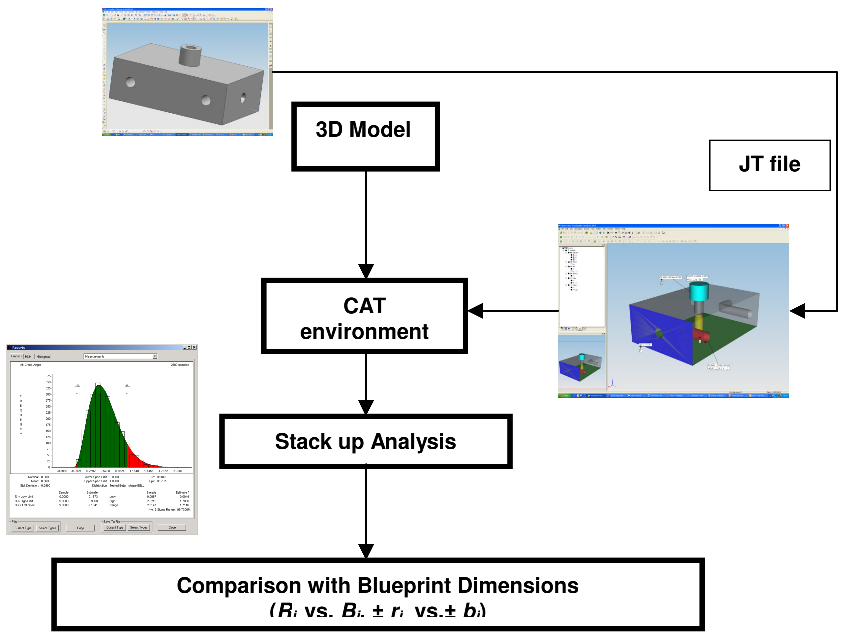


Fig. 3. Proposed operative steps

In order to let available the CAD information within the CAT environment a transfer format is needed (JT file). This operative step is performed within the CAD environment with a dedicated export template. When the geometric model has been built the next steps were: a) to create a file into the CAT environment able to contain: the information arising from the geometric features, GD&T (Geometric Dimensioning and Tolerancing) information, assembly sequence, measurements, results; b) to import the design model within the CAT tool. The authors have implemented a model having proper features plane in order to simulate datum and machined surfaces during the virtual cutting operations (*Opi*), obtaining the setup reported in the Fig. 4 to perform the "3D" tolerance chain.

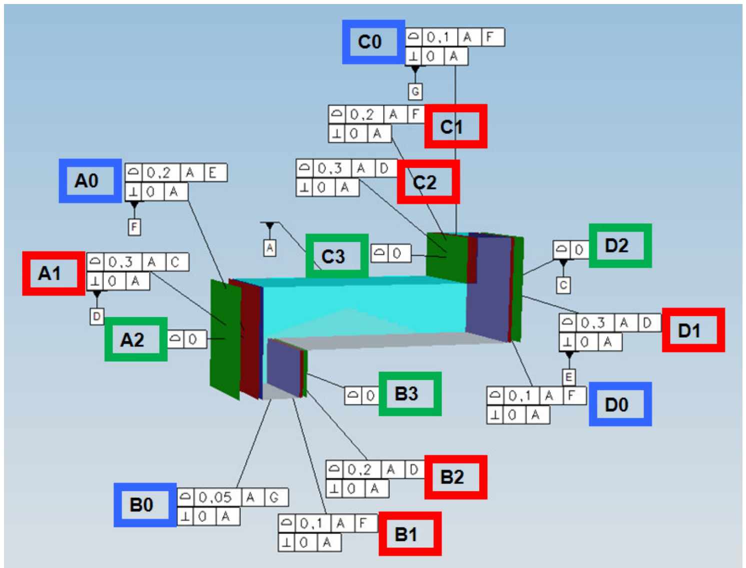


Fig. 4. CAT model

In particular, taking as reference the Fig. 4 layout it can be said that: green features planes represent the rough surfaces (A2-B3-C3-D2), red features planes represent the machined surfaces by *OPi* (A1-B2-B1-C2-C1-D1) and finally the blue features planes are the finished surfaces (A0-B0-C0-D0). For each feature plane it has been created: *i)* a profile tolerance of surface having as tolerance zone (Gaussian distribution) the *Cp* (Process Capability - x_i from Fig. 1). The defined profile tolerance of surface has as first reference the datum A and as second reference the machined surface *Opi* ; *ii)* a perpendicularity constraint (perpendicular tolerance) having a tolerance zone equal to zero and as reference the datum A; *iii)* a datum assigned to the machined surfaces in order to guarantee the process chain (Fig. 5).

Definition	Description	GD&T				Datum
		Symbol	Tol.[mm]	1°DATUM	2°DATUM	
D2	Unprocessed Surface	⌓	0			C
A1	Processed surface by S 1_OP 10	⌓	0.3	A	C	D
		⊥	0	A		
C2	Processed surface by S 2_OP 10	⌓	0.3	A	D	
		⊥	0	A		
D1	Processed surface by S 3_OP 20	⌓	0.3	A	D	E
		⊥	0	A		
B2	Processed surface by S 4_ OP 20	⌓	0.2	A	D	
		⊥	0	A		
A0	Finished surface by S 5_OP 30	⌓	0.2	A	E	F
		⊥	0	A		
C1	Processed surface by 6 _OP 30	⌓	0.2	A	F	
		⊥	0	A		
D0	Finished surface by S 7_OP 40	⌓	0.1	A	F	
		⊥	0	A		
B1	Processed surface by S 8_OP 40	⌓	0.1	A	F	
		⊥	0	A		
C0	Finished surface by S 9_ OP 50	⌓	0.1	A	F	G
		⊥	0	A		
B0	Finished surface by S 10_OP 60	⌓	0.05	A	G	
		⊥	0	A		

Fig. 5. Features plane definition

3.0 3D Tolerance Stack-up

A measurement setup has been carried out within the CAT software (Fig. 6) in order to check: the working dimension (X_i), the stock removal (Y_i), the resultant dimension (R_i) and the respective tolerance zones ($\pm x_i$, $\pm y_i$, $\pm r_i$). The numerical simulation has been launched having the setup reported below: Number of runs: 1000; Extreme Simulation, Monte Carlo Simulation in order to calculate the contribution of each tolerance [14], Geometric Tolerance (in this way the simulation uses the assigned geometric tolerances). Extreme Simulation is based on the Worst Case Model and usually it is referred to the "Method of Extremes" [14]-[15] that is the simplest and most conservative of the traditional approaches. In this approach, the tolerance at the interface is simply the sum of the individual tolerances. The following equation (1) calculates the expected gap variation.

$$t_{wc} = \sum_{i=1}^{n} |a_i t_i| \qquad (1)$$

Where: t_{wc} = maximum expected variation (equal bilateral) using the Worst Case Model; a_i = sensitivity factor that defines the direction and magnitude for the i^{th} dimension. In a one dimensional stack-up, this value is usually +1 or −1; t_i = equal bilateral tolerance of the i^{th} component in the stack-up.

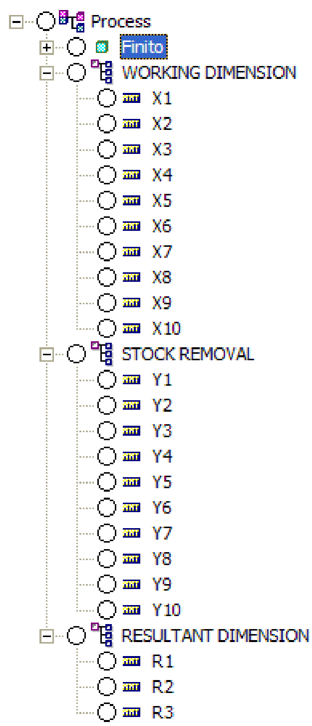


Fig. 6. Measurement setup

Once simulation has been performed the obtained results (Fig. 7) can be analyzed thanks to proper post-processing tables and they can be compared with Blueprint Dimensions.

Measurement	Mean	Sample Range
X1	75,00	0,30
X2	59,70	0,30
X3	72,00	0,30
X4	11,90	0,20
X5	71,00	0,20
X6	59,70	0,20
X7	70,00	0,10
X8	10,30	0,10
X9	60,00	0,10
X10	50,00	0,05

Measurement	Mean	Sample Range
Y1		
Y2		
Y3	3,00	0,60
Y4		
Y5	1,00	0,50
Y6	1,01	1,00
Y7	1,00	0,30
Y8	0,60	0,80
Y9	0,30	0,30
Y10	0,30	0,25

Measurement	Mean	Sample Range
R1	50,00	0,05
R2	10,00	0,15
R3	70,00	0,10

Fig. 7 – Working Dimension, Stock removal and Resultant Dimension obtained by "3D" tolerance stack-up within CAT

	Blueprint Dimension [mm]		1D - Resultant Dimension [mm]		3D - Resultant Dimension [mm]	
	Mean	± Tol	Mean	± Tol	Mean	± Tol
1	B_1 (50.0)	b_1 (.025)	R_1 (50.0)	r_1 (.025)	R_1 (50.0)	r_1 (.025)
2	B_2 (10.0)	b_2 (.075)	R_2 (10.0)	r_2 (.075)	R_2 (10.0)	r_2 (.075)
3	B_3 (70.0)	b_3 (.050)	R_3 (70.0)	r_3 (.050)	R_3 (70.0)	r_3 (.050)

Fig. 8. Comparison between Blueprint dimension, "1D" resultant dimension and "3D" resultant dimension

Comparing the obtained results with the values reported in the Fig. 1 it is possible to state that the proposed methodology can be used as a valid alternative method to the manual one (Fig. 8), moreover the proposed methodology, using a "3D" tolerance stack-up approach, is more flexible and efficient. When the resultant dimension is calculated (R_i, ± r_i) and it is compared with a Blueprint dimension (B_i, ± b_i), if there is a difference between R_i and B_i the process designer has to modify Y_i. Another possible scenario is related to possible differences between r_i and b_i; in this case, the process designer has to modify x_i, and/or the number and/or the operation sequence. Often, after these changes, it is necessary to make a new calculation for the tolerance chain with a subsequent time consuming calculation phase. In total according with a DFM/CE approach, the authors, with the proposed methodology, are able to modify rapidly, the tolerance stack-up changing for instance the x_i, or the operation sequence, etc.

4.0 Conclusions

This paper presented an efficient approach to allocate the tolerance during process planning phase. The proposed approach considers the chance to use a Computer Aided Tolerance software in substitution to a manual method (i.e. Digraphic Method, Surface Chain Model). The obtained results lead to assert: the global correlation between the *obtained* values and the effectiveness arising from the usage of the proposed methodology. Possible further development can be:

- Apply the approach to an industrial and more difficult case.
- Implement this methodology in a parametric CAD/CAM in order to perform automatically the tolerance chain starting from the CAM operation sequence.
- Take into consideration, in the simulation, directly the real process capability data for each operation (statistical method – Monte Carlo simulation).

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A NOVEL SEMIBONDED ABRASIVE PLATE FOR FINISHING ADVANCED CERAMICS

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Abstract

To reduce or eliminate the surface damage caused by lager particles invading into the machining zone, and improve the processing efficiency in the ultra-precision abrasive machining for advanced ceramics, the concept of semibonded abrasive machining, which employs a newly developed semibonded abrasive plate (SBAP) as machining tool is put forward in this paper. The manufacturing process of the SBAP is introduced. A high polymer SSB, which can be solidified as drying and be redissolved by water, is used as the semibond material, a SBAP made of 1000# SiC abrasive is presented as an example. Experiments for the studies of surface damage in semibonded and loose abrasive lapping are carried out with the polished damage-free silicon wafer and 180# B_4C as the large particles. The surface quality and material removal rate of workpieces in semibonded and loose abrasive lapping are discussed with SEM photos, AFM images, surface roughness and the weight of removed workmaterial. Experimental results show that the SBAP lapping leads to little surface damage, and the material removal rate in SBAP lapping is much higher than loose abrasive machining. In the case of large particles invasion, the surface damage of loose abrasive machining gets worse and the material removal rate increases greatly, while those of SBAP lapping are little affected. This result can be attributed to the 'trap' effect of SBAP to large particles. The feasibility of concept of semibonded abrasive machining is proved.

Keywords: Semibonded abrasive machining, semibonded abrasive plat, 'trap' effect, surface damage

1.0 Introduction

Advanced ceramics, such as silicon, sapphire, quartz, and silicon nitride, are key materials for optical, electronic, magnetic, and structure components, which set stringent requirements on surface quality and precision. Abrasive machining process is the essential method for finishing the advance ceramics. Abrasive machining, as the retaining state of the abrasive is concerned, can be classified into loose abrasive machining, such as lapping and polishing, and fixed abrasive machining, such as grinding. Lapping/polishing is an effective mean to obtain super smooth and low damage surface [1]. The disadvantages of loose abrasive machining are that the material removal rate is low, and the surface quality is sensitive to the size consistency of the abrasive grains. Once, larger particles, which are the larger ones mixed in normal abrasive grains, grain agglomerate, chips fallen off from workpieces, or large ones from the environment, invade into machining zone, surface damage such as scratch and deep crack will be caused [2]-[5]. Increasing reworks result in low processing efficiency and high cost.

Although the material removal rate in fixed abrasive machining is much higher, and the surface roughness is up to several nanometers, the surface damage is inevitable. Take Electrolytic in-process dressing (ELID) grinding for example, in the work of Ohmori.H [6], although the surface roughness Ra of ground silicon wafer is up to 2.8nm, the depth of surface damage layer is 1μm. Problems such as workpiece 'chipping' during grinding process, manufacturing of super-fine grinding wheel, and self-dressing of grinding wheel are not solved completely [7]. For these reasons, fixed abrasive machining has not been taken as the finishing process for the high surface quality required advanced ceramics.

High surface integrity and processing efficiency are expected to be reached simultaneously and it is hardly achieved by the existing abrasive machining process. In this paper, a novel abrasive machining employing the semibonded abrasive plate (SBAP) is put forward. It is conceived that the requirement of high processing efficiency and surface quality in the semibonded abrasive machining is met by the 'trap' effect of SBAP, which can reduce or eliminate the surface damage such as deep crack and scratch caused of large particles. The conception of the semibonded machining and manufacturing process of SBAP is introduced. The effectiveness and 'trap' effect of SBAP is investigated with experiments.

2.0 Conception of the Semibonded Abrasive Machining

During the ideal abrasive machining, grain particles are in same size, and loads on grains are even. Once larger particles emerge, the workpiece is supported with the several larger ones as shown in Fig.1. The increasing loads on these particles result in surface damages. It is essential to improve the consistency of grain and clean the environment. But, these works cost much and couldn't resolve the problem completely.

In order to avoid the surface damage from the 'invasion' of larger particles, a novel abrasive tool-SBAP is developed. As shown in Fig. 2, SBAP, same as the common grinding tools, consists of abrasive grains, bond material and pores. What makes different between common grinding tool and SBAP is that the adhesion between grains and bond material in SBAP is relative weak. When a larger particle emerges on the SBAP surface, grains surrounding the larger particle can be forced to move for adjustment. A 'trap' is formed on the surface of SBAP, and the larger particle is contained in SBAP. Fig.3 illustrates the 'trapping' process of larger particle. Since the adjustment of grains on SBAP surface is 'plastic', load on the larger particle will not increase obviously that prevents surface from damage such as deep crack and scratch.

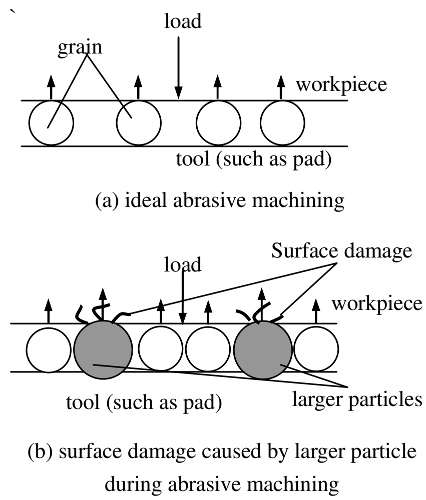


Fig. 1. Illustration of surface damage caused by larger particle during abrasive machining

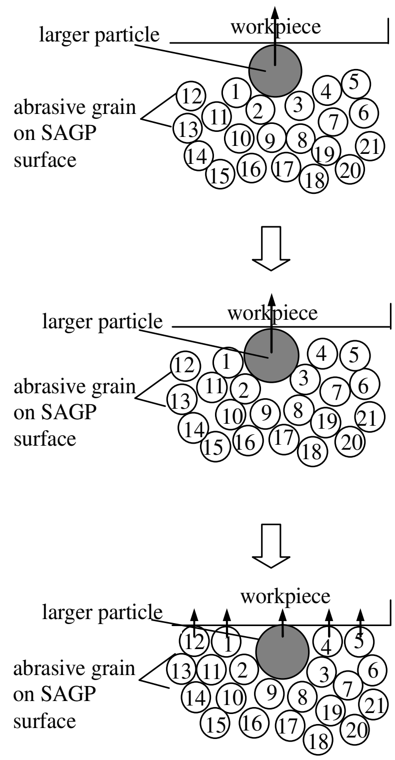


Fig. 3. 'Trapping' process of larger particle on SBAP surface

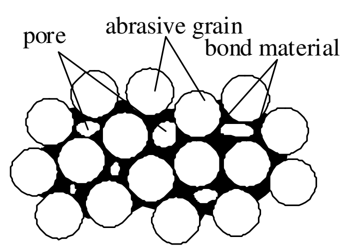


Fig. 2. Compositions of SBAP

Since retention force to retain the abrasive grains in the bond is intervenient between the fixed abrasive and the loose abrasive, the novel abrasive tool is named semibonded abrasive plate (SBAP). The ability of SBAP to contain the larger particles, here, is called 'trap' effect. According to this conception, the SBAP should possess the following primary characteristics: 1) porosity to provide enough space to contain the larger particle, and 2) relative low retention force to ensure the movement of gains to form a 'trap'. On the other hand, retention force on grains should not too weak to stand against collapse caused by the grinding force.

3.0 Manufacturing of SBAP

The bond material plays a key role in SBAP. A high polymer SSB, which can be solidified by drying, is developed to be used as bond agent. It can be redissolved in water forming a kind of glue-like liquid, which can be taken as the semibond material. SBAP is manufactured as a fixed abrasive tool. As shown in Fig.4, the surface layer of SBAP is wetted with water to form a semibonded layer before it is used to machine the workpiece. The adhesion between wetted SSB and abrasive grain can be adjusted by controlling the amount of water sprayed on the SBAP surface.

Fig.5 shows the manufacturing process of SBAP. SSB, abrasive and other additives are mixed together homogeneously in hot water. Then, the mixture is poured into a mould as shown in Fig.6, and baked under constant temperature 60°C for 72 hours. Fig.6 shows a SBAP, whose volume ratio of abrasive, pore and bond material is 5:3:2. Fig.8 is the SEM micrograph of the SBAP.

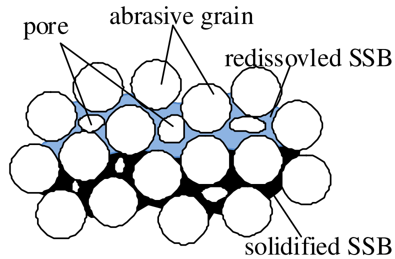


Fig. 4. Illustration of semibonded layer on SBAP surface

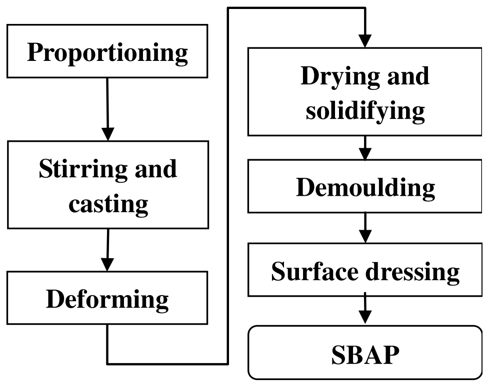


Fig. 5. Manufacturing process of the plates

Fig. 6. Mixture of SiC abrasive and SSB in a mould

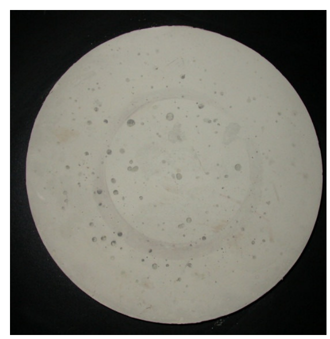


Fig. 7. A manufactured SBAP

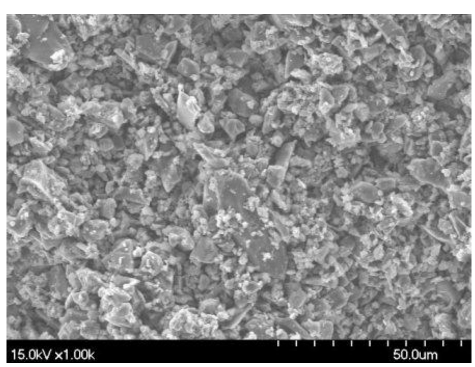


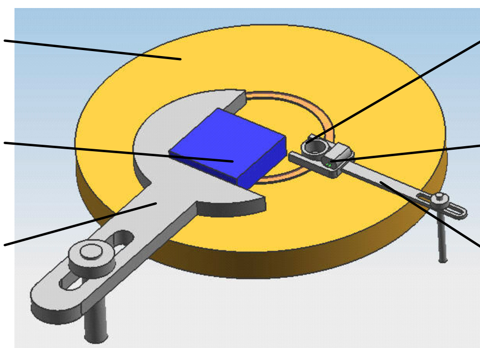
Fig. 8. SEM micrograph of SBAP

4.0 Experiment

To demonstrate the effectiveness of SBAP, a series of experiments are carried out. Larger particles are added onto SBAP surface during lapping process, and the silicon wafer surface lapped by SBAP is observed to analyze the 'trap' effect of SBAP. A silicon wafer lapped by loose abrasive is taken as a comparing sample.

4.1 Experimental Setup

Experiments are carried on a Nanopoli-100 ultra-precision polishing machine. As shown in Fig.9, a piece of polished wafer is fixed on the workpiece carrier, and loaded against SBAP. Large particles are stored in the filler. As the vibrator works, large particles fall onto the SBAP surface, and will be transported into the lapping zone. The area on the wafer surface lapped with larger particles and the area lapped without larger particles are observed respectively. In another experiments, silicon wafer is lapped by loose abrasive.



1-SBAP, 2-workpiece carrier, 3-clamp of workpiece, 4-filler of larger particles, 5-vibrator, 6-cross beam

Fig. 9. Schematic illustration of SBAP lapping system employed in this study

4.2 Experimental Conditions

The experimental conditions in this study are listed in Table 1. Fine finishing silicon wafer with surface roughness Ra 0.744nm and Rmax 11.54nm is employed as workpiece. SBAP used in this study is made of 1000# SiC abrasive. The volume ratio of abrasive, pore and bond material is 5: 3: 2. During the SBAP lapping experiment, SBAP surface is wetted by de-ionized water. In the loose abrasive lapping experiment, 20% wt 1000# SiC water based slurry is used. Processing parameters, such as load and rotational speed of plate, in the two experiments are same. To compare the effect of large particle on the surface quality in the two experiments, 180# B_4C abrasives are taken as the larger particle, and added into machining zone respectively. During SBAP lapping, the filling rate of larger particles is 0.2g/s. In the lapping process, 2%wt B_4C abrasives are added directly in slurry.

Surfaces lapped with or without larger particles are observed with SEM (Hitachi S-4700, resolution: 1.5nm/15KV, 2.1nm/1KV) and AFM (Vecco Nanpscope3a Enviroscope, scanning scope: 90μm×90μm×5μm, horizontal resolution 0.2nm, vertical resolution 0.03nm). Surface roughness is measured with Pethometer S2

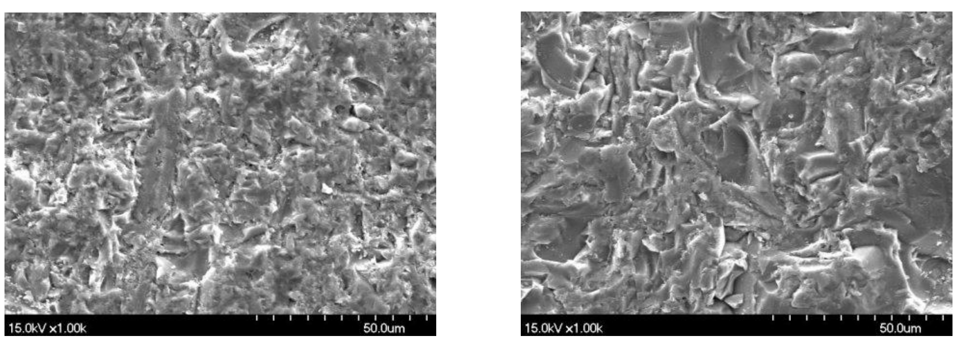
(Maer Co., accuracy: 0.1nm, Filter: ISO 2CR, cut-off 0.8 mm and Evaluation length 7 consecutive cut-off). Material removal rate is measured by a precision electronic balance (accuracy: 0.1mg).

Table 1: Experimental conditions

Items	SBAP Lapping	Loose Abrasive Lapping
Workpiece	Ø20mm Silicon Wafer, Ra 0.744nm, Rmax 11.54nm	
Lapping Machine	Nanopoli-100	
Abrasive	1000# SiC	
Added Larger Particle	180# B_4C	
Load	15kpa	
Rotational Speed Of Plate	50rpm	
Processing Time	10min	
Abrasive Concentration In Lapping Slurry	--	20% Wt
Lapping Plate	--	Iron Plate
Volume Ratio Of Abrasive, Pore And Bond Material	5: 3: 2	--

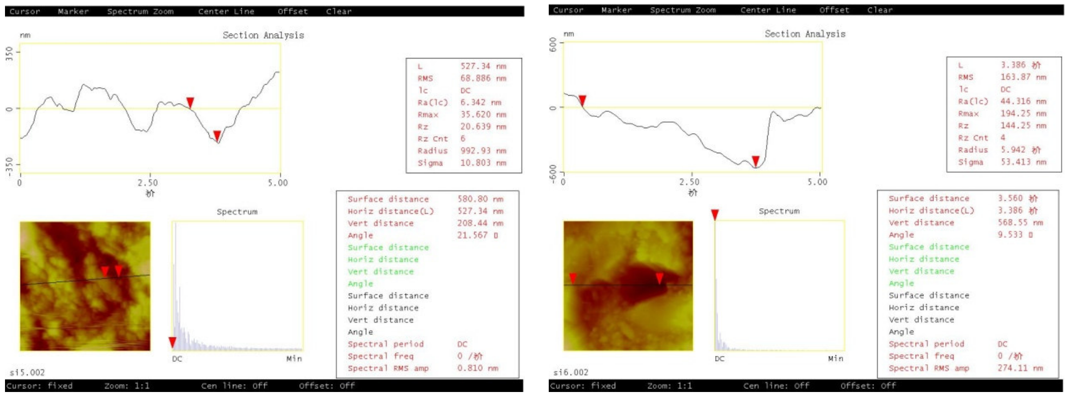
4.3 Results and Discussion

Fig.10 and Fig.11 show the SEM and AFM images of silicon wafers lapped with loose abrasive respectively. Fig. 12 and Fig. 13 show the SEM and AFM images of silicon wafers lapped by SBAP respectively. It can be judged from the Fig.10 that abrasive grains rolling against the wafer surface is the dominant material removal mechanism during the loose abrasive lapping process. As shown in Fig. 10(b), the surface quality is aggravated by the rolling actions of the larger particles added into lapping slurry. Fig.11 shows the effect of the added larger particle on the depth of scratch in loose abrasive lapping. The maximum depth of the scratch on the wafer surface increased obviously from 208.4nm to 568.6nm, as the larger particle is added into slurry. The results show that it is difficult to prevent the surface form the damages caused by the invasion of lager particles in loose abrasive lapping.



(a) Surface lapped without larger particle (b) Surface lapped with added larger particle

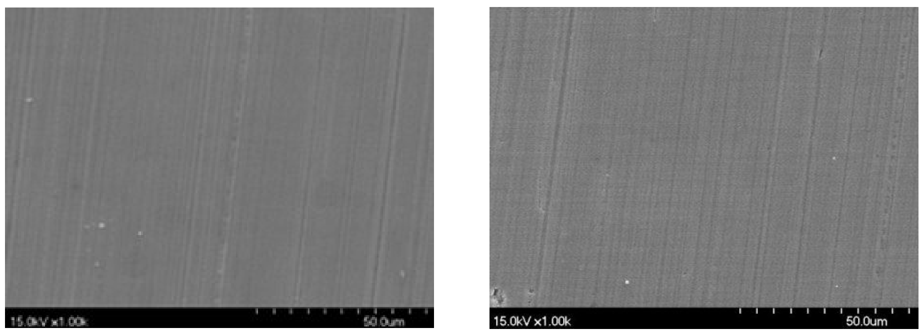
Fig.10. SEM images of lapped surface of silicon wafer with loose abrasive



(a) Surface lapped without larger particle
Maximum depth of the scratch is 208.4nm

(b) Surface lapped with added larger particle
Maximum depth of the scratch is 568.6nm

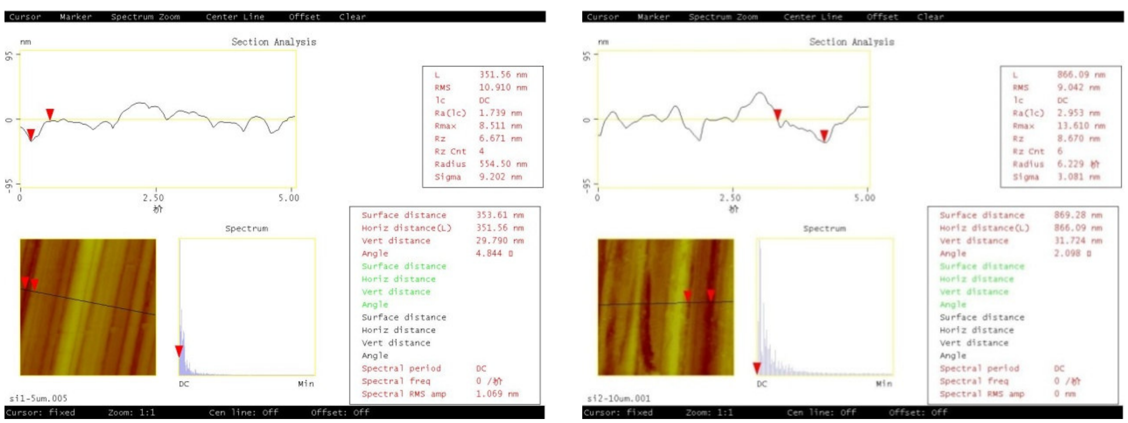
Fig. 11. AFM images of lapped surface of silicon wafer with loose abrasive



(a) Surface lapped without larger particle

(b) Surface lapped with added larger particle

Fig. 12. SEM images of lapped surface of silicon wafer with SBAP



(a) Surface lapped without larger particle
(Maximum depth of the scratch is 28.9nm)

(b) Surface lapped with added larger particle
(Maximum depth of the scratch is 31.7nm)

Fig. 13. AFM images of lapped surface of silicon wafer with SBAP

It can be judged from Fig.12 that abrasive grains groove across the wafer surface during SBAP Lapping. It indicates that the retention force of semibond material on SBAP surface is strong enough to retain the grains. It can be seen in Fig.13 that grooves on the surface lapped by SBAP do not become deeper obviously by the added larger particles. The maximum depth of groove in SBAP lapping is about 30nm, and is much lower than that in loose abrasive lapping. It indicates that the surface damages, such as deep crack and pit, can be eliminated or reduced by SBAP obviously. The reason is that larger particles are trapped in SBAP surface, and the negative effect on surface quality of large particles is counteracted by 'trap' effect of SBAP as discussed in the section 2.

Fig.14 shows the roughness of wafer surface lapped by loose abrasive and SBAP. It can be seen that the surface roughness obtained by loose abrasive lapping is worse than that obtained by SBAP lapping, and the surface roughness Ra is worsened from 0.7μm to 3.18μm by the added larger particles in loose abrasive lapping. On the contrary, the surface roughness Ra changes from 0.02μm to 0.03μm as the larger particles added, it indicates that the larger particles have no remarkable effect on the surface roughness in SBAP lapping.

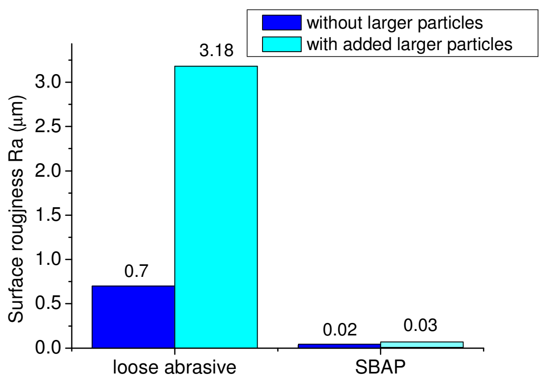


Fig.14. Surface roughness in loose abrasive and SBAP lapping

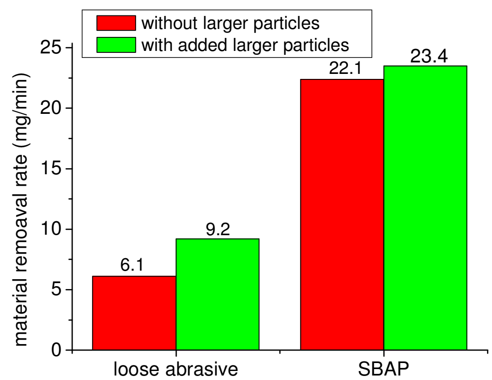


Fig.15. MRR in loose abrasive and SBAP lapping

Fig. 15 shows the material removal rater (MRR) in the two processes. As the lager particles added, the MRR increases from 6.1mg/min to 9.2 mg/min in loose abrasive lapping, and MRR increases from 22.1 mg/min to 23.4 mg/min in SBAP lapping. MRR in loose abrasive lapping is much lower than that in SBAP lapping. The main reason is that the number of abrasive grains taking part in action in SBAP lapping is much more than that in loose abrasive lapping. For the stronger mechanical action of larger particles, MRR in loose abrasive lapping increases as lager particle added. Since the larger particles are trapped in SBAP, the MRR in SBAP lapping is not affected by the added larger particles obviously.

As the above experimental results show, the effectiveness of 'trap' effect of SBAP is demonstrated. All of these characteristics of SBAP own to its special structure. SBAP has a porosity structure. Grains on the SBAP surface are semibonded, and can be forced to move for adjustment under certain load. It is much easy for the larger particles indenting into the SBAP surface than they into abrasive lapping plate. It means that the load on the larger particle in SBAP lapping is much lower than that in loose abrasive lapping. As a result, the surface damage caused by the larger particle in SBAP lapping is much less than that in loose abrasive lapping.

5.0 Conclusion

- A novel semibonded abrasive plate (SBAP) for finishing advanced ceramics is developed in this study. Retention force to retain abrasives in the SBAP is intervenient between fixed abrasive and loose abrasive. When a larger particle invades into the machining zone during SBAP lapping process, grains surrounding the larger particle are forced to move for adjustment, and a 'trap' containing the larger particle is formed on the surface layer of SBAP.

- A high polymer SSB, which can be solidified as drying and be redissolved by water, is developed to be used as semibond agent. The 'trap' effect of SBAP is demonstrated by a series of experiment. The experiment results indicate that surface damage caused by larger particles can be eliminated or reduced by the 'trap' effect of SBAP.

- Since the SBAP is newly developed abrasive tool, further studies, such as design method of SBAP, dressing of SBAP, lapping parameter optimization, and testing method for mechanical properties of SBAP should be carried out.

Acknowledgement

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DESIGN OF ANGULAR POSITION CONTROLLER OF FLUID DRIVE SPINDLE FOR DIAMOND TURNING

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Abstract

This paper describes the angular position controller for a fluid drive spindle. The fluid drive spindle is designed for the precision machine tool for producing various precise and complicated surfaces. The fluid drive spindle has the same operational principle with the water drive spindle[1]. Then rotational speed control system was designed for fluid drive motor that has simplified structure of the fluid drive spindle. In the present paper, the angular position control system is designed based on the rotational speed control system. We describes that transfer function of the angular position control system is the second ordered system. Thus desired response of the angular position control system can be obtained by specifying the natural frequency as well as the damping ratio of the transfer function. Performance of the designed angular position control system is studied via simulations and experiments. The results show that good step response is obtained. Steady state error of the step response is 0.18 degree that is equivalent to the resolution of the rotary encoder used in our experiment. In addition, it is verified that the designed controller is capable of compensating the influence of the external constant load torque on the angular positioning accuracy.

Keywords: Fluid drive spindle, Water drive spindle, Angular position control, Rotational speed control, Diamond cutting, Ultra-precision machine tool.

1.0 Introduction

The water drive spindle [1] was developed as a spindle for the ultra-precision machine tool. Features of the water drive spindle are the following: the water flow power is utilized for spinning the spindle rotor, and the water static pressure is utilized for supporting the rotor. Bend flow channels are formed in the spindle rotor so that the power of the water flow can be converted into the driving power for spinning the rotor. Performances of the water drive spindle were studied through experimental and simulation studies [1]. It is then verified that the spindle rotates 10,000 rpm by supplying the water flow of 20 *l*/min. Rotational speed of the water drive spindle can be controlled by the flow rate that is supplied to the spindle [2]. The water drive spindle was also applied to diamond cutting experiments. Then fine surfaces with optical quality were successfully obtained [3].

The water drive spindle was designed for diamond cutting of axisymmetric parts. The surfaces can be produced by simple rotation of the spindle for spinning workpiece, in addition to rectilinear motion of the diamond cutting tool. However, the rotational speed decreases as the external load torque due to the cutting forces increases. Accordingly, feedback controller is needed to design so that spindle speed can be maintained regardless of cutting forces acts on the spindle. So, rotational speed controller design for the water drive spindle was considered by using the fluid drive motor [4] that has similar driving principle to the water drive spindle.

Precision machining operations by the water drive spindle can be extended if the angular position of the spindle can be controlled. However, the angular position control of the water drive spindle currently cannot be carried out due to the limitation of the possible rotational direction of the spindle. Thus, a fluid drive spindle is proposed in the present paper so that bi-directional motion can be obtained. In the present paper, the angular position control design for fluid drive spindle/motor is considered. The angular position control system is designed based on the rotational speed control system together with disturbance observer [4]. Performances of the designed angular position control system are examined through simulations and experimental studies. The results show that good step response of the angular position control system is obtained. Steady state error of the step response was 0.18 degree that is equivalent to the resolution of the rotary encoder used in the experiments.

2.0 Water Drive Spindle

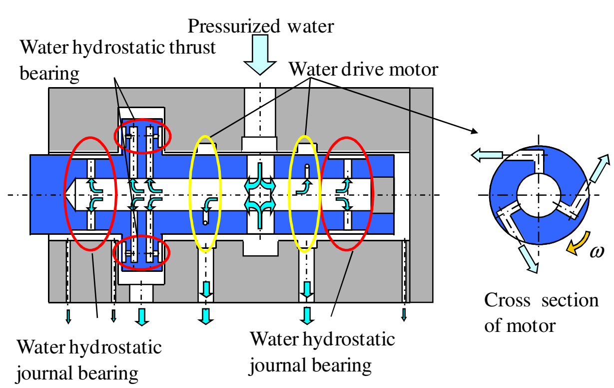
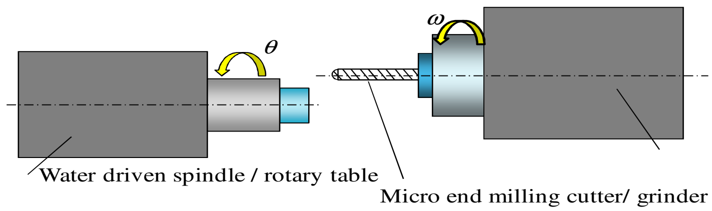


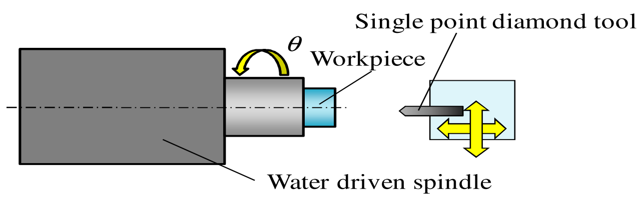
Fig. 1. Structure of water drive spindle

The structure of the water drive spindle is illustrated in Fig. 1. The spindle rotor is supported by the water hydrostatic bearings in the radial and axial directions. As shown in Fig. 1, the water drive spindle has bend flow channels, named the exit channels, which are formed at two cross sections of the rotor. The bend channels are designed for converting the angular momentum of the water flow into torque for spinning the rotor. In addition to use the water flow for lubricant and driving fluid, the water flow can be used as the coolant to prevent thermal deformation of the spindle. Performances of the water drive spindle have been experimentally and theoretically studied [3]. Experimental results have verified that runout of the water drive spindle was sufficiently small so that it meets the requirement for the diamond cutting.

Then the water drive spindle was tested for diamond cutting. Result of the cutting tests indicates that the surface roughness of workpiece is several 10 nanometers in R_a [3].



(a) Machining of asymmetric formed surface



(b) Machining of free form surfaces

Fig. 2. Spindle layout and control modes for producing various precise parts

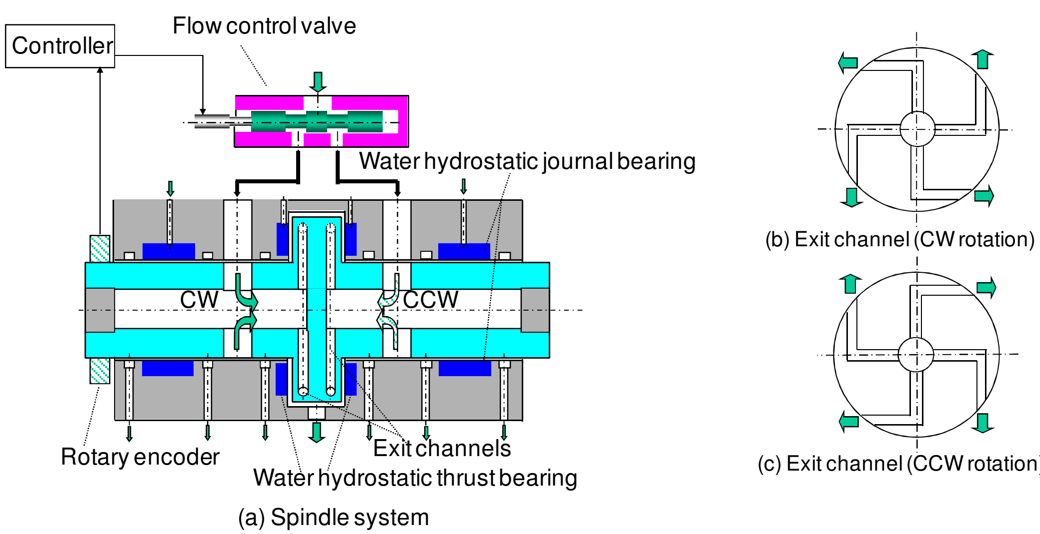


Fig. 3. Structure of fluid drive spindle

3.0 Spindle for Diamond Cutting/Grinding

Figures 2(a) and (b) illustrate possible two control modes of the spindle in the diamond cutting/grinding applications. For instance, Fig. 2(a) illustrates that asymmetric formed surfaces can be machined by diamond turning if the displacement of the cutting tool in the infeed direction as well as the angular position of the spindle can be synchronously controlled. In this case, the rotational speed of the spindle determines the cutting speed. Thus the spindle is usually operated in higher the rotational speed. Machining of precise free form surfaces or complex surfaces with micro milling/grinding tools is also carried out, as illustrated in Fig. 2(b). In this case, it is needed to control the angular position of the work spindle. In contrast, rotational speed control is needed for the spindle that rotating milling/grinding tools. In this machining process, the cutting/grinding speed can be adjusted by the rotational speed of the milling/grinding tools and its size. Thus the work spindle is usually operated in low rotational speed. From these considerations, it is verified that the angular position control of the spindle in the various speed range is required in the precision machining of parts with asymmetric formed surfaces.

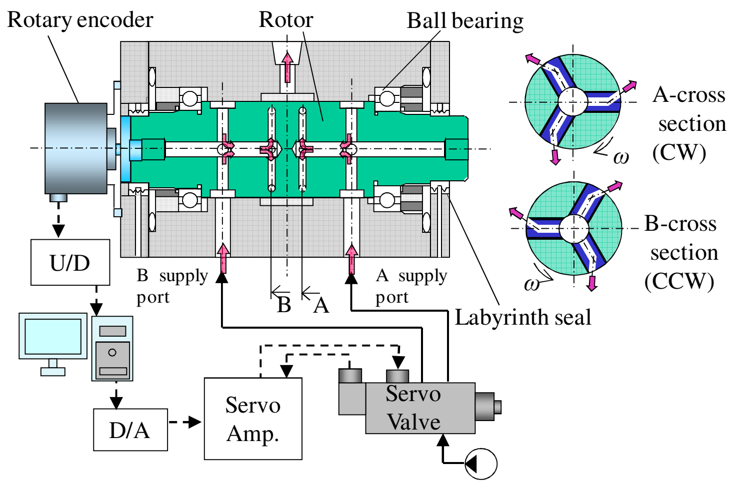


Fig. 4. Structure of fluid drive motor and experimental setup

Objective of the present paper is to develop fluid drive spindle that is capable of controlling not only the rotational speed but also the angular position in the various range of the speed. Advantage of the spindle is that the spindle can be used for various objectives of the precision machining, especially for producing small precise parts. In the present paper, design of the angular position controller is considered by means of the fluid drive motor that was designed for studying rotational speed control of the water drive spindle and the fluid drive spindle.

4.0 Structure of Fluid Drive Spindle

Figure 3 illustrates basic structure of the fluid drive spindle that is designed for conducting various machining processes as illustrated in Fig. 2. If the spindle is intended to be operated in the range of relatively low rotational speed, low viscosity oil can be used instead of water for driving the spindle. This is a case if the spindle will be used as rotary table as illustrated in Fig. 2, (b). So the spindle will be driven by water or low viscosity oil depending on the applications. Thus the spindle is called as the fluid drive spindle. Driving principle of the spindle is basically the same to that of the water drive spindle. Namely, the fluid drive spindle uses bend channels that are formed at two cross sections of the spindle rotor, which enables the spindle to convert fluid flow power to the torque for spinning the rotor. Unlike the water drive spindle, two independent exit channels are designed in the left and right hand sides of the rotor as shown in Fig. 3. The independent exit channels, having opposite directions in the bend direction, enable bi-directional rotations of the rotor by switching the supply ports A and B that are connected with the corresponding exit channels A and B, respectively. Thus the angular position control can be carried out by designing an appropriate controller.

Before developing the fluid drive spindle, a fluid drive motor as illustrated in Fig. 4 was designed for studying the rotational speed controller and angular position controller. The main difference of the fluid drive motor with the fluid drive spindle is that the rotor of the fluid drive motor is supported by ball bearings, instead of the hydrostatic bearings. In the present paper, the angular position controller is designed for the fluid drive motor. In the present study, low viscosity oil, 5×10^{-3} Pa·s, is chosen for driving the fluid drive motor.

As shown in Fig. 4, the rotation of the fluid drive motor is measured by a rotary encoder that is connected at the end of the rotor. In the experiments, a servo valve with single stage; the rated flow rate is 20 *l*/min; was used to control flow rate as well as to switch the control ports A and B. Oil temperature control facility was equipped to the hydraulic pump. Oil temperature was therefore normally controlled to 25 degree Celsius in the serious of the experiments.

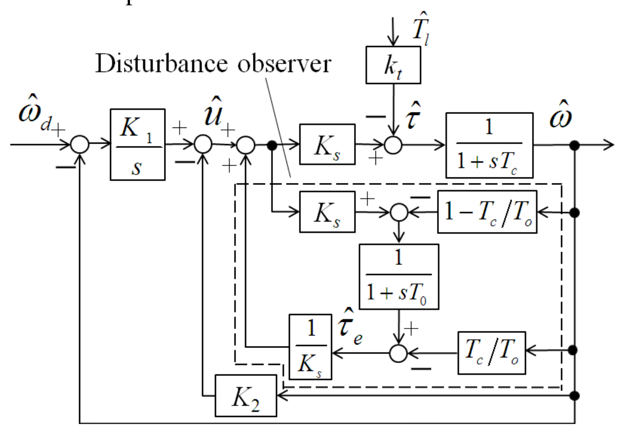


Fig. 5. Block diagram of rotational speed control system with disturbance observer

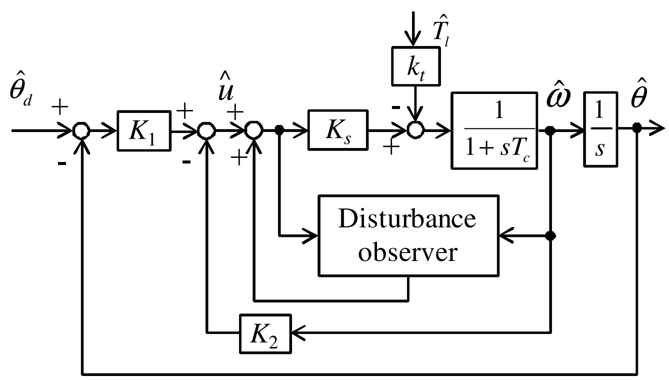


Fig. 6. Block diagram of angular position control system

5.0 Angular Position Control System

In our previous study, the feedback control system for the fluid drive motor was designed in order to regulate the rotational speed of the motor regardless of the external load torque [4]. In particular, the disturbance observer, which was designed for suppressing influence of the external load torque, was introduced. Then the compensator based on the disturbance observer was included in the feedback control system. Block diagram of the feedback control system is depicted in Fig. 5. It was verified [4] that the designed rotational speed controller effectively compensates the influence of the external load torque on the motor. Simulation and experimental studies verified that desired step response of the fluid drive motor can be obtained by means of the controller.

The designed rotational speed control system together with the disturbance observer can be used as an inner loop for the angular position control system. Then, the angular position control system is introduced in this section. Relationship between the input u and angular position θ is depicted in Fig. 6. The angular position feedback loop is then designed and added to the control system. Assuming that the influence of the external load torque acting on the motor can be canceled by the disturbance observer as well as the associated compensator, the transfer function of the angular position feedback control system is then given by Eq. (1).

$$G_p(s) = \frac{1}{1 + 2\frac{\zeta}{\omega_n}s + \frac{s^2}{\omega_n^2}} \tag{1}$$

In Eq. (1), ω_n and ζ can be represented by Eqs.(2) and (3), respectively.

$$\omega_n = \sqrt{\frac{K_1 K_s}{T_c}} \tag{2}$$

$$\zeta = \frac{1}{2}(1 + K_2 K_s)\frac{1}{\sqrt{T_c K_1 K_s}} \tag{3}$$

Here, T_c: the time constant of the spindle, K_s: the total gain of the controlled system. These relationships can be derived based on the mathematical model [4]. In addition, K_1 and K_2 are the controller gains to be determined so that desired response can be obtained. So, characteristics of the angular position control system are determined by specifying appropriate ω_n and ζ. Then K_1 and K_2 can be determined by Eqs. (4) and (5).

$$K_1 = \frac{T_c}{\omega_n^2 K_s} \tag{4}$$

$$K_2 = \frac{2\zeta K_1}{\omega_n} - \frac{1}{K_s} \tag{5}$$

6.0 Performances of Angular Position Control System

Design of the angular position feedback control system is carried out by determining the natural frequency ω_n and damping ratio ζ in Eqs. (4) and (5), respectively. Simulations and experiments were conducted by specifying ω_n =50 rad/s and ζ=0.7.

Performances of the designed control system were first examined through simulations. In a series of the simulations, the controlled system composed of the fluid drive motor as well as the servo valve was modeled based on the nonlinear equations [4]. Figure 7 represents step response of the angular position control system that was obtained by simulation. For comparison, the step response of $G_p(s)$ is also depicted in Fig. 7. Rise time of the step response in the simulation becomes slightly larger than that of the response of $G_p(s)$. This is due to the influences of the nonlinearities in the control system. However, if smaller step input was applied into the system, the difference in the rise time can be reduced, as shown in Fig. 8. In any case, however, steady state error in the simulation was less than 0.02 degree. Thus, it is verified that the designed controller is capable of controlling the angular position of the fluid drive motor.

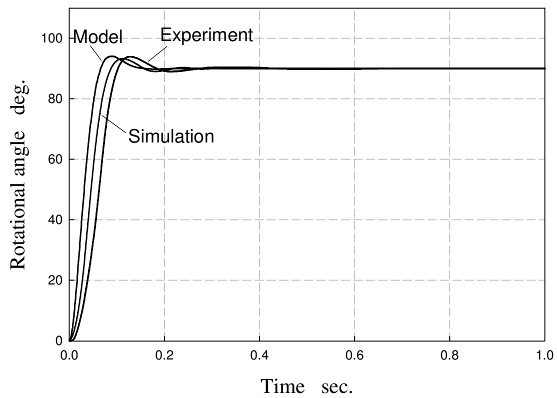


Fig. 7. Step response of angular position control system (step size : 90 degree)

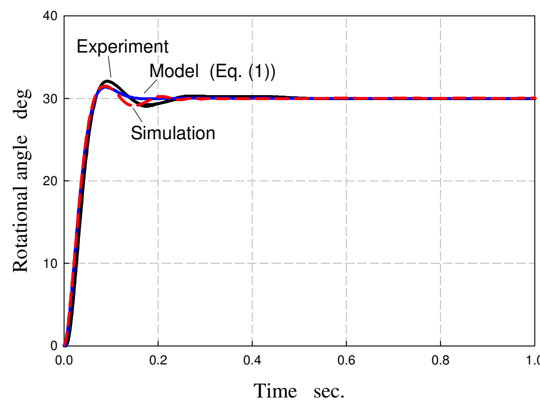


Fig. 8. Step response of angular position control system (step size : 30 degree)

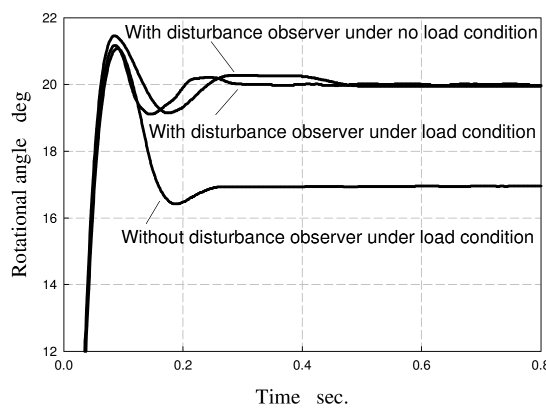


Fig. 9. Influence of external load torque on step response of angular position control system

Performances of the angular position control system were studied through experiments as well. The experimental results are indicated with the simulations in Figs. 7 and 8, respectively. In the experiments, step responses were measured for both rotational directions. It is verified that the same responses were observed regardless of the rotational directions.

Step responses of the angular position control system were also investigated when external load torque was applied to the fluid drive motor. In the experiments, the constant external torque was applied to the motor by hanging a weight from the rotor. The step responses of the motor are depicted in Fig. 9. The weight mass of 66.23 g was applied to the rotor in the experiment. As shown in Fig. 9, if the compensation by the disturbance observer was not used, the steady state error in the angular position of the motor becomes significantly remarkable. The steady state error reached -3 degree. In contrast, effectiveness of the disturbance observer is demonstrated because no steady state error can be observed. From the simulation and experimental studies, it is verified that the angular position control of the fluid drive motor can be carried out by the designed angular position controller.

7.0 Summary

In the present paper, the angular position control for the fluid drive spindle was considered. Performances of the angular position controller were examined using the fluid drive motor. It was described that various precise, free form and complex surfaces can be produced by controlling the angular position of the fluid drive spindle. Based on the mathematical model of the controlled system composed of the fluid drive motor and flow control valve, the angular position control system was designed. It was shown that the closed loop transfer function can be represented by the second ordered system. Consequently, the angular position controller design was carried out by specifying the natural frequency and the damping ratio of the transfer function.

Performances of the angular position control system designed in the present study were investigated through simulations and experiments. The results showed that desired step response of the angular position control system was obtained. Steady state error of the step response was 0.18 degree that is equivalent to the resolution of the rotary encoder used in the experiment. In addition, it was verified that the designed controller is capable of compensating the influence of the external constant load torque on the angular positioning accuracy. The designed angular position controller will be applied to the fluid drive spindle for producing various precise parts.

Acknowledgement

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MECHANISMS FOR GRINDING AND POLISHING OF SILICON CARBIDE WITH LOOSE ABRASIVE SUB-APERTURE TOOLS

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Abstract

Reaction-bonded silicon carbide component is fabricated by the reaction bonding of silicon carbide grains with silicon using liquid silicon infiltration, whose desirable properties include low density, high hardness and low thermal coefficient of expansion which make it particularly suitable to meet stringent requirements such as mirrors in aerospace or high-energy applications. However, the high hardness and complex crystal-phase structure imply the manufacturing of high precision mirrors very difficult. The present study focuses on the processes of computer-controlled small tool loose abrasive manufacturing for silicon carbide material. Here, the characteristics of material removal rate, surface roughness and surface morphology in grinding and polishing of silicon carbide using different sub-aperture pads are reported, and how these factors are affected by process parameters such as the machining force, the relative rotation speed, abrasive type and size, etc. are also examined in detail, and a summary of findings will be given in the concluding section.

Keywords: Silicon carbide, grinding, smoothing, material removal.

1.0 Introduction

Controlling such process parameters as the machining force, dwelling-time, relative rotation speed and abrasive grit size, etc. in computer-controlled sub-aperture tool optical fabrication can lead to a changing in material removal rate, in work-piece surface roughness and shapes. Moreover, small pad grinding/polishing is proven to be an effective strategy for high-accuracy machining of complex shaped optical components made of brittle materials (e.g., glass) [1]. Quantitative researches for iterative error-correction of optical lens or mirrors have been carried out with a sub-aperture pad, which is a conventional precisely shaped rigid pad made of pitch or polyurethane [2],or alternatively, a deformable tool [3] applies different loose abrasives. The transfers pressure through an abrasive slurry to the entire surface material of the components. Material is then removed by chemical and mechanical interactions between the abrasive and the components.

Silicon carbide materials characteristic as low density, high hardness and low thermal coefficient are provoking the interests of researchers, which are very good for optical components worked under poor conditions, i.e., with high-energy lasers and aerospace mirrors [4]. However, the high hardness and complex crystal-phase structure of silicon carbide and the labor-intensive nature of mirror fabrication made it difficult for us to make high-precision components with low costs. It has been shown that the high-speed lapping using bound pellet-shaped diamond abrasives fixed on a lapping disc and made into a special lapping tool can perform a high efficiency machining for rapid removal of surface error and initial smoothing [5]. However, after that, obvious scraping marks are often left on the work-piece surface, which make a further grinding process unavoidable in order to remove residual defects.

Therefore, the present study reports on the characteristics of material removal rate, surface roughness and surface morphology in grinding and polishing of silicon carbide using different sub-aperture pads, and how these factors are affected by process parameters such as the machining force, the relative rotation speed, abrasive type and size, etc. are also examined in detail.

2.0 Computer-controlled Loose Abrasive Manufacturing Methods

To improve the capability of loose abrasive manufacturing on large aspheric mirrors, a function-expanded optical manufacturing facility is presented with which it is possible to fabricate high-quality optical components. The system is based on sub-aperture scanning techniques, and combines the faculties of grinding and polishing, has the features of conventional loose abrasive machining and the characteristics of an automated tool tracking orbits in a planar model. This has proven to be a reasonable approach and the small pad can fit close to the local curvature of the work-piece surface and at the same time, computer control makes grinding and polishing processes repeatable and efficient [6].

Figs. 1(a) and (b) show an overall structure photograph and movement schematic view of the CNC machining system developed in house, respectively. The system arranged as gantry structure, four pillars, two crossbeams and a base form the main frame of the machine. The system is designed to be controlled on four axes. As the heart of this apparatus, a sub-aperture pad measuring 50 millimeters in diameter is screwed on an end face of a principle axis, and is rotationally driven by a motor via a coupling. In order to follow the work-piece surface shape and keep better fitting with it as the pad moves along the surface, a ball hinge is screwed on an end of the motor principle axis to combine the upside end of the pad as shown in Fig. 1(c). A tool feed mechanism consisting of two crossed linear guides, two ball screws, and two serve motors provide back-forward and left-right feed of the tool-table. A work-piece holder is mounted on a Z-axis rotary stage.

The manufacturing process is used in an iterative manner to produce the desired surface. First, the surface must be tested and providing either digital residual shape-error data or an interferogram which represents the surface errors distribution. The digital surface error data are obtained directly by using an interferometer or surface profiler. Next, the measured surface errors are compared to the errors predicted prior to the last figuring operation. The parameters for the next processing cycle are chosen and a NC code matrix is computer generated. According to the prior data, a computer algorithm predicts the expected figure for the next process will be performed, and after the pre-determinist manufacturing time the work-piece is tested again and the cycle repeated.

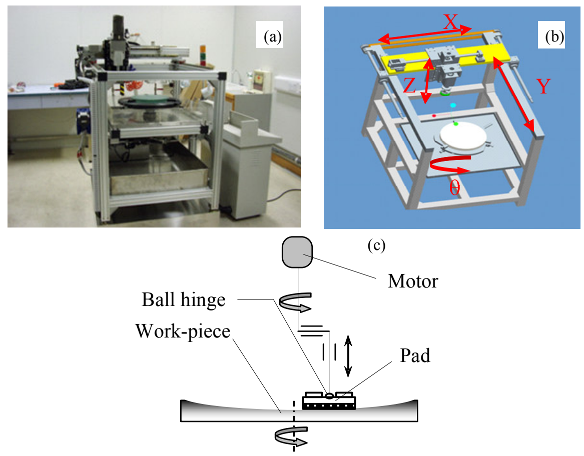


Fig.1. . Photograph (a) and movement representation (b) and schematic illustration of sub-aperture pad machining (c) of the new CNC machine

3.0 Experimental Details

The machining process of a silicon carbide work-piece was divided into two stages. Firstly, grinding process was performed to remove the scraping marks on the surface after rapid lapping and initial smoothing efficiently. Three pads made of cast aluminum alloy, cast iron and silicon carbide were adopted to grind the work-piece respectively by using different loose abrasive particles, say, selenium carbide, boron carbide and diamond powder. After that, fine error removal and finishing was performed using traditional precisely shaped pads made of pitch and polyurethane and fine diamond particles. Empirical results were presented to establish the validity of the process in terms of efficiency and surface quality. Material removal rates were analyzed and measured. How these factors are affected by process parameters such as the relative pressure, rotation speed, abrasives grit size, etc. were also examined.

3.1 First Stage of Grinding

Silicon carbide specimen was used as the work-piece. A series of experiments were conducted using different pads, loose abrasives, pad rotational speeds, and relative pressures to study their influences on the grinding performances. Detailed grinding parameters used were listed in Table I.

Firstly, considering the high hardness of silicon carbide materials, three different pads, i.e., cast aluminum alloy, cast iron and silicon carbide were adopted to perform the grinding process by using selenium carbide particles, boron carbide particles size as W14 (size@7~14μm) and diamond ones size as W7 (size@3.5~7μm) respectively. The relative pressure is 3kgf and rotational speed is 200rpm. The maximum material removal rate versus the above parameters plotted in Fig. 2(a). Obviously, diamond particles can produce the rapidest material removal, and the cast aluminum alloy pad and the cast iron pad have nearly the same removal rate. When the diamond particle sizes are increased from W7, W10 (size@5~10μm), W28 (size@20~28μm) to W40 (size@28~40μm), the max material removal rates increase greatly as shown in Fig. 2(b). The effect verifies that the diamond abrasives have a good removal ability which is applicable for the initial and fine grinding of the silicon carbide mirrors.

Table I. Parameters of Grinding Experiments

Parameters	Value
Pads	cast aluminum alloy, cast iron, silicon carbid
Size of Diamond Particles	W7,W10,W28,W40
ze of Selenium Carbide Particles	W14
Size of Boron Carbide Particles	W14
Relative Pressure (in kgf)	1,2,3,4,5

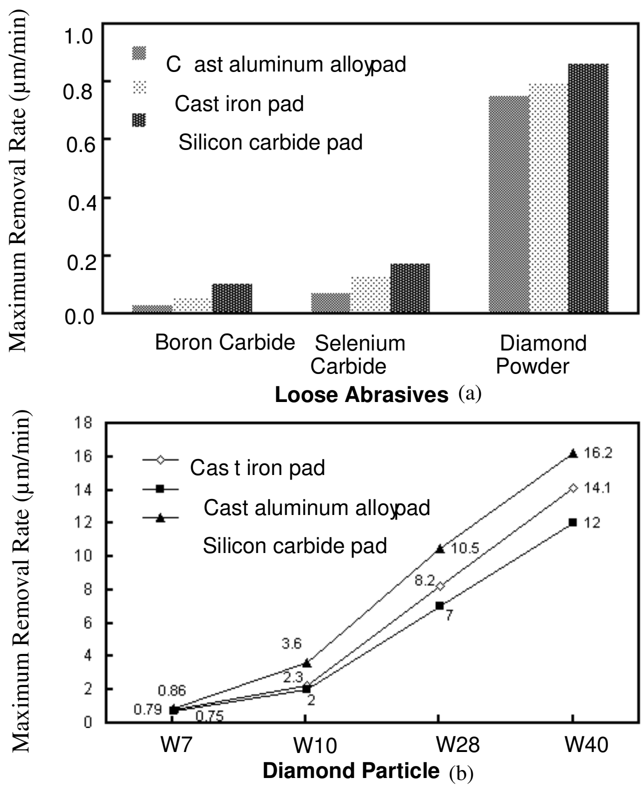


Fig. 2. Maximum material removal rates of different pads and abrasives.

As expected, the silicon carbide pad has the highest removal rate for its high hardness whereas the pad is hard to fabricate. The cast aluminum alloy pad is easier to be made and fit well with the work-piece surface.

Considering the important influence of the relative pressure and the rotational speed on the material removal, experiments are made using the cast aluminum alloy pad and diamond abrasives size as W7, W10, W28 and W40 under different tool speeds and the relative pressures. It can be seen from Fig. 3 when the relative pressure keeps constant 3kgf and the pad rotational speeds are increased from 50rpm to 300rpm, the removal rates increase steadily. But the removal rates decrease greatly when the rotational speeds are exceeded 300rpm. That means the effect of the rotational speed is significant during grinding, loose abrasive particles would be threw out of the working area when a too high rotational speed is used, too less abrasives to perform effectively grinding. Therefore an obviously decreased trend can be observed from the removal rate curves as shown in Fig. 3. It can also be seen from Fig. 4 that the removal rate keeps a nearly linear relationship to the relative pressure when the pad rotational speed keeps constant 200rpm, and increasing the relative pressure between the pad and the work-piece from 1kgf to 5kgf.

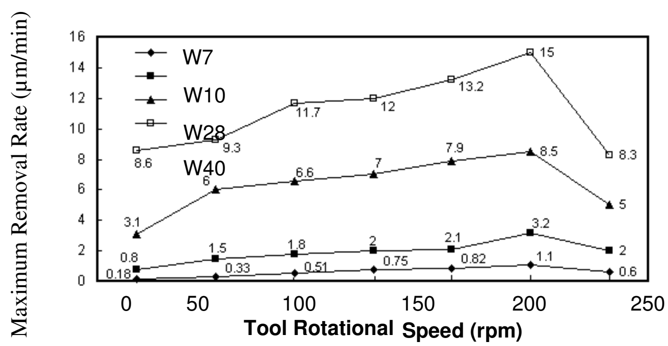


Fig. 3. Maximum material removal rates of different tool rotational speeds.

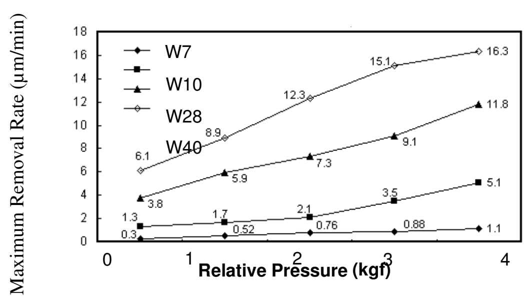


Fig. 4. Maximum material removal rates of different relative pressures.

The above experimental results provide a guidance to choose diamond particles as loose abrasives to grind the silicon carbide work-piece. According to experiences, take both the removal rate and the grinding accuracy into consideration, diamond particles size as W40 is useful to initial grind the surface with a figure error larger than 100µm (root-mean-square). W28 abrasive is more proper for grinding the surface with an error between 30µm and 100µm. The AFM result in Fig. 5(a) shows that obviously accidented structures residual on the ground surface. Observing the local micro-structure shown in Fig. 5(b), there is a plastic deformation phenomenon can be found and the materials are pushed to one side, which is different from the brittle removal mechanism. Based on a more reliable explanation, the high pressure and speed, and then a high temperature produced would make a temporal strongly scraping action on the working area, and results in a plastic deformation with large residual stress. Therefore, fine grinding process with a low pressure and speed is necessary.

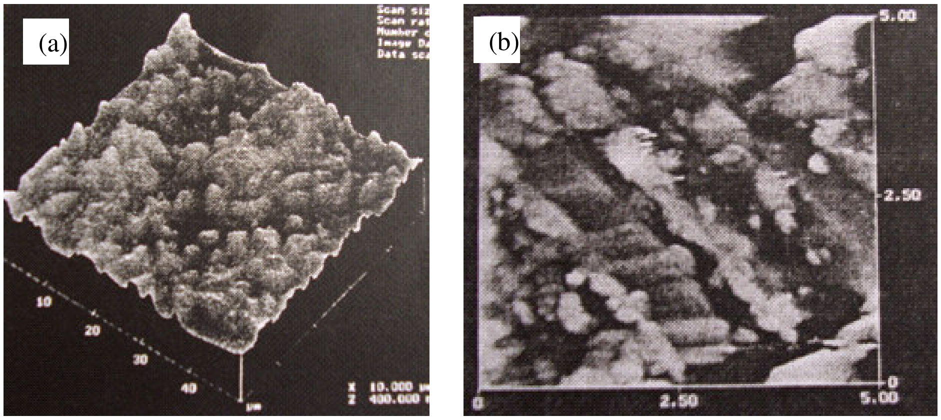
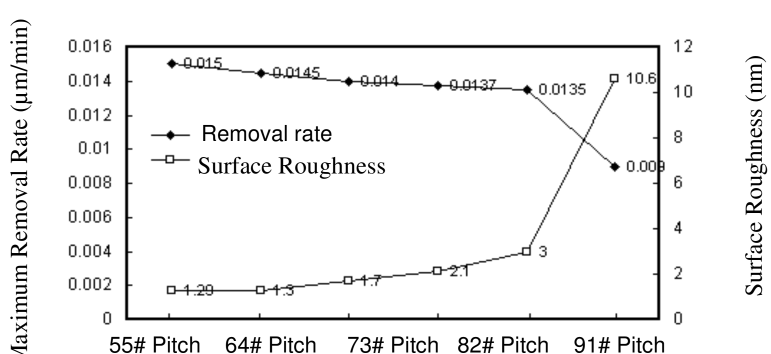


Fig. 5. The AFM Photographs of the ground area.

3.2 Second Stage of Polishing

In order to carry out proper polishing process to achieve a higher level surface quality, detailed experiments have been made focusing on error-smoothing. The pads made of pitch and polyurethane, and diamond particles were used to perform the polishing experiments. When using diamond abrasive sizes as W0.5 (<0.5μm) and under the constant rotational speed 200rpm and relative pressure 3kgf, it is found in Fig. 6(a) the max material removal rate decreases and the surface roughness increases as the pad hardness increases, say from 55# to 91# pitch and to another kind of pad polyurethane. Therefore, pitch pads with relative low hardness are apt to achieve a high-quality optical surface. Using pad made of 55# pitch to polish, as expect, the removal rate and the surface roughness increase along with the abrasive size increases shown in Fig. 6(b). From Fig. 6(c) and (d), the material removal and the surface roughness were found to be sensitive to both the speed of the tool and the relative pressure. When the speed is lower than 250rpm, both the removal rate and the roughness are keeping steadily, and great changing occurred as the rotational speed higher than 250rpm. The same case also appears as the pressure larger than 3kgf. In the above discussion of polishing processes, it is important to determine the reasonable range of the said parameters.

Referencing to the above processing experiments, a smoothing optical surface with nanometer accuracy can be fabricated. From the Veeco interferometer measuring results shown in Fig. 7(a), the surface roughness can achieve to 9.11nm, and the AFM result in Fig. 7(b) shows that the accidented structures have been removed and obviously flatting areas produced on the polished surface.



(a)

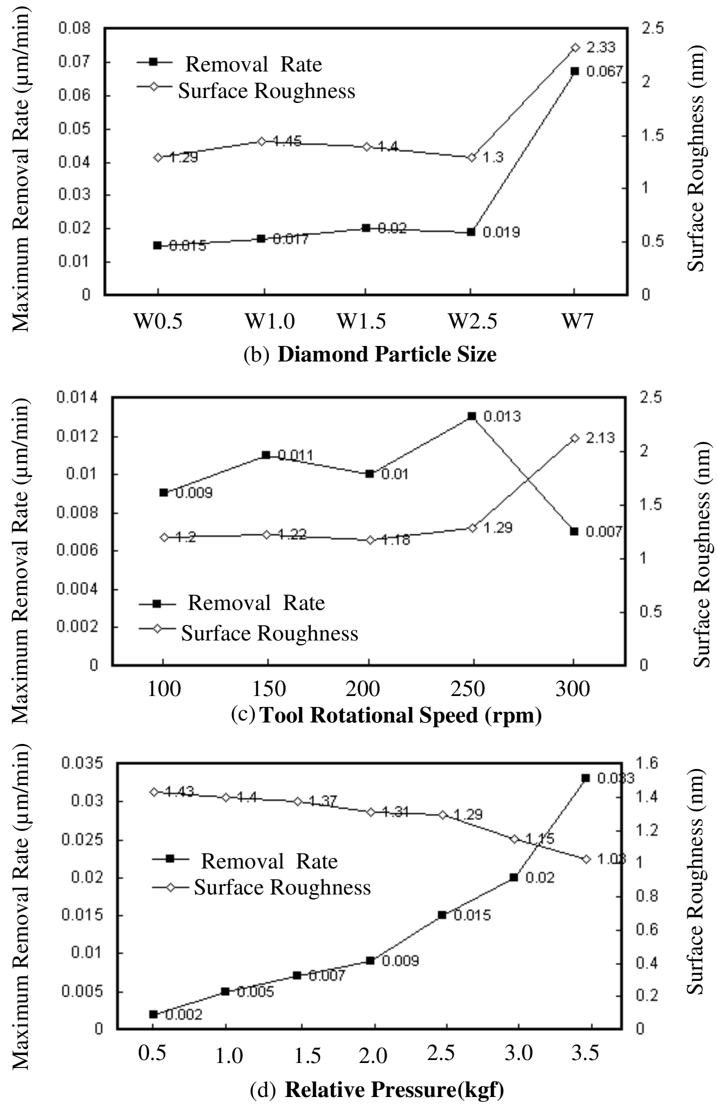


Fig. 6. material removal rate and surface roughness along with the changing of (a) the pad hardness; (b) the diamond particle size; (c) the rotational speed; and (d) the relative pressure

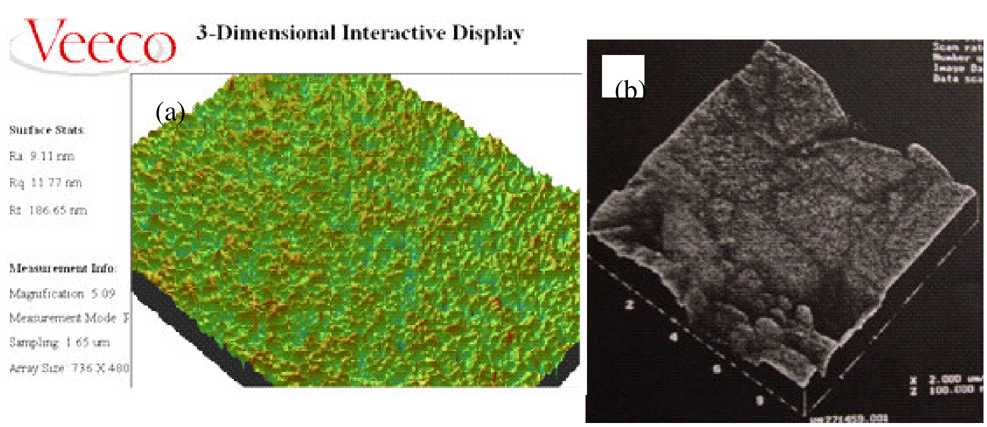


Fig. 7. . Veeco measured roughness result (a) and the AFM measured microstructure (b) of the polished surface.

MECHANISMS FOR GRINDING AND POLISHING OF SILICON CARBIDE WITH LOOSE ABRASIVE SUB-APERTURE TOOLS

4.0 Conclusion

This paper investigates the mechanisms of loose abrasive machining of silicon carbide components. Experiments of the grinding and polishing for the work-piece are performed by virtue of a computer-controlled small tool manufacturing facility. The changes of the material removal rate and surface roughness with the varying the relative pressure, rotation speed, abrasive type and size are revealed. According to the experiments, different sized diamond particles are effective loose abrasive for both grinding and polishing of silicon carbide material. Further experimental results and analysis are also helpful for matching process parameters to achieve a high quality surface, which confirms the validity of the proposed loose abrasive machining approach for grinding and polishing the silicon carbide components.

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TECHNICAL ADVANCES IN ULTRA-PRECISION MACHINING OF FREEFORM OPTICS BY FUNCTION-ORIENTED TESTING

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Abstract

Freeform geometries enable new systems in geometrical optics by combining the functionality of different optical components and, thus, reducing the required number of components in the system. The main problem in using that kind of freeform shaped optics is the deterministic manufacturing of these geometries and their evaluation in measurement. While ultra-precision diamond turning assisted with Fast Tool Servo Systems is shown to be a suitable process to manufacture freeform geometries for the application of reflective and refractive optical components [1], till recently it was difficult to assess the quality of the manufactured work pieces in means of form accuracy. While it was known that Fast Tool Servo Systems can position very accurately in the submicron range [2], the measurement of the produced work pieces was another issue. In the first case just the linear positioning of the mechanical axis has to be measured – in the latter case, a 3D measurement of a surface is required. The fringe deflectometry measurement technique shown in this paper fills this gap and gives feedback for implementing corrections in the manufacturing process. Surface deviations are measured and their reasons can be analyzed. With this information the causes for systematic manufacturing errors can be eliminated or compensated for. The paper exemplarily shows that approach in manufacturing, measuring and correction the production of a freeform mirror for illumination optics.

Keywords: ultra-precision, diamond machining, Fast Tool Servo System, freeform optics, fringe deflectometry measurement.

1.0 Introduction

The manufacturing of optical components with complex geometries like freeform surfaces is getting more and more important. Mass production of these optics is enabled by replication methods like injection molding. For the machining of the required mould inserts with freeform geometries, ultra-precision technologies like Fast Tool Servo turning can be applied to achieve the appropriate optical surface quality in the range of 10 nm Ra and a form accuracy below 1 µm. Furthermore, the machined surfaces need to be measured to guarantee the manufacturing quality. Especially, the measuring of the form accuracy remains challenging regarding the requested accuracy. NURBS (Non Uniform Rational B-Splines) are widely accepted in industry to describe freeform geometries. The set-point generation for Fast Tool Servo Systems directly based on that mathematical representation has been significantly improving manufacturing accuracy and was shown in the past.

The form testing of aspheric and freeform surfaces, as a part of the high-precision measuring technology, has a high economic impact for the modern industry. The new measurement principle of phase measuring deflectometry enables fast, full surface and contactless measurement of optical surfaces. Compared to conventional optical measuring methods, like interferometry which is limited to plane, spherical und slightly aspherical surfaces, the deflectometric testing of almost any geometry is a great advantage. The analysis of the originated data provides the established performance indicators for optical components, like astigmatism, coma, peak-to-valley as well as a target-actual comparison. In addition, the determination of local slope and curvature offers essential information regarding the optical function. For future developments it is intended to carry out a target-actual comparison based on these measurands.

Within the scope of this research, reflective demonstrator geometries with optical test functions were manufactured to analyze the ability of the deflectometry measurement system. Furthermore, different techniques to compensate for systematic machining errors in form accuracy were tested and compared. The freeform measurement system was used to verify the improvement regarding form accuracy. The direct measurement of the geometry unveils manufacturing errors which are not visible directly. Sources of such errors are for instance effects of systematic errors of clamping devices and of manufacturing with uncontinuous cut. In the process chain of ultra-precision machining of freeform geometries in optical quality the approached measurement technique is so far the missing quality feedback to the production system. On the basis of the results shown in this paper, it is envisaged to analyze the manufacturing of optical freeform surfaces regarding the occurring disturbances and to develop applicable performance indicators in order to achieve a reliable compensation of systematic errors during the machining.

2.0 Process Chain for Manufacturing Freeform Geometries

The process chain for the manufacturing of complex optical components starts with the optical design. The main functions of the design process are the calculation of the optical path and the analysis of the optical components concerning applicability, producibility and manufacturing tolerances. Besides the homogeneity of the used materials, the achievable surface roughness and form tolerances of optical surfaces are responsible for the quality of the whole optical system. The finishing process for the freeform mirror is Fast Tool assisted diamond turning. The turning process, which is normally only applicable for rotationally-symmetric geometries, is enhanced by a highly dynamic axis (Fast Tool Servo System) moving the diamond tool. The applied aerostatically beared Fast Tool Servo System is able to move the tool in an operational range which is limited by the mechanical stops of the axis to a stroke of 10 mm. The dynamic of the axis is mainly limited by the maximal electrical power. The uniphase linear motor is able to drive to approximately 50 µm at 300 Hz. The basis form of the work piece with 1 mm non-rotationally symmetric geometry parts is premachined using a micro milling process, since the diamond turning process is only able to apply a chip thickness of up to 20 µm in a roughing process. The setpoint generation in the control system of the milling machine is trajectory oriented. The freeform geometry provided by the CAD (Computer Aided Design) system is split into linearly interpolated points on the trajectory. The resulting manufacturing errors are acceptable for the premachining step. However, the ultra-precision machining with the Fast Tool Servo System demands for a geometry representation with less interpolation errors, if a sub micron form accuracy is aspired. Furthermore, discontinuities in the setpoints, which are inevitable with only linear interpolation, lead to non-acceptable dynamic positioning errors and higher positioning noise of the axis in the transition zones. To achieve the demanded manufacturing accuracy even so, the interface from the CAD to the Fast Tool Servo System was revised.

Freeform geometries in CAD usually are specified in NURBS (Non-Uniform Rational B-Splines). This mathematical description can be used for analytical surfaces which can even incorporate edges as well as for real freeform geometries. For manufacturing purposes, restrictions regarding the shape of the surface need to be introduced. Especially using the ultra-precision turning production process, the surface slope needs to be in the range of the diamond tool's cutting edge. The applied direct processing of the NURBS data in the Fast Tool Servo System implements access to the complete original surface. The data processing of the Fast Tool Servo System and the basis machine are synchronized by the measured actual axes' position of the basis machine. In addition to the increased positioning precision, the provision of a complete surface allows for advanced pre-control, since the surface can be derivated analytically without numerical differentiation errors. The surface geometry of the first produced prototype is measured to analyze and correct systematic errors in the production chain.

3.0 Measuring Freeform Geometries

The characterization of the prototype was carried out using a deflectometry measurement system. The measurement device is used in the production environment with the goal of implementing a quality control feedback, improving the production process of optical surfaces with freeform geometries.

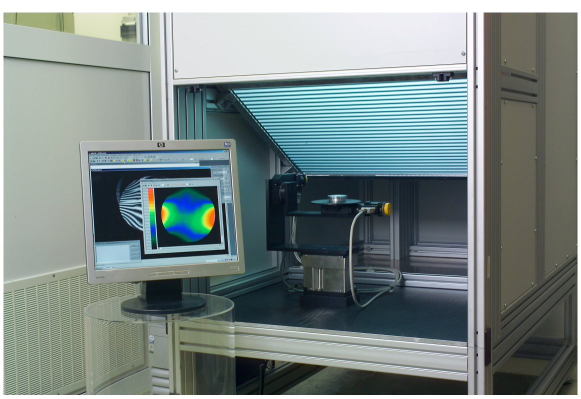


Fig. 1. SpecGAGE^{3D} – Measurement device

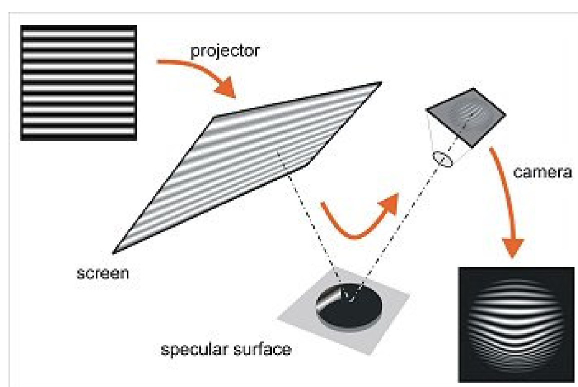
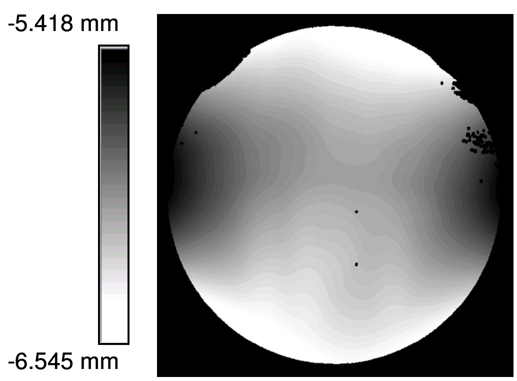


Fig. 2. Measurement principle [3]

Fig. 1 shows the measurement device. The new principle of phase measuring deflectometry, shown in Fig. 2, enables non-contact and full surface measurement of optical components. Sinusoidal fringe patterns are projected onto a screen. Their reflections on the surface of the sample are recorded by a camera. Using well-known phase-shift algorithms, the system measures the reflection angle in each pixel of the camera and thus calculates the slope of the surface. The topography is then reconstructed by integrating the local slope data and the required information of the local curvature via differentiation. The used measuring system has lateral and vertical measurement ranges of 80 x 80 mm^2 and ±18° respectively and a lateral resolution of 80 µm. The range of its applications, due to the measurability of almost any geometry, extends to lenses and mirrors, like lenses for mobile phones, eyeglass lenses and head-up displays, as well as mold inserts, polished surfaces, wafers and solar cells.

4.0 Data Acquisition and Analysis

First of all, a suitable orientation of the prototype relative to the camera was determined. To accomplish high contrast, the angle of elevation was reduced until the reflectivity was sufficient. Afterwards, the measuring setup was adjusted, so that the visible surface area under test was at maximum and the occlusion was minimized. For this position, a distance between camera and surface was calculated with the objective to accomplish the required lateral resolution and sensitivity for the biggest part of the surface [4]. Afterwards, a comprehensive 3D acquisition of the surface (Fig. 3) was carried out. Additionally, the target surface was converted into the measurement data format in order to achieve a target actual comparison.



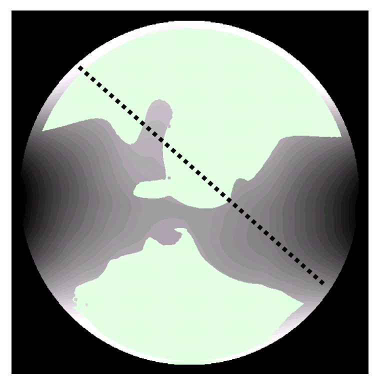


Fig. 3. Actual surface

Fig. 4. Matched data with cross section

The determination of the form deviations via error map or cross sections requires the matching of the target and the actual surface. This was done via a coarse registration on the basis of three selected points and a subsequent fine registration which minimizes the distances between the actual and the target surface.

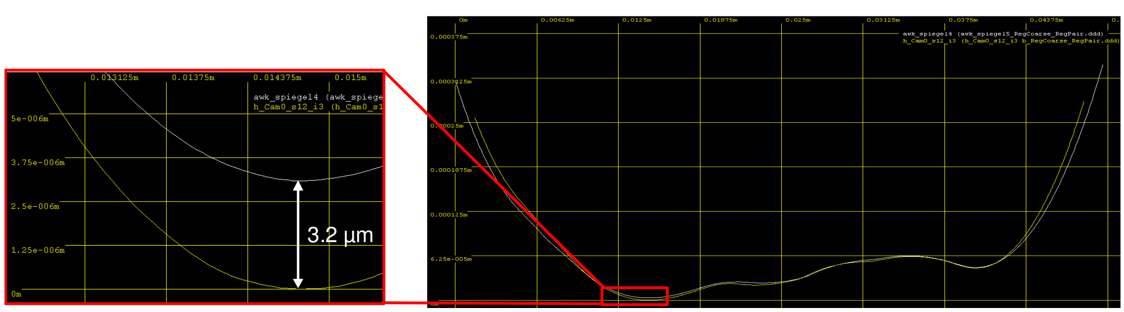


Fig. 5. Cross section of matched target and actual surface

As a result, form deviations of 3 µm at the center and 20 µm in areas with steeper slopes were detected, as Fig. 5 shows. Influences on production quality originate from machining errors from different sources which can be categorized in systematical and stochastic errors. Systematic errors of the machine system are geometrical and static alignment errors of the machine axes. Especially the highly dynamic Fast Tool Servo System has dynamical errors, since the working range is up to 1 kHz. Long production times combined with the thermal behavior of the machine system and the work piece itself lead to thermal errors, which are especially hard to compensate. Stochastic errors, which cannot be compensated for, and only minimized or prevented, are effects of the properties of the machined material like impurities and chip removal characteristics, but most importantly, environmental influences like temperature and humidity should be held constant. The dependence of the form error on the actual slope can be explained by geometrical errors of the diamond tool's radius shaped cutting edge. This error mainly affects the shape of the surface in regions with high slopes and highly affects the optical function of the surface which firstly depends on the slope in the case of geometric optics. Since this kind of geometrical error is systematic. It can be compensated by including the radius into the calculations of the tool path.

5.0 Compensation of Systematic Machining Errors

Fig. 6 on the left schematically shows the form error without a correction of the tool's cutting edge geometry, assuming a tool radius of R=0.2 mm and a surface slope of the contour of 20°. The correction value depends on the local slope of the surface perpendicular to the direction of the tool path. The correction value can be extrapolated from the original point. The local slope is represented by the normal vector. In the case of a surface encoded in NURBS, the normal vector can be easily evaluated [5]. With these basic conditions, the correction value is

$$\kappa = R \cdot \frac{1-\cos(\eta)}{\cos(\eta)}, \quad with \quad \eta = f(N, \rho, \varphi) \tag{1}$$

The form error without compensation always results in the removal of too much material. Thus, the compensation value is always positive, moving the tool away from the work piece. In the example of Fig. 6, using a tool radius compensation the form error can be significantly reduced from 10 µm to 1 µm.

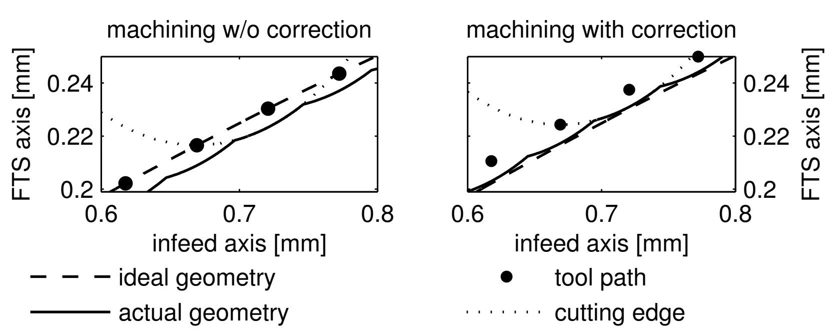


Fig. 6. Form error resulting from the tool geometry regarding first order correction

6.0 Measurement of Prototypes Manufactured with Radius Compensation

After the renewed manufacturing of the freeform geometry, another measurement was carried out. As a result, the form deviations of the manufactured prototype with radius compensation were significantly smaller with <1.6 µm peak-to-valley for the whole surface. Another advantage is the improved optical quality of the surface which is visible in the measurement data due to the absence of areas with invalid data.

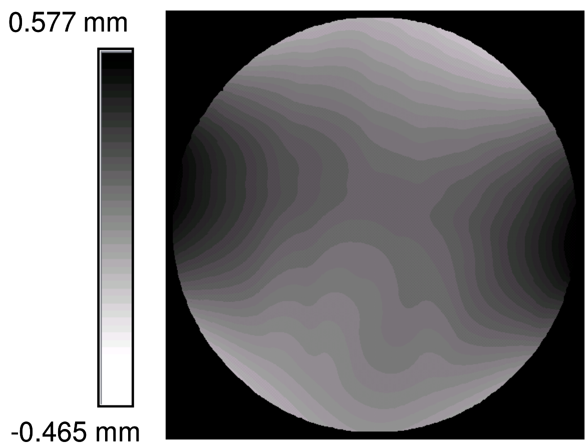


Fig. 7. Actual surface after radius compensation

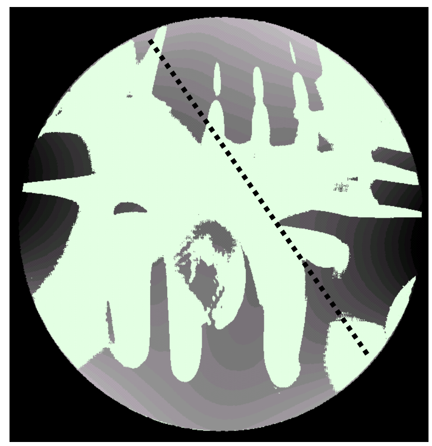


Fig. 8. Matched data with cross section

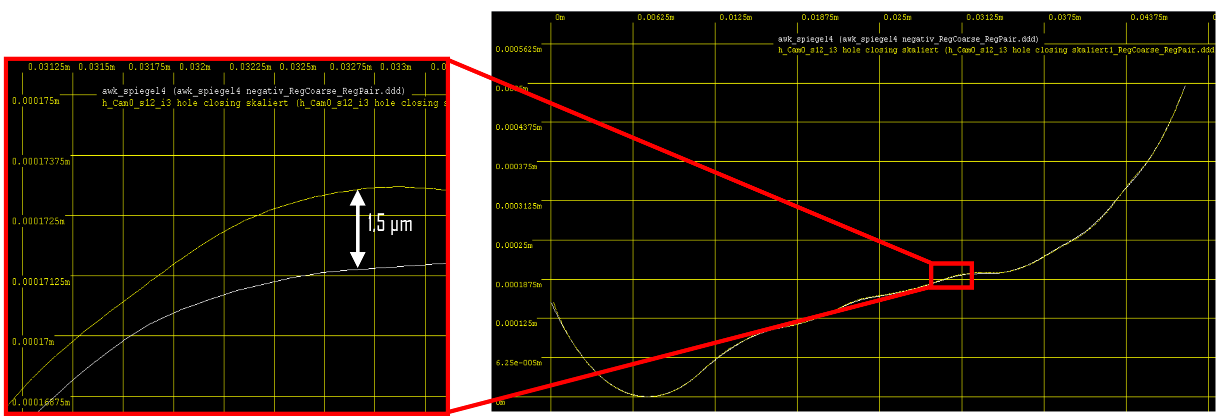


Fig. 9. Cross section of matched target and actual surface after renewed manufacturing

In addition to provide an analysis of the topography (Fig. 7), the measurement system also measures the slope and curvature of the surface. In contrast to the undistinguishable topography, the slope and curvature supply a more direct visualization of the beam shaping function of the surface.

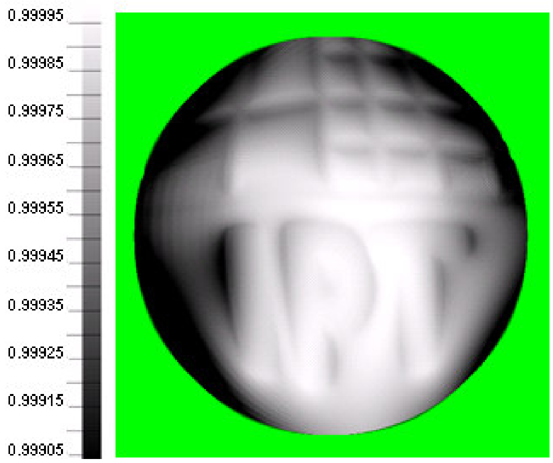


Fig. 10. Slope

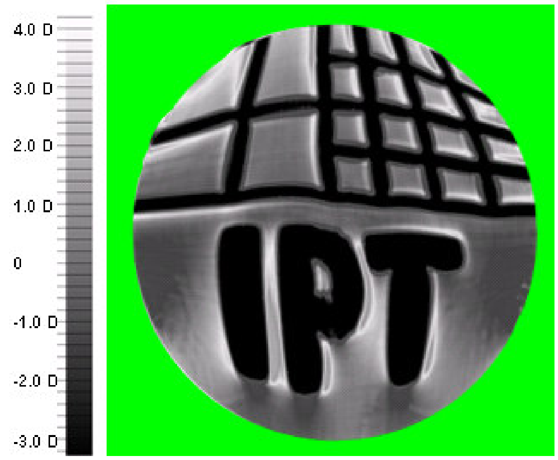


Fig. 11. Curvature

In the future, it is intended to carry out target vs. actual comparison on the basis of slope and curvature. Currently, the feedback of these correction values is insufficient, due to the fact that the majority of manufacturing machines still use height information as input data. The slope and the curvature information have the advantage of emphasizing the local surface geometry variation included in high spatial frequencies parts, while downsizing low spatial frequency information which is expressed in the position data and conceals the local variations in matters of scale.

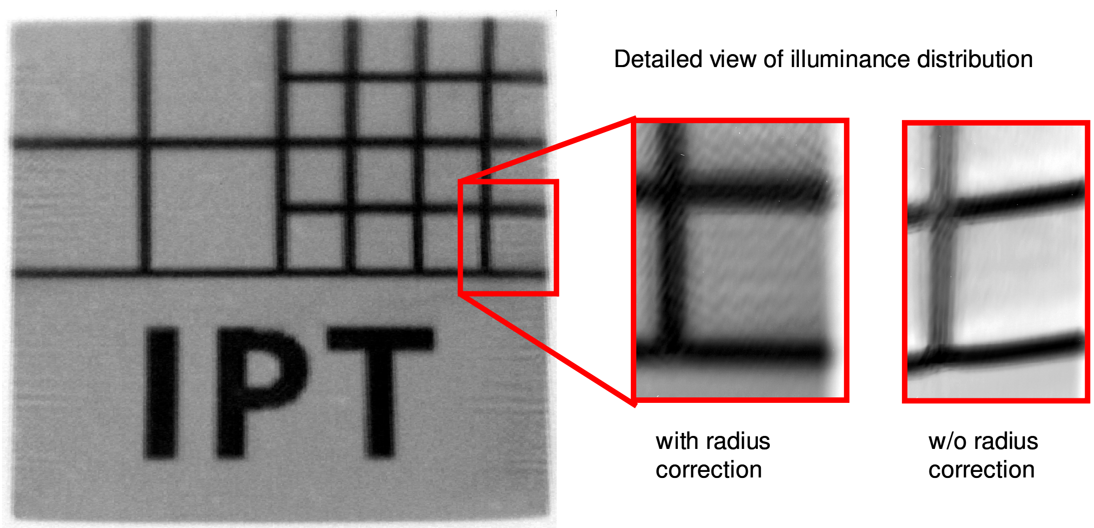


Fig. 12. Illuminance distribution of demonstrator optical element

Fig. 12 shows the measurement of the illuminance distribution itself. The illuminance was measured with a CCD chip by directly exposing it to the projection without the object lens of the camera. In the left figure, a global view of the function, representing the IPT logo, is shown. In the right figure, the enhancement of the radius correction is shown. The illuminance in the fence parts of the logo is distorted and unevenly distributed, depending on the cutting direction, which is directly affected by the tool radius without compensation. Applying the radius compensation, these geometrical errors could be corrected.

7.0 Conclusion

The Fraunhofer IPT provides the complete production chain for the manufacturing of optical components with freeform geometries. Both the direct manufacturing of mirrors and lenses as well as the manufacturing of molds including the replication of lenses with injection die molding of plastics and compression molding of glass are covered. The CAD data from the optical design can be directly and optimally employed in the production process. The quality feedback for the production chain can be supplied with the fringe deflectometry measurement technique in the case of freeform geometries. The measurement system enables the detection of effects caused by systematic manufacturing errors like geometrical errors resulting from the actual shape of the diamond tool's cutting edge and their elimination in the production process step.

The functionality of optical components is strongly influenced by the local slope of the geometry. Since the deflectometry measurement technique directly measures the slope, in the future, this surface information can possibly be included into the interpolated surface data and enhances its usability for optical surface measurement.

Acknowledgement

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OPTIMIZATION OF SURFACE FINISH AND KERF TAPER IN DESIGN OF EXPERIMENTS BASED ABRASIVE WATER JET CUTTING OF ARAMID COMPOSITES

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Abstract

Abrasive water jet cutting (AWJC) is particularly useful for cutting difficult-to-cut materials like composites, rocks, super alloys, glass and ceramics. However, the produced surface quality is poor particularly towards the jet's exit side, requiring post processing operations. These finishing operations cause further delamination in case of polymer composite laminates. Therefore, optimum selection of process parameters is a major issue in good quality AWJC. In the present research work, a standard L27 (313) orthogonal array based on Taguchi design of experiments is used for carrying out AWJC of aerospace grade aramid composites. The utility concept has been applied for multi-objective optimization of surface roughness and kerf taper. The experimental results and analysis of variance indicate that quality level has the most significant influence on multiple kerf quality characteristics.

Keywords: Abrasive water jet cutting; Surface roughness; Kerf taper; Aramid composites; Utility concept.

1.0 Introduction

Abrasive water jet machining (AWJM) is one of the recent non-traditional machining process widely used in the industry for machining of difficult-to-cut materials such as composites, Ti alloys, concrete, glass and ceramics. It is a contact less machining process with the distinct advantages of no thermal distortion, high machining versatility and small cutting forces [1]. In AWJM, material removal depends upon the erosion caused by abrasive particles on the work surface. A small stream of abrasive particles is entrained in the water jet so that water jet's momentum is partly transferred to the abrasive particles. Water as a carrier fluid is used to accelerate abrasive particles to produce a highly coherent AWJ, which is focused on the work piece surface through a nozzle [2]. The schematic of AWJC process is shown in Figure 1. The different material removal mechanisms and characteristics of machined surface in AWJM have been presented and discussed by several investigators [2]–[5].

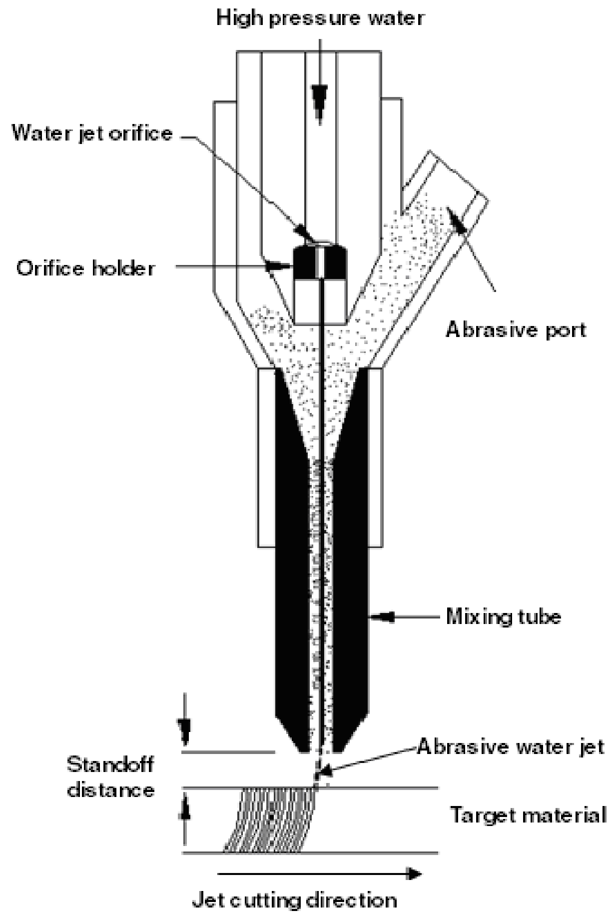

Fig. 1. Schematic diagram of AWJC process

Composite materials are increasingly used in the aerospace industry, due to their superior properties like high specific strength, high specific modulus of elasticity, high corrosion resistance and low density. Unlike glass and carbon fiber reinforced plastic (FRP), the machining of aramid FRP laminates is comparatively more difficult due to their higher toughness [6]. But due to their increased use in high performance anti-ballistic and aircraft structural components, an efficient method is necessary for cutting aramid composites.

Studies by Konig [7] on cutting of FRPs revealed that the cut surface quality was dependent upon the process parameters such as water jet pressure, abrasive flow rate, nozzle diameter, standoff distance and material thickness. Singh et al. [8] experimentally studied the effect of different process parameters on AWJ cut surface finish for different materials (aluminium, steel, glass and rubber). It was found that better surface finish was obtained on the top part of the cut surface at lower water jet pressure and by increasing abrasive flow rate and decreasing traverse speed. Wang and Guo [9] developed a semi-empirical model for the predictive depth of jet penetration for AWJC in order to achieve through cuts and to eliminate delamination effect in polymer matrix composites. It was found that the depth of penetration decreases with an increase in jet traverse rate and increases with water jet pressure and abrasive flow rate however the rate of increase decreases with increase in abrasive flow rate. Azmir and Ahsan [10] conducted Taguchi method (TM) based experiments on AWJM of glass-epoxy composites. It was observed that hydraulic pressure and traverse speed were most significant factors affecting the surface roughness while abrasive flow rate and standoff distance were insignificant.

From the literature review it can be concluded that the design of experiments (DOE) based studies on AWJC so far have considered only a single quality characteristic at a time to optimize the process performance. This paper illustrates the application of Taguchi method using the utility concept for multi-objective optimization (MOO). The utility concept [11] employs weighting factors to signal-to-noise (S/N) ratios of each response to obtain a multiple signal-to-noise ratio (MSNR) for each trial of the orthogonal array. In the present work, the above approach is employed for simultaneous minimization of surface roughness (Ra) and kerf taper (KT) in AWJC of aramid composites.

2.0 Selection of Process Parameters and Their Levels

In the present work, three process parameters namely water jet pressure, abrasive flow rate and quality level each at three levels were used as shown in Table I. The dimensionless cutting quality level is defined by the mean Ra of the upper, middle and lower zones of the AWJ cut surface. The process parameters and their levels selected were primarily based on AWJ machine constraints and literature review on AWJM of aramid composites. The initial setting of parameters is: Water jet pressure–250 MPa, Abrasive flow rate–250 g/min and Quality level–3.

Table I: L_{27} TOA process parameters and their levels used in

Process Parameters	Symbol	Units	Low	Medium	High
Water Jet Pressure (WJP)	A	MPa	250	300	350
Abrasive Flow Rate (AFR)	B	g/min	250	325	400
Quality Level (QL)	C	--	3	4	5

3.0 AWJC Process Details (Material and Measurement)

The OMAX 2652 Machining Centre was used to cut 20 mm long, through cuts in a single pass on 2 mm thick specimen. The orifice diameter (0.33 mm), mixing tube diameter (0.762 mm), standoff distance (3 mm) and garnet abrasive size (80 mesh) were kept as constant fro all te experiments. In the present work, composite laminates have been prepared by the standard autoclave vacuum bagging process using bidirectional aramid-prepregs (VICOTEX 913/50%/K285, fibre volume fraction 0.50) supplied by Hexcel Composites were used. The application of this material is in impact resistant structural components of Dornier transport aircraft. Ra was measured by ‘Stylus profilometer’ (Taylor-Hobson subtronic 10) near the top and bottom surface to avoid the jet striation effect at entry and exit. Two measurements per trial were taken for Ra and their average values used. The TKW and BKW were measured using the Tool Maker’s Microscope at 20X magnification. The KWs taken are the average of two measurements of each cut. The kerf taper (in degree) is calculated as follows:

$$Kerf\ taper = \tan^{-1}[(Top\ kerf\ width - Bottom\ kerf\ width)/(2 \times Specimen\ thickness)] \quad (1)$$

The kerf geometry of a through cut generated by AWJ is shown in Figure 2.

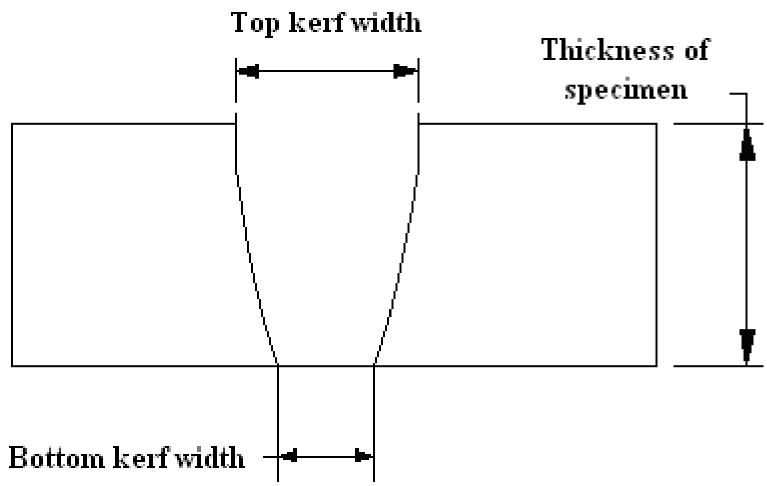

Fig. 2. Schematic diagram for kerf geometry

4.0 Taguchi Method

TM is an important DOE tool for robust process design and provides a simple and systematic way to optimize design for performance, quality and cost. TM defines the quality of a product, in terms of the loss imparted by the product due to deviation of the product's functional characteristic from the desired value. The uncontrollable external factors which cause the functional characteristics of a product to deviate from their target values are called noise factors such as vibration, temperature and human factors etc. The overall aim is to design a process that is robust against these noise factors.

4.1 Taguchi Design of Experiments

The experimental design based on a Taguchi orthogonal array (TOA) is orthogonal. i.e. the effect of each process parameter at different levels to be separated out. TOA provides an effective way of conducting minimum number of experiments that give full information of all the parameters affecting the two responses. To select an appropriate orthogonal array for conducting the experiments, the total degrees of freedom (dof) are computed as follows [12]:

$$dof = ((number\ of\ levels - 1)\ for\ each\ control\ parameter + (number\ of\ levels - 1)\ for\ each\ interaction + 1) \quad (2)$$

In the present case, the *dof* comes out to be ((3-1)×3 + (3-1) (3-1)×3 + (3-1) (3-1) (3-1) +1 = 27). Hence, a standard L_{27} (3^{13}) TOA (27 runs of a maximum of 13 control parameters at 3 levels each) is chosen for the experimental design matrix. The computed S/N ratios and the corresponding MSNR are shown in Table II.

TableII: S/N ratios of R_a and KT and the computed MSNR

S No.	S/N ratio (R_a)	S/N ratio (KT)	MSNR
1	-18.06	-9.73	-13.89
2	-16.26	-8.92	-12.59
3	-13.44	-7.55	-10.50
4	-18.17	-7.59	-12.88
5	-16.26	-6.38	-11.32
6	-13.44	-7.73	-10.59
7	-18.28	-10.24	-14.26
8	-16.65	-7.98	-12.32
9	-13.80	-7.84	-10.82
10	-17.27	-10.28	-13.77
11	-15.42	-9.89	-12.65
12	-12.67	-9.64	-11.16
13	-17.39	-10.65	-14.02
14	-15.42	-9.93	-12.67
15	-12.87	-7.57	-10.22
16	-17.50	-10.72	-14.11
17	-15.56	-10.46	-13.01
18	-12.87	-7.35	-10.11
19	-16.52	-10.43	-13.47
20	-13.44	-10.43	-11.93
21	-11.82	-7.39	-9.60
22	-16.52	-10.43	-13.47
23	-13.63	-11.45	-12.54
24	-12.26	-9.35	-10.80
25	-16.65	-10.61	-13.63
26	-14.15	-11.56	-12.86
27	-12.26	-8.32	-10.29
Mean	-15.13	-9.27	-12.04

4.2 Determination of Optimal Process Parameters

The optimum level for a factor is the level that results in the highest value of S/N ratio in the experimental design. Generally, there are three categories of quality characteristics for S/N ratio, i.e. smaller-is-better, larger-is-better and nominal-is-better. In the present work, the smaller-is-better quality characteristic is used for both Ra and KT as we intend to minimize them. ANOVA was then conducted to observe the effect of different process parameters on the two responses. From the S/N ratio and ANOVA analysis, the optimal combination of the process parameters can be determined.

5.0 Data Analysis and Results

5.1 S/N Ratio

The term 'signal' represents the desirable value (mean) of the output characteristic and the term 'noise' represents the undesirable value (Standard deviation) for the same output. Therefore, S/N ratio is the ratio of the mean to the S.D. Taguchi method uses the S/N ratio to measure the quality character deviation from the desired value. The S/N ratios are computed as follows:

$$\eta_i = -10 \log10 (y_j^2) \quad (3)$$

where yj is the value of the ith experimental response for jth quality characteristics.

In the utility concept [11], the MSNR (η) is computed as follows:

$$\eta = w_1\eta_1 + w_2\eta_2 \quad (4)$$

where w1 and w2 are the weights associated with S/N ratios of Ra and KT respectively. Equal weights (w1 and w2=0.5) have been assigned to Ra and KT because both are equally important for producing a better AWJ cut surface quality.

5.2 Analysis of Variance

ANOVA is performed to investigate the effect of different process parameters on the quality of a process/product and their percentage contribution. The ANOVA response for MSNR is given in Table III and the contribution of different main factors and their first order interactions in decreasing order is QL (65.62%), WJP×QL (12.40%), AFR×QL (9.16%), AFR (5.82%) and WJP (3.94%) as shown in Figure 3.

Table III: ANOVA response table for MSNR

Factors	Sum of Squares	Degree of freedom	Mean sum of squares	Contribution (%)
WJP	2.68	2	1.34	3.94
AFR	3.96	2	1.98	5.82
QL	44.63	2	22.32	65.62
WJP×QL	8.43	4	2.11	12.40
AFR×QL	6.23	4	1.56	9.16
WJP×AFR	0.00	4	0.00	0.00
Error	2.08	8	0.260	3.06
Total	68.01	26	2.62	100

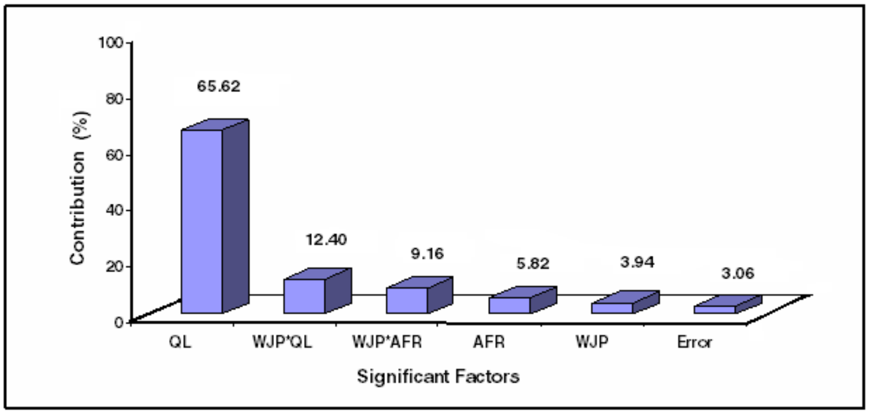

Fig. 3. Percentage contribution of different factors for MSNR

5.3 Confirmation Experiments

After the determination of optimal parameter settings, the final step is to predict and verify the improvement of the quality characteristic by conducting confirmation experiments at the optimal settings. The predicted S/N ratio (η_p) using the optimal levels of the control parameters are computed as follows:

$$\hat{\eta}_p = \eta_m + \sum_{i=1}^{k}(\eta_i - \eta_m) \tag{5}$$

where η_m is the total mean S/N ratio, η_i is the average S/N ratio corresponding to the ith control parameter at its optimal level, and k is the number of control parameters that affect the quality characteristic. The results of the confirmation experiments shows an increase of 4.28 dB in MSNR at the optimal settings as compared to the initial settings. A significant reduction in Ra and KT of 3.4 µm and 1.43º respectively is obtained by MOO. Computed increase in individual S/N ratios for Ra and KT is 6.44 dB and 3.11 dB respectively at the optimal settings as compared to initial settings as shown in Table IV. Figure 4 illustrates the response plot for MSNR while Figures 5 and 6 shows S/N ratio response plots for Ra and KT.

Table IV: Effects of factor levels on S/N ratios

Factors	MSNR w_1=0.5, w_2=0.5			S/N ratio (Surface roughness)			S/N ratio (Kerf taper)		
	Level 1	Level 2	Level 3	Level 1	Level 2	Level 3	Level 1	Level 2	Level 3
WJP	-11.64*	-12.41	-12.07	-16.04	-15.22	-14.14*	-7.25*	-9.61	-10.01
AFR	-12.17	-11.52*	-12.43	-14.99*	-15.1	-15.3	-9.36	-7.94*	-9.57
QL	-13.48	-12.29	-10.36*	-17.37	-15.2	-12.83*	-9.59	-9.38	-7.9*
Optimum parameters settings			$A_1B_2C_3$	$A_3B_1C_3$			$A_1B_2C_3$		
Improvement (dB)			4.28	6.44			3.11		

*Optimum Level

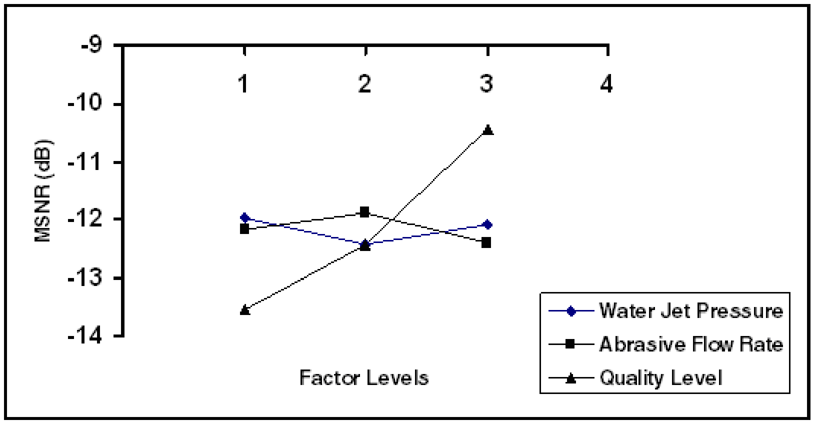

Fig. 4. Response plot for MSNR

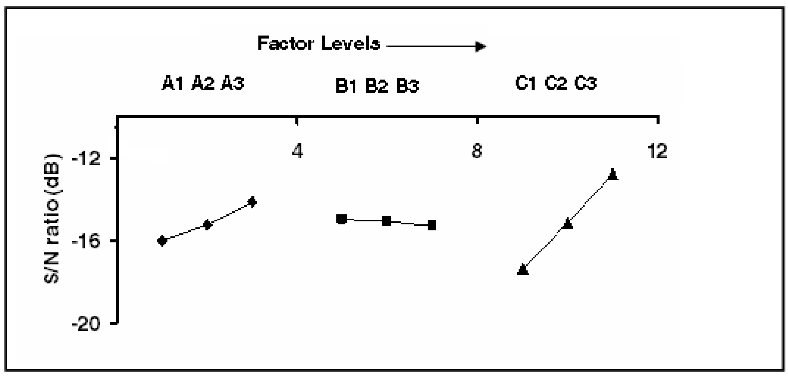

Fig. 5. Response plot for Surface roughness

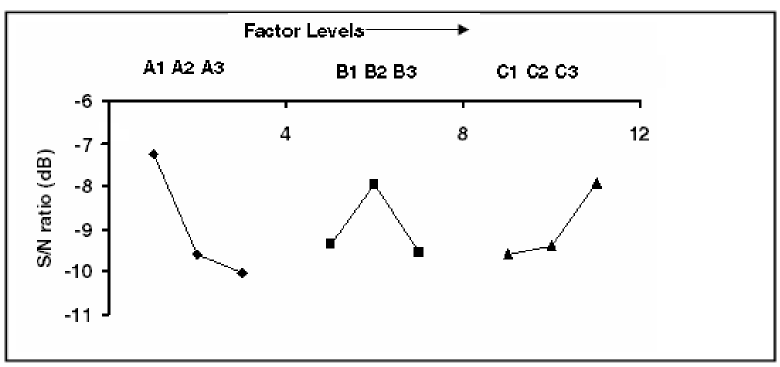

Fig. 6. Response plot for Kerf taper

6.0 Conclusions

The following conclusions can be drawn from the results of the present research work:

1. The optimum parameter settings for simultaneous optimization of Ra and KT are found to be water jet pressure-250 MPa, abrasive flow rate-325 g/min and quality level-5.
2. The contribution of cutting parameters by ANOVA in decreasing order is QL, WJP×QL, AFR×QL, AFR and WJP.
3. This approach will prove to be very useful for the AWJC community for simultaneous optimization of kerf quality characteristics of aramid composites.

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NEW METHODS FOR ENHANCED STUDY OF THE ELECTROCHEMICAL MACHINING PROCESS

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Abstract

Generally, the machining technique using electrochemical erosion is based on the material removal from the workpiece as a consequence of the chemical reactions developed between the workpiece material and the electrolyte, in the presence of the electric current. In the case of most of the electrochemical machining techniques, the concrete process develops in closed spaces. Therefore, the direct observing of the material removal from the workpiece and of the gradual forming of the machined surface is not possible. In order to enhance the study of the electrochemical erosion process, two devices are suggested and discussed in the paper. The first device is simple yet highly suggestive in illustrating the evolution of the electrochemical erosion process with natural depassivation. This device is based on the use of two electrodes (test piece – anode and electrode–tool – cathode) made of thin plates (0.1...0.3 mm). The electrodes are clamped on the internal surface of the parallelepipedic recipient made of transparent material. If the two electrodes are connected to the direct current source and the electrolyte (sodium chloride aqueous solution) is found in the recipient, the electrochemical process is then initiated, one having the possibility to observe it through the recipient transparent wall. This solution does not permit an intense circulation of the electrolyte in the work gap. For this reason, the second device was designed and manufactured. In this case, both electrodes (made also of thin plates) are placed between the base piece of insulating material and the transparent cover. The device could be placed on the guide of the universal lathe tool slide; thus, the slow mechanical work motion of the electrode tool could be obtained. The system of existing holes in the base piece allows for the forced electrolyte circulation, due to the presence of a hydraulic pump. The existing gap value between the electrode-tool and the test piece could be theoretically established and practically verified using the two devices.

Keywords: electrochemical machining, device, natural depassivation, hydrodynamic depassivation.

1.0 Introduction

As part of some specialized directions for the education of future engineers in the field of industrial engineering, at the Technical University "Gh. Asachi" of Iaşi the curriculum contains the subject named "Non-conventional Technologies". The main objective of this discipline is to provide a basic understanding of the aspects specific to the research and practice of certain machining techniques by non-conventional methods and, at the same time, the development of those competences able to allow the future engineer to handle with problems of design and use of non-conventional machining methods.

Generally, in universities, the non-conventional technologies are considered to be technologies based *essentially on increasing the energy available in the work zone, through different methods, so that either a traditional machining process develops under better conditions, or the machining process develops on new principles, fundamentally different in comparison with the basic principle of the traditional machining process* (*the principle of plastic deformation*; even the cutting process is based on such a principle, because the workpiece material is pressed by the cutting tool until a shearing phenomenon determines the chip forming). Currently, the non-conventional technologies include [1]-[5] the electrical discharge machining, the electrochemical machining, the plasma or ion beam machining, the laser beam machining, the electron beam machining, the water jet machining, the magnetic field machining etc. The actual name of *non-conventional technologies* is sometimes considered to be not exactly adequate, because in its first stage, each new technology could be regarded as *a non-conventional* (*non-traditional*) technology. Therefore, in the future it is possible to consider that the name used by the prestigious journal CIRP Annals. Manufacturing technologies (the name of "Electro-Physical & Chemical Processes) or the name used within the international symposia ISEM (name of "Electro machining") illustrate much better the discipline content.

A relatively important group of technologies included within the non-conventional technologies is the group of *electrochemical machining methods*; of course, the group could include electrochemical processes which imply the material removal from the workpiece (manufacturing methods by electrochemical erosion), but also some manufacturing methods which involve the addition of material (there are electrochemical plating or certain processes that determine a change in the chemical composition of the surface layer).

2.0 Assessment of the Current Situation

The machining methods by electrochemical erosion (usually known as *the electrochemical machining – ECM*) are based on the electrochemical (anodic) dissolution of the workpiece material within some characteristic processes of electrical charges and mass changes between the electrolyte, the anode and the cathode. Sometimes, electrochemical machining is considered to be *the reverse process of electroplating* [5].

Nowadays, electrochemical machining is one of the mostly used non-traditional machining processes by erosion [6]-[7]. The main characteristic of the process is the metal removal without the use of mechanical or thermal energy; the high material removal rate is another argument to explain the extent of some electrochemical machining processes. As a consequence of the dissolution process development, the electrolyte concentration diminishes near the two electrodes; the phenomenon is called *the polarization of the concentration.* At the same time, the products of the chemical reactions could gradually generate a layer with a decreased conductivity level or even with properties corresponding to an insulating material; this layer appears on the workpiece surfaces affected by electrochemical erosion. In this way, the so-called *passivating film* is generated.

Usually, the continuous generation and developing of the passivating film is considered to be an inconvenience, because it determines the reduction of the material removal rate (an exception being *the electrochemical surface marking, when precisely the passivating layer is the marking observed*). The researchers took this into consideration and finally found certain ways to diminish the negative effects of the passivating film forming or of the presence of the concentration polarization.

Figure 1 presents a schematic graphical representation which emphasizes the process of material removal in the case of the electrochemical machining with forced hydrodynamic depassivation.

Usually, the monographs concerning the non-conventional technologies include at least a chapter intended to present the knowledge in the field of the electrochemical machining techniques existing at a given moment [2]-[5].

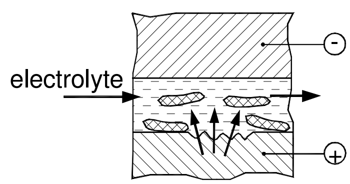

Fig. 1. Material removal during the electrochemical erosion process.

More than two hundred years ago, the English scientists *Humphry Davy* and *Michael Faraday* laid the foundations of the science called *electrochemistry*; nowadays, one considers that the electrochemical machining develops essentially in accordance with Faraday's laws. The main advantages of the electrochemical machining technologies are: *a)* High material removal rate, especially in the case of the electrochemical machining techniques with forced hydrodynamic depassivation; *b)* Lack of any thermally or mechanically affected layer; *c)* Lack of the burrs at the ends of the machined surfaces etc. On the other hand, some disadvantages of the use of electrochemical machining methods are the following*: 1)* A more reduced machining accuracy, in comparison with some other classical or non-traditional manufacturing methods; *2)* An increased roughness of the machined surfaces and the possibility for the surface roughness to be influenced by the chemical composition of the workpiece material; *3)* A more difficult electrode tool design (the work gap value is not the same along the machined surface; together with many other factors, a more intense electrolyte circulation can influence the material removal rate from the workpiece) etc.

As previously mentioned, at the Technical University "Gh. Asachi" of Iaşi, the curricula valid in the case of some so-called specializations in the field of industrial or mechanical engineering include a compulsory or optional subject of *non-conventional technologies*; to this discipline, 2 classes of course (lectures) and 1 or 2 classes of applications are allocated on a weekly basis, for a period of one semester (14 weeks). Under such conditions, at least an application activity (2 classes) is intended to the study of the aspects concerning the electrochemical machining methods.

It is known that in the case of most of the electrochemical machining techniques, the concrete process develops in closed spaces. Therefore, the direct observing of the material removal from the workpiece and of the gradual forming of the machined surface is not possible, therefore this direct observing of the machining process can be performed in the case of some classical cutting machining methods (turning, milling, slotting etc.). The didactic staff considered that it would be useful to identify practical solutions able to allow the students the possibility to directly observe the evolution of the electrochemical erosion process, for different theoretical considerations and relations to be thus verified.

The study of the specialty literature emphasized the existence of less information able to permit the fulfilment of the above mentioned desideratum. Usually, different schematic representations are used to explain the material removal in the case of the electrochemical machining, but without specifying a simple way to verify or study in detail the phenomena specific to this machining method. Under such circumstances, by taking into consideration the information available in the specialty literature and the authors' own experience, two devices were designed and built.

3.0 Device for the Study of the Electrochemical Machining Process with Natural Depassivation

A simple yet suggestive variant to illustrate the way to develop the electrochemical erosion process with natural depassivation is presented in Fig. 2. As anode, one uses the test piece (the workpiece) *1* of thick steel sheet (having a thickness of 0.2 – 0.3 mm). The test piece *1* can also be made of other metallic materials, whose behaviour during the electrochemical erosion process must be studied.

The electrode tool (the cathode) *2* is made of copper thick sheet (the thickness being also of 0.2-0.3 mm). Both electrodes (the test piece and the electrode tool) are clamped on one of the vertical transparent walls of a parallelepipedic tank *3*. The electrodes' clamping is ensured by means of two tongs *4* and *5* of insulating rigid material; the tongs ends, which are in contact with the electrodes, are made of rubber, to avoid the electrodes slipping or damage.

The two electrodes *1* and *2* are connected to a direct current source, by means of two additional metallic tongs and connection cables. The electrodes *1* and *2* are partially immersed in an electrolyte which can be, for example, the aqueous solution of sodium chloride. For a better and direct following of the machined surface shape and for material removal only from a certain test piece surface, both the electrode tool *2* and the test piece *1* are covered with a transparent insulating layer on the surfaces, which in a first stage should not be affected by the electrochemical erosion process. Only the electrodes' narrow surfaces placed face to face are not covered by the insulating layer and thus they directly ensure the conditions necessary for the material removal from the test piece during the electrochemical erosion process with natural depassivation. This depassivation is possible as a consequence of the hydrogen bubbles generation and their motion to the upper free surface of the electrolyte. Nevertheless, it is necessary to mention that during the machined surface evolution, the maintaining of the insulating film makes the stirring and the circulation of the electrolyte near the test piece exposed surface more difficult, as a consequence of the generation and motion of hydrogen bubbles.

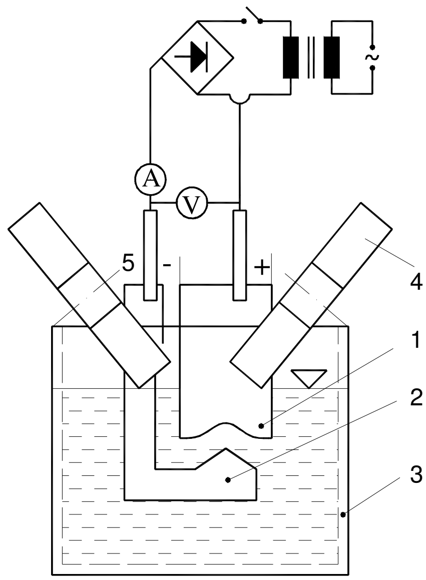

Fig. 2. Device for the illustration of the electrochemical machining process with natural depassivation.

There is no motion between the electrodes, so there is no so-called *work motion*. Because both electrodes are made of thick metallic sheets, the time necessary for the experimental test is reduced to only a few minutes and there is the direct possibility to see how the machined surface develops. The factors which can be changed in the case of an extended experimental test are the following: the type of test piece material, the test piece thickness, the shape and the dimensions of the active part belonging to the electrode tool, the chemical composition and the concentration of the electrolyte, the voltage applied to the electrodes etc. The active zone of the electrode tool can have different plane shapes (angular shape, with different values of the angle, curvilinear shape, a concatenation of curve and straight lines etc.), by taking into consideration the phenomena and the effects that one intends to study.

An interesting aspect was emphasized by the unintended existence of some pores in the insulating transparent film which covers the test piece lateral surface; due to the presence of the electric field, a faster dissolution of the workpiece material in the non-protected zone generated a penetrated hole, having reduced enough errors from the circular shape.

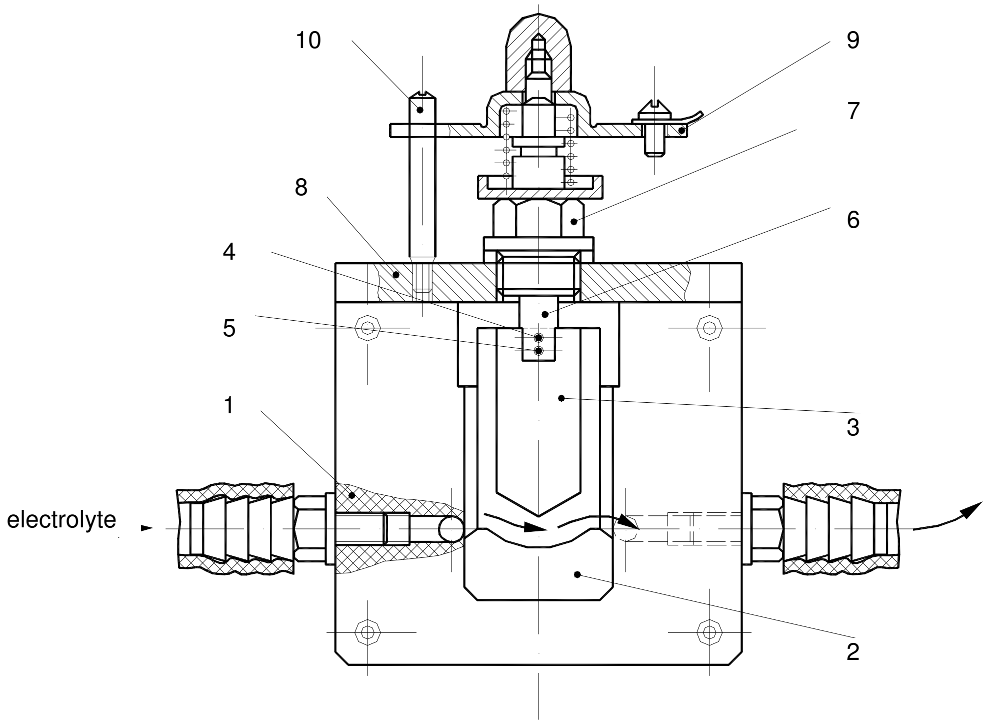

Fig. 3. Device for the illustration of the electrochemical erosion process with forced hydrodynamic depassivation.

4.0 Device for the Study of the Electrochemical Erosion Process with Forced Hydrodynamic Depassivation

The device above presented did not permit the illustration and the study of the electrochemical erosion process with forced electrochemical depassivation; the only possibility for electrolyte stirring or for breaking and removing the passivating film was based on the generation and motion of the hydrogen bubbles.

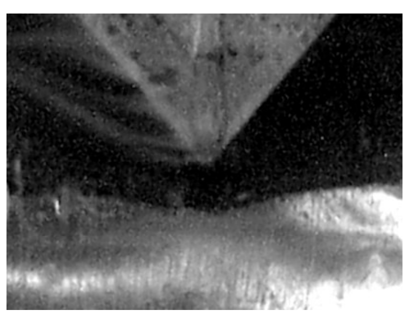

Fig. 4. The gap evolution during the electrochemical erosion process with hydrodynamic forced depassivation.

In order to illustrate the electrochemical erosion process by the use of the hydrodynamic depassivation, the device schematically presented in Fig. 3 was designed and built. Essentially, there is a parallelepipedic body *1* made of insulating material, in which a cavity permitting the placement of the thin test piece *2* was previously designed. The electrode tool *3*, made of copper thin sheet, can have a fixed position, but it may also have a rectilinear slow motion. The cavity existing in the device body *1* can be closed by means of a cover made of insulating transparent material; this transparency permits the observing of the gap size evolution and of the surface shape developing gradually as a consequence of the electrochemical erosion process (Fig. 4). The electrode tool *3* is clamped at one of its ends by means of two screws *4* and *5* in a slit existing at the end of the bar 6, which can move along its axis. The bar motion occurs into a sleeve *7* that screws in the metallic wall *8* bordering the machining space.

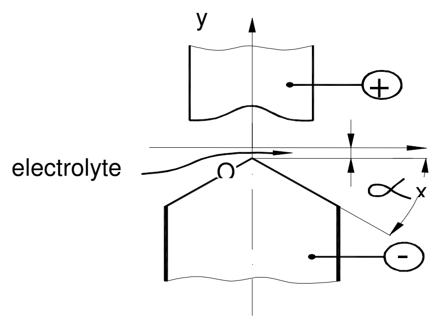

Fig. 5 Theoretical modelling of the machined surface evolution during the electrochemical machining process.

To ensure only a rectilinear motion to bar *6* and thus to avoid its rotation, at its end there is a flange *9*, which can be moved along a guiding rod *10*. The device could be placed on the guide of the universal lathe tool slide; thus, the slow mechanical work motion of the electrode tool could be obtained. The system of holes existing in the base piece permits the forced electrolyte circulation, due to the presence of a hydraulic pump.

5.0 Modelling of the Gap Size Evolution

To theoretically model the gap size evolution, the scheme presented in Fig. 5 could be taken into consideration; the coordinate system *xOy* has the origin at the intersection of the symmetry axis of the electrode tool profile (an angular shape of the electrode tool active zone is considered) and the line corresponding to the initial surface of the test piece. The active zone of the electrode-tool has a symmetric angular shape, characterized by the angle 2α. In the case of electrochemical machining without work motion of the electrodes, after a duration *t* of electrochemical erosion, the machined profile corresponds [8] to the following relation:

$$s = \sqrt{2Ct + s_0{}^2} \quad (1)$$

where s_0 is the initial gap size and the constant *C* is given by:

$$C = \frac{A(U - \Delta U)k}{F\delta_m} \quad (2)$$

A being the atomic mass of the test piece material, *U* – the voltage applied to the two electrodes, U_{pol} – the voltage for the two electrodes polarization, *k* – the electrochemical equivalent of the test piece material, *F* – Faraday's constant, δ_m – the test piece material density.

The initial gap size s_0 is practically determined by the minimum distance s_0 between the electrodes and the distance Δs, generated by the inclined position of the electrode tool profile:

$$s = s_0 + \Delta s \quad (3)$$

By taking into consideration the geometrical aspects, the distance Δs can be expressed [9] as a function of the tangent to the angle α:

$$\Delta s = \frac{x}{tg\alpha} \quad (4)$$

Thus, the initial gap size s_0 becomes:

$$s = s_{\min} + \frac{x}{tg\alpha} \quad (5)$$

On the other hand, the profile of the surface resulted as a consequence of the electrochemical machining process is:

$$y = s - s_0 \quad (6)$$

By considering the above written relations (1), (5), (6), the function y can be conveyed as follows:

$$y = \sqrt{2Ct + \left(s_{\min} + \frac{x}{tg\alpha}\right)^2} - s_{\min} - \Delta s \quad (7)$$

The relation (7) provides an image concerning the theoretical influence exerted by some factors on the profile of the machined surface (the time t, the angle α, the initial gap size s_{min} etc.).

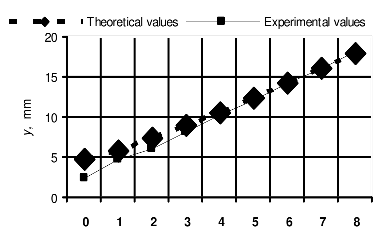

Fig. 6 Theoretical and experimental values of y (α=90°, I=1.4 A, A=28, U-ΔU=40 V, k=0.2, F=1608 A·min, ρ_m=7.8 g/cm^3, s_{min}=0.44 mm, t=5 min).

In order to verify the validity of the mathematical model represented by the relation (7), the second device (with forced hydrodynamic depassivation) was used. A photography of the obtained profile after a machining time t=5 min allowed one to measure the value y along the distance x=8 mm. The experimental and the theoretical values of y were graphically represented in Fig. 6. The more reduced correspondence between the theoretical and experimental values can be noticed for smaller values of x, when the real gap is smaller than the theoretical gap; this means that in reality the dissolution phenomenon is less intense than that supposed by the relation (7). The fact could be explained, for example, by the diminution of the electrolyte concentration along the gap, by the more intense bubbles generation in this zone etc.

6.0 Conclusion

The electrochemical machining process develops usually in closed spaces; therefore, the work gap size evolution can not be directly observed. Two solutions to see how the machined surface develops as a consequence of the electrochemical machining process were proposed and applied. The first solution uses two electrodes made of thin metallic sheets, connected to a direct current source and partially immersed in an electrolyte; the depassivation is determined through the electrolyte stirring as a consequence of the generation of hydrogen bubbles and their motion to the free surface of the electrolyte. Using a hydrodynamic forced depassivation as a second solution, the two electrodes were placed in a device having a transparent cover. The electrolyte circulates through the gap size due to the presence of the hydraulic pump. The experiments proved the possibility to use both devices so as to directly observe the evolution of the machined surface during the electrochemical erosion process and to verify the validity of some theoretical considerations. A better understanding of the electrochemical erosion process by the students is possible through the use of the two devices built.

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USE OF PRECISION MEASUREMENTS OF EVOLVED GEOMETRICAL AND DIMENSIONAL DEVIATIONS AS A DIAGNOSTIC TOOL FOR AIR-COOLED DIESEL ENGINE CYLINDER

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Abstract

Micro-scale measurements of geometrical and dimensional features of components require an advanced precise and accurate device such as the CMM machine. Evolved changes in the geometrical and dimensional measurements as referred to benchmark values can be employed as a reliable diagnostic tool in monitoring the functional deterioration of mechanical parts that involve working surfaces during their operation. It is evident that excessive wear in a cylinder bore of an internal combustion engine can dramatically affect the quality of performance, the sealing function, the scheme of lubrication, and eventually the service life span of the piston rings and in turn of the engine as a whole.

In this work, precise and accurate measurements of evolved deviations in roundness, straightness, and concentricity in a cylinder bore of an air cooled Automotive Diesel Engine using a CMM machine have been executed and analyzed. The results have been presented, discussed, and interpreted in order to demonstrate making use of them in monitoring the status of the engine during operation. Locations of severe wear occurrence in the cylinder bore are then detected and investigated. The measurements within relevant uncertainties would reflect the quality of the engine performance, the suitability of the applied scheduled maintenance plan, and the adverse operating conditions which may have been probably encountered during service life. Thus, in the light of the findings, recommendations can be provided to the engine designer to improve his design regarding changes of material selection and/or surface treatments.

Furthermore, an innovative constructional modification may be suggested to homogenize the wear occurrence in the cylinder bore during operation. For instance, a device may be added to the construction in order to cause continuous slow rotation of the cylinder about its geometrical axis while the engine is running, without having to dismantle the components. This may extend the operating life span of the cylinder and in turn reduces the maintenance expenses. In addition, power loss due to friction and wear in the engine may be favorably affected.

Keywords: Dimensional metrology, surface geometry, uncertainty, diesel engine, friction and wear.

1.0 Introduction

Accurate geometrical and dimensional measurements using precision devices are crucial during the manufacturing processes of parts to insure their compliance with the design requirements. In addition, those measurements may also be employed with reference to their benchmark values to monitor the extent and severity of functional deterioration of the parts, especially those working with their surfaces during service. This helps the maintenance engineer take proper decisions regarding his forthcoming maintenance plan and/or repair actions. Thus, the durability and reliability of the parts and the assembly would be favorably affected.

Air-cooled Diesel engine, for instance, is commonly used in heavy duty transport fleets applications due to their high performance, efficiency, and low fuel consumption. The surface contact problems between cylinders and pistons through their rings are vital to the engine performance within the adverse operating conditions of high pressure, temperature rise, and high relative velocity of the contacting surfaces [1]-[2]. Fine finish and surface treatment together with proper geometrical and dimensional tolerances standards implementation are required in order to ensure good sealing between cylinder wall and piston rings, good load-carrying capacity, good lubrication conditions, less friction, suitable wear resistance, low translated vibration levels, high engine efficiency, and longer service life span [3]-[4]. The main function of the piston rings assembly is to provide a good dynamic sealing between combustion chamber and crankcase during compression and power strokes. Reasonable sealing minimizes power loss due to charge escape from the combustion chamber within suitable ring expansion gap and limited friction force. For long sealing service life, friction and wear between piston rings and cylinder wall have to be properly controlled [5]. They are controlled by lubrication of the interface with dry lubrication of cylinder bore material composition besides an oil film thick enough to separate the asperities of piston rings and cylinder surface [2]-[5]. The friction loss varies according to piston velocity between top dead center (TDC) and bottom dead center (BDC), where the oil film thickness depends on the instantaneous relative velocity of the piston ring, which varies from zero at TDC and BDC to a maximum in the midstroke section. This means that wear conditions will vary along the piston ring traveling distance, from mild to severe [6].

Normally the cylinder bore is not perfectly cylindrical along its entire length. Practically, the bore distortion causes loss of conformity between piston rings and cylinder wall which in turn produces some troubles to oil film distribution. Variation in the oil film thickness exposes piston rings and cylinder to the whole spectrum of lubrication regimes, from mixed and probably elastohydrodynamic to full film hydrodynamic lubrication [4]-[5]. Consequently, different wear mechanisms will develop geometrical departures in transverse sections along the cylinder bore [6]. TDC location on the bore suffers heavily from oil starvation more than that at the BDC and its vicinity. Although the piston at both locations are kinematically characterized by marginal inversion velocity situations where it reaches zero before starting to get inverted, the most severe wear is expected to appear at the TDC due to the oil shortage while at the BDC the oil is available either from the source or due to gravity. However, the BDC may also experience high wear rate due to the existence of hard grit and wear debris accumulated by the gravity at this location and the neighboring area. The midstroke location and the nearby zone, where the piston velocity reaches its maximum value, mild wear only is expected because the oil film becomes dynamically thick enough to separate the mating solid surfaces and prevent metal-to-metal contact [7].

Although there are many new advanced inspection equipment such as CMM machines of which their use is so far only monopolized to the manufacturing fields [8]-[9], rare published research work yet exists in the use of such advanced CMM metrology utilities in the field of engine health monitoring through geometrical departure measurements and analysis.

Characterization of engine cylinder bore geometry and dimensions is a two manifold problem. The first is related to the applied techniques and quality standards adopted during manufacturing inspection process. This concerns the prescribed surface design parameters such as dimensional and geometrical tolerances, and surface roughness. The second is related to processing such data with the purpose of monitoring the changes that happened to the surface geometry and dimensions during engine service life span. This would help in two aspects: the first is related to maintenance decisions, while the second is related to design modifications. Research work has been done on surfaces with Gaussian distribution roughness, but cylinder wall fine finished surface with specified geometrical features and properties participate simultaneously together to controlling the environment that critically affects the engine functional performance and life [10]-[11]. Although the specified surface parameters represent advanced features, their definition is generally unrelated to any physical or mathematical properties of the surface topography [12]. The plotted accumulation of surface asperities heights according to the Gaussian distribution appears as straight line scales. For transitional surface topography, such a scale appears as two intersecting straight lines. The slopes of the lines are proportional to the standard deviations of the two distributions, while the point of intersection represents the depth of transition from one finish to another. Difficulties encountered using this technique to apply, has recently solved with developing advanced calculations software [8].

On the other hand, the numerical description of the changes in the operating surface geometry during service life span necessitates detecting and follow up the surface geometrical deviations. However, some changes occur in such a way that a band of surface fine wavelength may disappear. Hence, Fourier Transformation Analysis is needed in this case to determine the surface power spectrum response of special software to characterize the changes in the surface straightness and roundness relevant to operation environment changes [7]. Statistical calculation analysis of standard uncertainty (type U_A) is also needed for CMM measurements [13].

The purpose of this work is to demonstrate employing the accurate precise surface geometrical and dimensional measurements to monitor and follow up the extent of severity of wear changes in a worn out cylinder of an Automotive Diesel Engine as related to the resulted geometrical distortions in both transverse directions (out-of-roundness, and derived concentricity), and longitudinal directions (out-of-straightness). Thus, design improvements and/or correction actions to the scheduled maintenance plan could be suggested in the light of the analysis of the obtained measurements within the relevant uncertainties. Innovative design modification and inspired ideas may also be pointed at for the sake of extending the engine service life span and minimizing the running operational and maintenance expenses.

2.0 Cylinder Forces and Surface Measurements

2.1 Dynamic Friction Forces

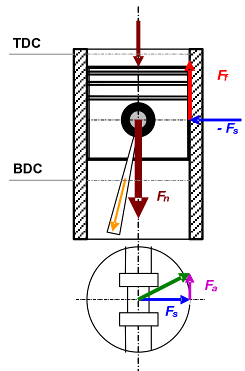


Fig. 1. Forces acting on the cylinder bore

Combustion gas pressure represents the essential axial force acting on the piston crown area to move it downwards against reciprocating mass inertia. Fn is the instantaneous sum of the normal acting forces on piston pin, Fig. 1. Reciprocating piston motion on angular movable connecting rod generates a variable piston side force Fs. An axial transmitted force Fa of the crankshaft due to clutch engagement force and timing gear force components affect the cylinder wall. The resultant of piston forces Fs and Fa attacks the wall at an angle with Fs. The angle value varies as a function of the force amplitude to generate a resultant force causing rotation around the cylinder axis. Dynamic friction force Ff has been produced due to relative motion of piston rings with respect to the cylinder wall under the effect of the resultant force in a spiral like motion. This causes the cylinder bore to wear at rates corresponding to the resultant force amplitude and direction to generate eventually a cylinder out-of-roundness (OOR) and out-of-straightness (OOS).

2.2 Surface Geometry Measurements

Geometrical and dimensional characteristics of the cylinder bore surface have been measured using a computerized Coordinate Measuring Machine (CMM) equipped with a contact scanning probe and a Least Square (LSQ) computing algorithm. The CMM used throughout this work was Carl Ziess bridge model available at the Engineering and Surface Metrology Lab, Precision Division, Egyptian National Institute of Standards (NIS). It is capable of producing accurate results with a reasonable repeatability and reproducibility for the surface geometrical departure features. The maximum permissible specific error value of the used CMM machine can be judged using the following equation:

$$MPE_E = \pm \{0.9\ \mu m + (L/350)\},\ \mu m \qquad (1)$$

Where *L* is the measured length in mm.

The CMM measurement performance was verified according to ISO-10360 [14]. An experimental investigation has been conducted on an air-cooled Diesel engine cylinder made of high quality grey cast iron (GG 25) having initially a design diameter of 110 mm and configuration shown in Fig.2a. The chemical analysis and mechanical properties of the cylinder material are presented in Table I, where HB is the Brinell hardness and σ_t is the tensile strength. The piston stroke is 140 mm.

Table I: Cylinder material specifications

Chemical analysis, wt. %							Mechanical properties	
C	Si	Mn	P	S_{Max}	Cr	Ni	HB	σ_t, MPa
3.10	2.10	0.65	0.30	0.10	0.20	0.32	220	Min. 220

(a) Cylinder configuration (b) Locations for roundness and straightness measurements

Fig. 2. Engine cylinder configuration and locations of measurements

A straight Stylus tungsten carbide shaft probe with a ruby tip attached to PRISMO CMM machine was used to quantify the surface geometric and dimension departure characteristics of the cylinder bore. The CMM traveling speed was 40 mm/s and the probe scanning speed was 10 mm/s during measurements. The straightness measurements were carried out along four longitudinal equispaced locations, 90^o apart around the circumference, at 1, 2, 3, and 4 as indicated in Fig.2b. Cylinder bore roundness quantification was conducted at sections I, II, III and IV nearby TDC, midway, and BDC planes as shown in Fig. 2b. The surface geometrical and dimensional features were represented by mean average values of five repeated test measurements.

3.0 Uncertainty Assessment of Measurements

The mean average values and uncertainty of roundness and straightness measurements for the engine cylinder bore have been presented in Table II. Where M_{AV} is the mean value of five repeated test measurements, S_D is the standard deviation, and U_A is the uncertainty due to measurement repeatability ($U_A=S_D/\sqrt{n}$), where n is the number of repeated tests for each target measurement [13]. It worth mentioning that type B source of uncertainty is not accounted for by U_A values because of its relative insignificance to the OOR and OOS. The accuracy and uncertainty of these measurements have been determined and found to be within the acceptable standard limits.

Table II: Measurements of both roundness and straightness together with the uncertainty assessment

Tests / Points	Test 1	Test 2	Test 3	Test 4	Test 5	M_{AV}	S_D	U_A
1. Roundness, µm								
@ circle I	91.0	90.9	90.9	90.9	91.0	90.94	0.0548	0.0245
@ circle II	32.1	31.8	32.1	31.9	31.80	31.94	0.1152	0.0678
@ circle III	23.0	23.5	24.2	24.0	24.3	23.80	0.5431	0.2429
@ circle IV	18.2	18.3	18.3	18.5	18.9	18.44	0.2793	0.1249
2. Straightness, µm								
@ line 1	71.0	71.0	70.3	70.5	70.1	70.58	0.4087	0.1828
@ line 2	54.4	54.1	54.3	54.5	54.5	54.36	0.1673	0.0748
@ line 3	13.6	13.8	13.7	13.6	13.7	13.68	0.0837	0.0347
@ line 4	34.6	34.7	34.8	34.8	34.9	34.76	0.1140	0.0510

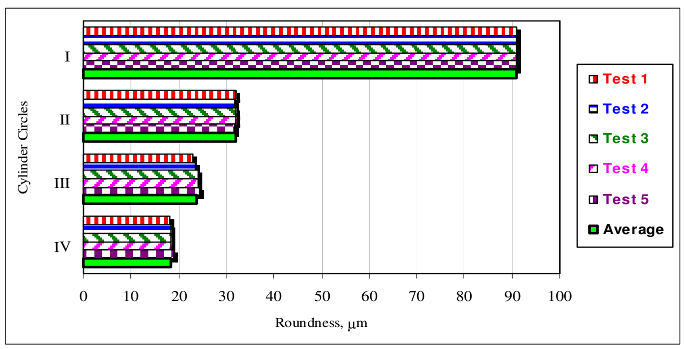


Fig. 3. Bore roundness measurements at four transverse sections along piston stroke.

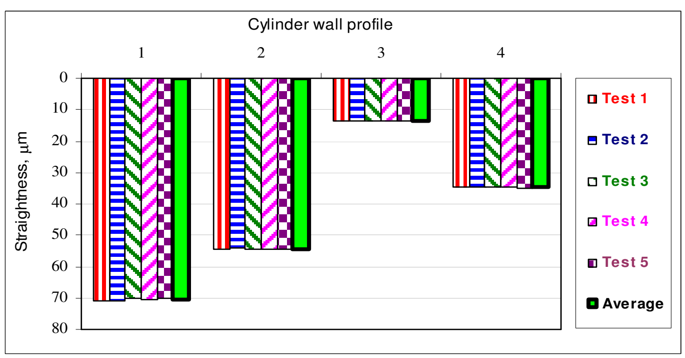


Fig. 4. Bore straightness measurements at four longitudinal equispaced locations.

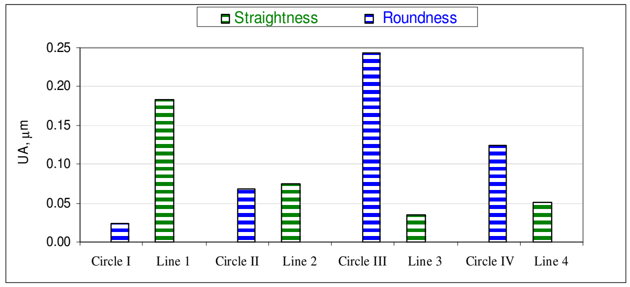


Fig. 5. Uncertainty values of five repeatable tests of OOR and OOS

The roundness and straightness results of five repeated laboratory tests conducted on each one of the adopted four transverse sections I, II, III, and IV, and the four longitudinal profiles 1, 2, 3, and 4, have been processed and presented in Fig. 3 and Fig. 4, respectively. The results are also tabulated in table II and the calculated values of the relevant uncertainty are plotted in Fig. 5.

4.0 Results and Discussion

Average run out measurements of worn cylinder bore; roundness, straightness, and concentricity, have been conducted using accurate stylus surface scanning technique on a programmable CMM machine. The concentricity is represented by the relative roundness run out at the selected transverse sections I, II, III, and IV with respect to circle I taken as a datum as shown in Fig.2b. RMS averaged values of five similar arrays of measurements have been considered. The results have been presented, discussed, and interpreted.

4.1 Out-Of-Roundness Measurement Results

Average out-of-roundness results (R_a values) have been processed for each measured circle on the bore surface and presented in figure 6 with reference to the nominal diameter which is numerically computed and found equal 111 mm. The roundness is represented at each transverse section by the domain between the two virtual enveloping circles tangent to the distorted shape processed using LSQ fitting technique built in the machine as indicated in figure 6.

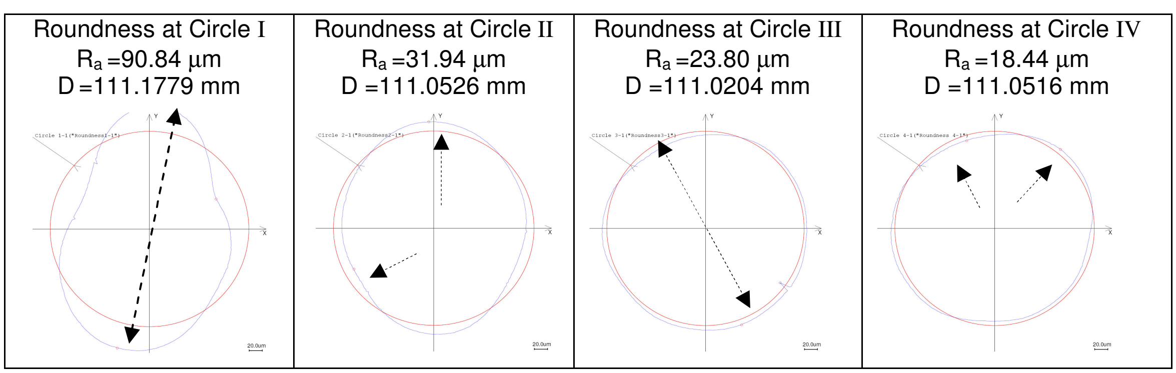


Fig. 6. Roundness sample measurement records of engine cylinder bore (--- maximum amplitudes)

Analysis of the roundness patterns of the cylinder bore, illustrated in Fig 6, indicates the following points:

- The CMM machine software establishes a reference geometric feature of ideal regular form, deduced numerically from one or more realistic irregular scanned shapes. The established reference datum can be used in the assessment process of the run out values of the geometric features of the object under investigation.
- Circle I nearby the TDC, as expected due to lubricant starvation, depicted the highest average distorted dimension of D_I=111.1779 mm and the largest average out-of-roundness (R_a=90.84 µm).Whereas, the smallest distorted dimension was depicted at section III (D_{III}=111.0204 mm) in the vicinity of the mid-stroke point of the piston crown ring with average OOR value R_a=23.80 µm., while the smallest out of roundness value was found nearby the BDC at circle IV (R_a=18.44 µm).
- Roundness of circle I has two maximum amplitudes (arrow tips in Fig. 6) at points corresponding to location of resultant surface reaction $\sqrt{F_s^2+F_a^2}$ of piston side force F_s and crankshaft axial force F_a. The side force amplitude and direction vary according to the nature of piston traveling displacement especially at compression and power strokes.
- Amplitudes of circle III have the smallest wear variation rate with relatively small out of roundness which may be due to good lubrication conditions and light side forces at that location. Whilst, roundness nearby the BDC (circle IV) has different directions of peak amplitude going with the indicated direction of cylinder distorted shape. This may be attributed to the stud clamping force situation (magnitude and direction) when the piston passes by this location. At both BDC and TDC marginal inversion locations, the loads on the piston generates a stringent translated piston dynamics.

4.2 Concentricity Measurements

Experimentally measured values of the relative roundness on the bore at different transverse locations (concentricity) have been found 39.10, 44.40, and 61.20 µm between circles I and II, circles I and III, and circles I and IV, respectively as shown in Figs 2, 6. This would reflect the distortion resulted from the extremely severe wear mechanisms to which the engine cylinder bore was being experienced during service.

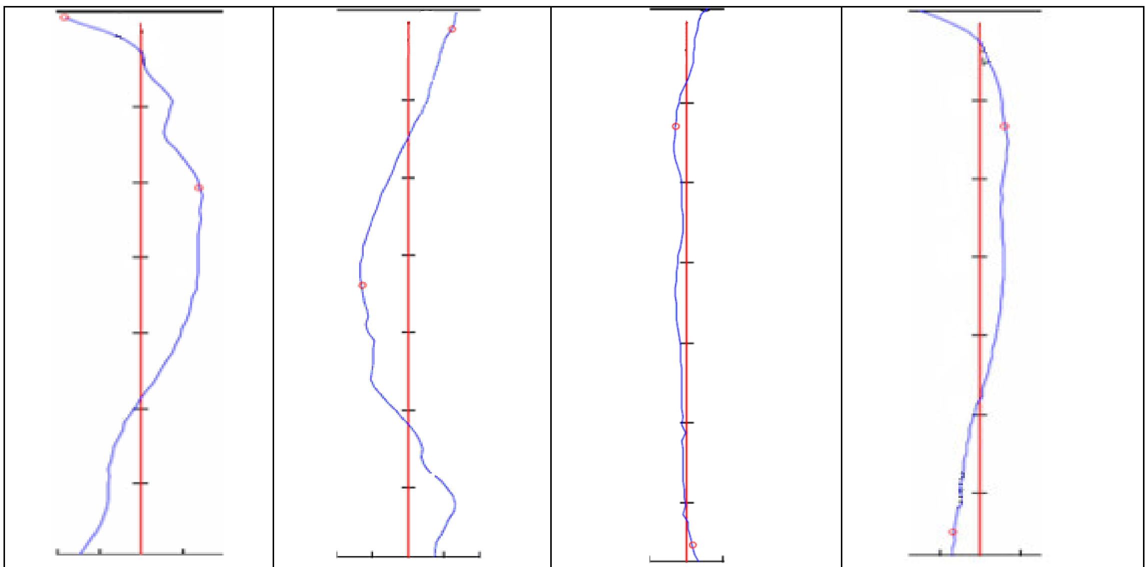
4.3 Out-Of-Straightness Measurement Results

Figure 7 shows sample record of four averaged longitudinal profiles at equispaced locations 1, 2, 3, and 4 along the cylinder inner wall as indicated in Fig. 2 above. The maximum out of straightness value (S_a) processed from the measurements along each longitudinal profile represents the deviation domain around the relevant reference line obtained by applying LSQ fitting technique.

Straightness profile sample records shown in Fig. 7 disclose the following points:

- Non uniform wear rates are exposed along all averaged longitudinal profiles. It is clear that every point on the cylinder bore is subjected to different concurrent dynamic and environmental conditions of pressure, friction, lubrication scheme, sliding velocity, contact temperature, and contact force (orientation and magnitude). Thus, frequent evaluation of bore surface geometrical status is needed whenever possible to help monitoring the functional degradation and diagnosing the surface failure symptoms in anticipation. So that, reasonable decisions can be taken regarding surface treatment implementation and/or constructional design improvement inspiration.

- Maximum wear rates have been found to consistently lie within the TDC of the first pressure ring contact area for all averaged profile measurements of 71.58, 54.38, 13.68 and 34.76 µm. This may be explained by the bad tribological conditions at the TDC location as aforementioned. The largest value of straightness departure (71.58 µm) which lies on profile 1 was formed during power strokes as a direct response to large side force reaction at high combustion temperatures. These findings are in agreement of a study carried out by Schneider et al [3].
- Wear valleys of bore straightness has large values for profile at points 1 and 2 of power and compression stroke ends (nearby BDC) due to side force reaction of concentrated piston inertia, while profile of points 4 and 3 have shown the smallest amplitude valleys, respectively.
- An extended valley of straightness has the first profile of power stroke till 70 mm long; it may be produced of piston-skirt stringent side pressure and combustion gas high temperature beside piston rotation around its pins under the effect of the friction force moment. Strong piston skirt dynamics accelerates the wear of the crankshaft axial movement control washers.



Profile at line 1	Profile at line 2	Profile at line 3	Profile at line 4
S_a=70.58 µm	S_a=54.38 µm	S_a=13.68 µm	S_a=34.76 µm

Fig. 7. Longitudinal sample profiles of cylinder straightness (S_a is the averaged straightness of the profile).

5.0 Conclusions

- Precision geometrical and dimensional micro scale measurements of straightness, roundness, bore diameter, and concentricity of the internal surface of a worn out engine cylinder have been executed using CMM machine. Compared to its original design GT&D tolerance limits, these measurements proved to represent successfully a reliable diagnostic tool for the wear development and aggression monitoring. Scenarios of the probable adverse operating conditions during service may also be drawn. The dimensional measurements of the bore diameter at different transverse locations along the traveling stroke have assured previous findings using other different complicated measuring techniques. In turn this may provide feedbacks to both the engine designer for modifications and the maintenance engineer for his forthcoming preventive and corrective maintenance plans.

- The wear at the TDC and BDC transverse sections have been found much larger than the wear occurred at the middle of the stroke and in the vicinity of the BDC. This phenomenon is attributed to the continuous existence of lubricating oil film dynamically preserved at that location.

- CMM machine precision measurements may also provide an insight in the engine dynamics that may contribute to the excessive wear occurrence in the engine cylinder. The geometrical deviation due to inhomogeneous wear has caused ovality in the bore where ($S_{a1}>S_{a2}>S_{a4}>S_{a3}$), as depicted in Fig. 8. This may inspire the engine designer to introduce an innovative modification to the engine by developing a controllable cylinder rotating device about its axis probably without having to dismantle the engine parts, so that the wear can be homogenized. Thus, the power loss due to friction and wear in the cylinder may be minimized and the engine operating life span may be rather prolonged. In addition, the maintenance expenses may be also reduced.

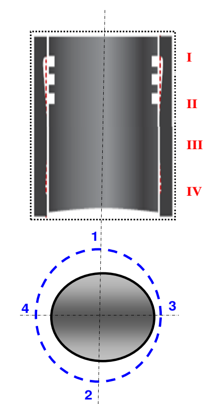


Fig. 8. Bore geometrical deviation

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AUGMENTED REALITY DESIGN METHODOLOGY FOR COMPUTER NUMERICAL CONTROL MACHINERY

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Abstract

Virtual manufacturing is a synthetic environment exercised to enhance all levels of decision and control in a discrete or continuous manufacturing organization. Machine tools are the key components of the discrete manufacturing system. Computer numerical control machine tools provides basic human computer interface at the discrete manufacturing processes. This paper describes the augmented reality methodology for building the virtual model of computer numerical control machine tools. Such augmented reality models are used as the micro element of the global virtual manufacturing organization. The virtual manufacturing organization apportions planning for a non existent manufacturing system, operation monitoring of the existent system, fault diagnostic and rapid maintenance, maintenance planning, practicing quality assurance, optimizing the local and global human computer interfaces, optimizing the flow of information, acquiring rapid response from the system, training at the manufacturing systems, distance learning, practicing e-commerce and possibility of implementing different production philosophies.

Keywords: Discrete Manufacturing, Continuous Manufacturing, Computer Numerical Control, Augmented Reality, Virtual Reality

1.0 Introduction

According to MSN Encarta the term ‘virtual reality’ is commonly used to express Simulated Reality, Computer Simulation, Simulation, Cyberspace, Computer Modeling or Computer Graphics. In today’s scientific scenario, virtual reality is classified on a continuum from Real environment to its variations to virtual environment. These variations of virtual reality are from real environment to augmented reality to augmented virtuality to the virtual environment. All the intermediate representations are known as mixed reality [1].

Azuma et. al. describes the Augmented Reality (AR) in their survey paper [1] as having the following properties:

(i) AR combines real and virtual objects in a real environment;

(ii) AR runs interactively and in real time, and;
(iii) AR registers (aligns) real and virtual objects with each other.

A discrete manufacturing operation involves tangible activities such as machinery and its operation, use of tools and measurement gadgets, use of pick and place technology and use of storage and transportation equipment etc. On the other hand, the intangible part includes services such as process planning, scheduling, inventory, management information system and business accounting etc [2][3]. Establishment of discrete manufacturing facility for specified range of discrete products includes the factory and offices layout, machinery layout, operation of design office, operation of new and old machinery, production planning and control, scheduling, assembly, quality assurance, inventory, transportation, budgeting and accounting and financial activities. Monitoring of all these and other functions is required once the facility has been setup and is functional.

In contrast to discrete manufacturing systems, a continuous manufacturing system produces liquids, gases solids, grains or powders. These continuous systems are less flexible as compared to discrete manufacturing systems. However, the application of virtual reality principles to continuous manufacturing systems considers both tangible and intangible parameters associated with these systems.

Comprehensive control of the manufacturing processes and the manufacturing systems is of prime importance for the sake of materializing the goals set for manufacturing since the industrial revolution. One of the basic control instruments that prevailed from centuries to today for manifesting control is the man machine interface for the processes and the systems. With increased computer based automation it is now evolving towards human computer interaction supplemented by virtual representation of the real processes and systems.

The design of virtual reality (VR) for discrete and continuous manufacturing covering manufacturing processes and systems is addressed. The discrete and continuous manufacturing systems are considered to be composed of physical structure for the processes and the system, control characteristics of the processes and the system and dynamics involved in the operation of the processes and the system. Virtual reality for discrete and continuous manufacturing systems involves defining steps required to build an Augmented Reality (AR) for a manufacturing process such as metal cutting process from component to mechanism to machine level and subsequently integrating the Augmented Reality (AR) of the process into the virtual reality (VR) of the manufacturing system such as job shop, project shop, cellular system, flow line or continuous manufacturing system [4][5][6]. This paper presents the augmented reality design methodology for Computer Numerical Control machinery.

2.0 Manufacturing System and Processes

The basic configuration of discrete and continuous manufacturing systems by Chryssolouris [7] is considered. This comprises:

1. Job shop
2. Project shop

3. Cellular system
4. Flow line
5. Flexible manufacturing system, and;
6. Continuous manufacturing

These ideal layouts for discrete and continuous manufacturing along with assembly methods constitute the core of the virtual reality template required for defining any virtual reality application in manufacturing. The processes required to build a manufacturing system are mainly adopted from Kalpakjian [8] description of current manufacturing processes comprising the following general areas:

1. Metal forming processes
2. Bulk deformation processes
3. Sheet metal working processes
4. Metal cutting processes
5. Metal joining processes
6. Thermal properties modification processes
7. Surface properties modification processes
8. Fabrication of micro mechanical and micro electronics devices
9. Non conventional processes
10. Continuous Manufacturing Processes

In a true virtual reality of discrete or continuous manufacturing system, the manufacturing processes should be defined with high level of virtuality encompassing all their functionality and should be capable of being configured on a chosen manufacturing system layout along with comprehensive energy, information and material flow capability [2][4][6].

The simulated processes should have the capability to mimic real manufacturing processes and are configured on a simulated factory layout. It is also possible to configure each of the tangible and intangible operations in variable quantity and size depicting a real factory. The manufacturing system and the manufacturing processes chosen in the virtual domain are reconfigurable thus allowing infinite possibilities for the development of virtual manufacturing organization. The processes may be operated using standards such as variants of EIA 274D and JIS SLIM (Standard Language for Industrial Manipulator), techniques used in programmable logic controllers (PLC) such as defined by IEC 61131-3, Embedded system and Supervisory Control and Data acquisition (SCADA) and other pertinent standards [9].

3.0 Automation of Production Equipment

Discrete manufacturing processes are developed as mechanical artifacts to perform production. These machines produce variety of components, structures, assemblies, mechanisms and machines. Each manufacturing process implementation into mechanical artifacts has three distinct features [6]:

1. The input to the equipment e.g. raw material type, form and feeding mechanism; final dimension of the product, energy source and other auxiliaries.

2. The process implementation allowing transformation of raw material into required size, shape and surface finish using tools (e.g. tools as used in metal cutting, high energy beams or various types of jets); utilizing tool holding devices and work holding devices; measuring devices and manufacturing instructions. In process supplies such as lubricating oil and coolants may also be used.
3. The out put from the equipment comprising a component (the building block of structure, mechanisms or machines); and, scrap.

There may be several other features present at the production machinery to make the task of manufacturing simpler, easy to control and resulting in high production rate.

Like any other discrete product, the manufacturing equipment commonly utilizes standard mechanical components, machine elements, control elements, electrical and electronics components and software components.

Special assemblies and other accessories utilized at the construction of manufacturing equipment may also include:

1. Tool (Referring to mechanical tool, Light Beams, Water Jets etc.)
2. Tool Holding Devices
3. Work holding Devices
4. Lubricating oil pump assembly
5. Coolant circulation pump assembly
6. Material Handling Equipment, and,
7. Scrap Handling Equipment

Computer Numerical Control, whether implemented in open loop or closed loop configuration, is the most common human computer interface at discrete manufacturing equipment. It is widely used to control features, assemblies and accessories at the discrete manufacturing machinery. Computer Numerical Control is commonly implemented at the following discrete manufacturing equipment [9][10][11][12]:

1. Mills and Machining Centers
2. Lathe and Turning Centers
3. Drilling Machines
4. Boring and Profilers
5. Electro Discharge machines
6. Punch Press and Shears
7. Flame Cutting Machines
8. Water Jet and Laser Profilers
9. Cylindrical Grinders
10. Welding Machines
11. Benders, Winding and Spinning Machines

The above listed processes cover the complete horizon of discrete manufacturing process classification as identified by Kalpakjian [8].

4.0 EIA 274D Standard

Electronics Industries Association (EIA) RS 274 D interchangeable variable block data format for positioning, contouring and Contouring/Positioning Numerically Controlled Machines [1979] is the most basic and most common standard used in the manufacturing industry for controlling CNC Machinery. A subset of this standard, as shown in figure – 1 and figure – 2, is used to demonstrate augmented reality design methodology for computer numerical control machinery [9].

5.0 Axes Classification for Metal Cutting Machinery

Axes classification for numerically controlled machines is defined by another commonly adopted EIA standard: EIA RS 267 Axis and motion nomenclature for numerically controlled machines. In this paper this standard is utilized for the axes classification of CNC machinery [9].

6.0 Software Tools for Virtual Manufacturing

The development of virtual model for describing the functionality of a product, to demonstrate operation of manufacturing, pick and place or assembly equipment or to demonstrate the operation of a complete virtual organization requires simulation of all tangible production functions while mathematical modeling of all related intangible functions. All these suites of programs should be modeled, developed and run using state of the art software modeling tools, software development technique and software execution architecture [6].

Object-oriented software development offers a new and powerful model for writing computer software. This approach speeds the development of new programs and, if properly used, improves the maintenance, reusability, and modifiability of software.

There are a large number of object-oriented programming languages in use today. But the leading commercial object oriented languages are far fewer in number. These are:

1. C#
2. Smalltalk
3. Java

These object oriented languages can be used in virtual reality design in conjunction with following graphic support tools [13][14][15][16]:

1. VRML (Virtual Reality Modeling Language)
2. OPEN GL (Low Level Graphics Library)
3. Other Graphic Design and Rendering Tools

7.0 Software Development Tools

The Augmented Reality for metal cutting machinery is designed and developed using the following tools:

7.1 Unified Modeling Language

The Unified Modeling Language (UML) is the standard language for visualizing, specifying, constructing, and documenting the artifacts of a software intensive system. Complex software design that would be difficult to describe textually can readily be conveyed through design diagrams. Each diagram focuses on one aspect of application. One may focus on structure, another on behavior, and yet another on the physical partitioning of the application. The model can be used to clearly communicate with the members of programming team. Similarly the model can be used to automatically generate source code. Modeling provides three key benefits: visualization, complexity management, and clear communication [17].

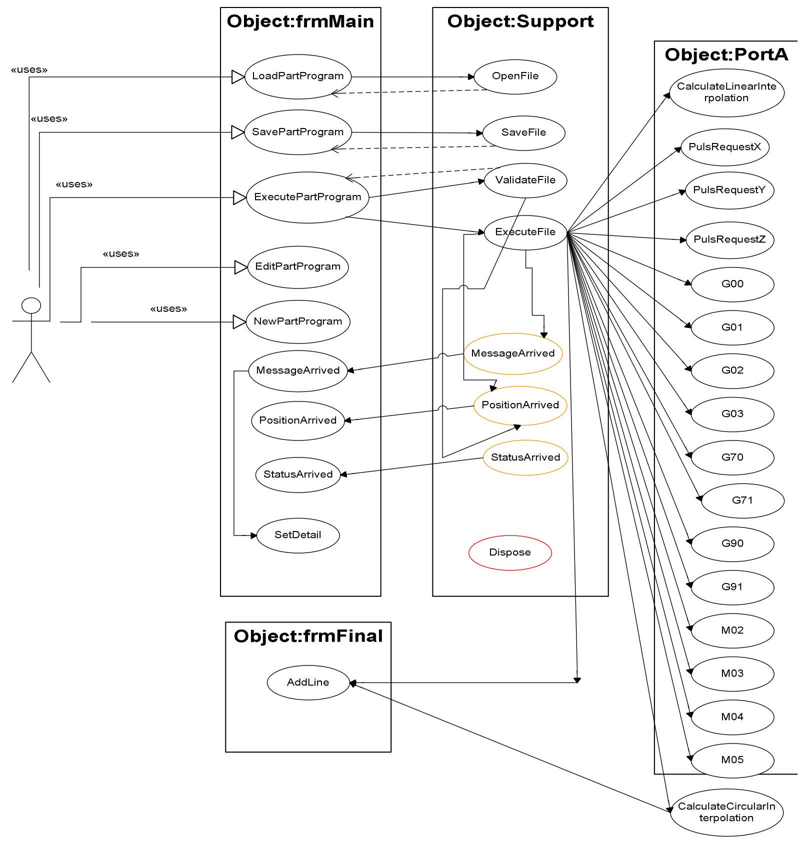

Fig. 1. A UML Use Case Diagram for CNC Operation

7.2 Visual Studio .Net 2003

Visual Studio .Net Version 1 is an IDE (Integrated Development Environment) developed for Windows Operating System. It is a complete suite of tools for building both high-performing desktop applications and team-based Enterprise Web applications. It has a rich set of languages available like Visual C++, C#, VB .NET, J# etc. The system presented in this paper utilizes C# .NET for developing the augmented models [18].

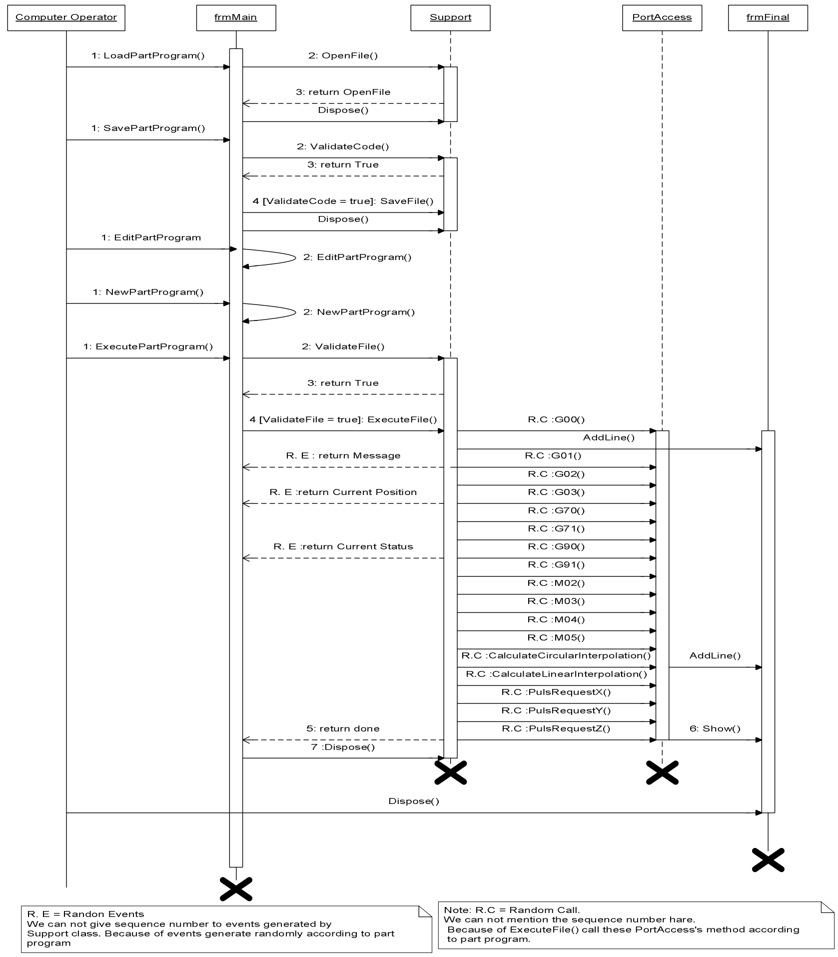

Fig. 2. A UML Sequence Diagram for CNC Operatio

7.3 True Vision 3D SDK 6.2

True Vision TV3DSDK is a 3D rendering engine written using Direct X and provides powerful functions for accomplishing 3D abstraction. It helps to develop a powerful 3D application/much faster than the basic graphics libraries like Direct X. This 3D Rendering Engine is used to access its built-in functions in C# for loading and drawing complex graphics models [16].

7.4 Direct X 9.0

Direct X is an advanced suite of multimedia application programming interfaces (APIs) built into Microsoft Windows operating systems. It provides a standard development platform for Windows-based PCs to access specialized hardware features with easy programming code. The Direct X library is used through the True Vision SDK to access the graphics hardware using the .NET environment [19].

7.5 3D Studio Max 6.0

3D Studio Max is a 3-dimensional vector graphics and animation program. It is a powerful 3D modeling and animation software used to design large scale animations for games, mechanical models and other 3D simulations. 3D Studio Max is used for designing the machine models [20].

8.0 Discussion

A methodology for augmented reality representation of discrete manufacturing machinery is developed. This methodology covers processes as identified in section – 3. A UML use case diagram is provided as figure – 1 to demonstrate the working of augmented reality for Computer Numerical Control machines. Figure – 2 presents the sequence diagram for the augmented reality representation. Figure – 3 shows an augmented reality representation of a sawing machine. This representation has the capability to mimic the operation of the machine tool and provides the shape of the final product.

The augmented reality components of the machine tools requires modeling of mechanical components (Power Screw), Electrical Component (Motors), Electronics Components (Limit Switches, Shaft Encoder) and Computer Science Components (Interpreter for EIA 274 D Standard, Graphics model of the machine tool, Graphics model of the work piece and rendering methodology). The electronic signals generated by the interpreter are simultaneously sent to the visual display unit of the machine tool controller and the controller machine tool interface is allowing higher level of human computer interaction. Such a virtual model has the capability to become a micro element of a virtual organization defining both tangible and intangible functions of discrete manufacturing system.

Using same principles, a virtual organization for discrete or continuous manufacturing can be developed to work as the proxy to the real organization. Such a scheme has the possibility of planning for a non existent manufacturing system, operation monitoring of the existent system, fault diagnostic and rapid maintenance, maintenance planning, practicing quality assurance, optimizing the local and global human computer interfaces, optimizing the flow of information, acquiring rapid response from the system, training at the manufacturing systems, distance learning, practicing e-commerce and possibility of implementing different production philosophies.

The oral presentation of this paper includes AR simulation of several CNC machine tools such as Turning, Milling, Drilling and Sawing machine. The AR simulation of Job Shop and Cellular Manufacturing amalgamating CNC machine tools with material handling equipment while producing specified objects shall also be presented.

9.0 Conclusion

A prototype for the dynamics of micro element of virtual discrete manufacturing organization in a job shop is presented. It proves that the computer and communication technologies have reached a level whereby the realization of a virtual manufacturing organization is possible. This shall lead to the availability of micro and macro decision variables to the mangers allowing optimum decision making for higher profitability.

Fig. 3. A CNC Sawing machine augmented reality representation

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OPTIMIZATION OF RESIN FLOW IN A FLEXIBLE MOULD INFUSION PROCESS FOR LARGE PRESSURE VESSELS

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Abstract

Permeability and fibre volume fraction of reinforcement fabrics are two parameters that are greatly influenced by the mould compression effect during the resin infusion process for the manufacturing of textile composite parts. In closed mould processes, such as resin transfer moulding (RTM), compression is determined by mould cavity, while in open mould processes such as vacuum assisted resin transfer moulding (VARTM) with flexible tooling on at least one side, the compression of the fabrics is mainly determined by the vacuum outflow pressure conditions.

In our specific application of the production of a large pressure vessel, the mould set-up consists of a fixed external mould and a flexible rubber tooling bag as the internal mould. The bag can be pressurized externally under controlled conditions in order to provide a compression force to the reinforcement fabrics before infusion. The effect of the enforced pressure conditions on the flexible tooling will be reflected on the fabric, as the generated compression effect will modify the permeability and fibre volume fraction.

The object of this study is to optimize the pressure history and control of the inflatable bag during an infusion process for large textile composite pressure vessels in order to better control resin flow and minimize the effect of permeability and fibre volume fraction changes on process time and final part quality. Numerical simulation techniques of resin flow will assist in finding better process conditions such as flexible tooling pressure, infusion time, and final thickness of the part. Results of numerical simulations conducted show the importance of the thickness reduction phenomena in bag moulds and its influence on the real part. The inflatable bag used, considered as a rigid mould, gives improved results and manifests itself as best choice for the

application. Simulations allowed reduced the need of expensive experimental prototype testing by means of virtual infusion process optimization.

Keywords: Permeability, Resin Flow, Flexible mould

1.0 Introduction

The use of composite vessels has extended widely in many industrial applications. Most of these vessels are made of fibreglass and a polymer resin such as polyester. Vessels have been produced since many years ago with a large variety of manufacturing techniques, targeted to suit the focus on a specific application field. In particular, for low-tech applications, a combination of spray-up and hand lay-up has been, for years, the production process that is most adapted to the necessities of low costs, size flexibility and final part quality. This open mould process consists of a spray gun projecting resin over the mould, in conjunction with a roving chopping head. However, using this method, the quality of the part is highly influenced by thickness and fibre volume fraction variations that are subsequently remediated by a manual compaction process.

With the incoming of tighter cost limits, to uphold a competitive production strategy, and with ever more strict environmental laws, open mould processes have come strongly under pressure because of the associated high volatile compound (VOC) emission level. About 14.1 and 25% of styrene emissions are produced. The above technological and legislative challenge had formed the foundation for the creation of a new production process for large vessel manufacturing.

The new process can be split in two main stages. The first stage includes the production of a preform from roving fibreglass, which is chopped and mixed with binder and projected over the preform mould. After a compaction process, one-layer of mat fabric with a shape and thickness close to the final part is obtained.

The second stage then introduces a moulding technique in the process. Major advantages of closed mould processes are the significant reduction of volatiles and the fact that the part weight is reduced as because less resin is used. Also mechanical properties are improved due to the reduction of voids and the better thickness control of the part. However, disadvantages are the high tooling cost and sometimes the reduction of final part thickness due to the compaction effect in the closed mould

The following paper uses numerical simulation to analyze the production of a generic large vessel geometry in a specific mould setup to investigate whether the above described second stage moulding process can better be implemented by means of a closed mould technique such as resin transfer moulding or via a flexible mould technique as is vacuum bag moulding (VBM).

2.0 Description of the Part and the Mould Setup

The design of a new range of vessels, lea to the design of a full new production process that upholds cost limits, environmental requirements, and improves the properties of the actual vessels suppressing the joint between the two middle-parts of the current geometry configuration.

To achieve that, a mould setup consisting of an external two-part rigid mould and an internal bag has been developed. The production process includes the self-production of a preform made from chopped roving fibre and with the shape of a half vessel. On the resin infusion stage, the bottom half-vessel preform is placed over the half-vessel bottom mould, and the upper perform is placed over the inflatable bag. Both are joined and the upper mould closes the system. The whole set will be sealed to start the infusion. An illustrative image of the set-up is shown in Figure 1.

The untypical conception of the mould, with the internal mould being the flexible one, gives the opportunity to include pressure to this bag if necessary. Hence, depending on the pressure of the bag, it can be considered as:

Rigid Mould: The inside pressure of the bag is enough to consider the system as a rigid mould during the infusion process. The compression effect is then negligible and the resin infusion can be described as a RTM.

Flexible Mould: A silicone bag without structural resistance is used, and the setup becomes a typical VBM process. Compaction behaviour of the fabric must be reflected on simulations.

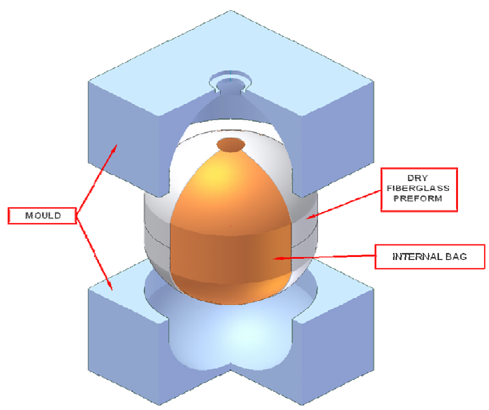

Fig. 1 Representative configuration of the mould setup with the two external parts of the mould, the inflatable bag and the two preforms

3.0 Theoretical Background

3.1 Resin Transfer Moulding Modelling

A typical setup for Vacuum Assisted Resin Transfer Moulding (VARTM) consists on a rigid mould in one side and a flexible mould in the other side of the cavity. Resin is conducted through the mould with the help of a vacuum from vents. In the first setup considered, a vacuum is used with rigid moulds on each side of the mould cavity: Hence, RTM theoretical background must be considered.

RTM simulation had been widely studied by different authors [1]-[2]-[3]. The porous media flow approach to analyze the flow of resin is commonly used, with a combination of Darcy's law and a continuity equation. The flow front advance through an incompressible mould cavity for an anisotropic, homogeneous medium can be expressed as:

$$\begin{pmatrix} u \\ v \\ w \end{pmatrix} = -\frac{1}{\mu} \begin{bmatrix} K_{xx} & K_{xy} & K_{xz} \\ K_{yx} & K_{yy} & K_{yz} \\ K_{zx} & K_{zy} & K_{zz} \end{bmatrix} \cdot \begin{pmatrix} \partial P / \partial x \\ \partial P / \partial y \\ \partial P / \partial z \end{pmatrix} \tag{1}$$

Where u, v and w are the volume averaged flow velocity, μ is the viscosity of the fluid and the matrix K describes the permeability of the reinforcement in each direction. Pressure gradients in each direction are represented by the last column.

The fluid mass conservation equation is introduced and integrated over a control volume. Using the divergence theorem, the control volume integral can be transformed into a control surface integral, giving the following expression:

$$\iint_S \lfloor n_x \quad n_y \quad n_z \rfloor \cdot \begin{pmatrix} u \\ v \\ w \end{pmatrix} dS = 0 \tag{2}$$

Where n_x, n_y and n_z are the normal components of the surface vector of the control volume. Replacing equation (1) into equation (2), the governing equation describing flow through a general anisotropic media is obtained.

$$\iint_S \frac{1}{\mu} \lfloor n_x \quad n_y \quad n_z \rfloor \cdot \begin{bmatrix} K_{xx} & K_{xy} & K_{xz} \\ K_{yx} & K_{yy} & K_{yz} \\ K_{zx} & K_{zy} & K_{zz} \end{bmatrix} \cdot \begin{pmatrix} \partial P / \partial x \\ \partial P / \partial y \\ \partial P / \partial z \end{pmatrix} dS = 0 \tag{3}$$

3.2 Vacuum Bag Moulding Modelling

Vacuum Bag Moulding is understood as an infusion process with the mould cavity delimitated by, at least for one flexible mould. The lack of resistance of this mould implies that the dry preform placed on the internal cavity to a compaction pressure that modifies parameters such as thickness or fibre volume. Also, this changes influence in the infusion results, decreasing permeability and flow front velocity.

For flow through compressible media, a compacting mould cavity must be considered, hence, following the analysis of Gutowski et al [4]-[5]-[6]-[10], the 1D in-plane flow continuity equation that must be followed is:

$$\frac{\partial h}{\partial t} = \frac{\partial (v \cdot h)}{\partial x} \tag{4}$$

Where *h* is the local material thickness and *t* is time. The combination of (1) and (4), including the fact that thickness and permeability are functions of pressure, which is a function of the position in the mould, x (h [P(x)]) and K [P(x)], leads to the following expression

$$\frac{\partial h}{\partial t}=\frac{1}{\mu}\cdot\left[\left(K\cdot\frac{\partial h}{\partial P}+h\cdot\frac{\partial K}{\partial P}\right)\cdot\left(\frac{\partial P}{\partial x}\right)^2+h\cdot K\cdot\left(\frac{\partial^2 P}{\partial x^2}\right)\right] \tag{5}$$

Finally, a consideration of the flow front movement, changing pressure along the mould, must be solved. Making the domain of the equation includes a parameter α=x/L where L is the instantaneous flow front position. This defines a domain of α being within the limits α=0 at inlet and α=1 at flow front position. Equation (5) can be written as (6) being able to be solved using an iterative finite element method to compute the pressure field, from which flow front progression can be determined using Darcy's law.

$$\left(\frac{d^2P}{d\alpha^2}\right)=-\left[\left(\frac{1}{h}-\frac{\alpha}{[h]_{\alpha=1}}\right)\cdot\frac{dh}{dP}+\frac{1}{K}\cdot\frac{dK}{dP}\right]\cdot\left(\frac{dP}{d\alpha}\right)^2 \tag{6}$$

Specific models of compaction and permeability must be included in the governing equation of flow to fully simulate the infusion behaviour.

With the mould cavity fully vacuumed, compaction pressure over the reinforcement is defined by vacuum pressure. This pressure state changes with inlet opening, when a wet zone is created and the compaction behaviour can be defined as a difference between the pressure outside of the bag (atmospheric) and the vacuum driving pressure. From previous studies [7]-[8], part thickness in flexible bag moulds is again related to the position of the flow front, decreasing from inlet to vents position. Correia et al. [9] unified most used expressions for compaction, such as the one used by Gutowski et al. [5] as,

$$P_{comp}=A_s\frac{\left(\frac{Vf}{Vf_0}-1\right)}{\left(\frac{1}{Vf_0}-\frac{1}{Vf_a}\right)^4} \tag{7}$$

where A_s, Vf, Vf_0 and Vf_a are the reinforcement spring constant, the fibre volume fraction, the fibre volume fraction at zero compaction pressure and the theoretical maximum fibre volume fraction. Other researchers [6] used (8) as expression for compaction

$$Vf=Vf_0\cdot P^B \tag{8}$$

Where Vf_0 is the fiber volume fraction at 1 Pa and B is the stiffening index determined by the fiber structure.

To describe the permeability modelling, different authors [8]-[9] use the Kozeny-Carman equation

$$K = k \cdot \frac{(1 - Vf)^3}{Vf^2} \tag{9}$$

where *k* is determined experimentally for each fabric.

4.0 Simulation Conducted

Simulations of the large vessels production process had been conducted using LIMS[12]-[13]-[14], a finite element/control volume simulation code with capacity of analyzing 2D and 3D flows developed at the University of Delaware. LIMS also includes LBASIC, a built-in script language that enables users to modify different conditions during the simulation.

The RTM-like process was simulated with the user interface of LIMS, LIMS-UI, which allows direct solution of the case analyzed. In order to simulate the flow through a compressible media of the flexible mould consideration, it is required to update thickness, fibre volume and permeability locally as a function of compaction pressure. This can be done with LBASIC script, which is able to update the required changes and check iteratively for convergence by resolving the pressure field under the new conditions. The flow front is then advanced and the procedure is repeated.

To simulate flexible mould infusions, some assumptions must be considered, such as a laminar flow, no pressure gradient in through-the thickness direction and incompressible resin with constant viscosity while filling. These assumptions can be only made when, as in our case, flow through the thickness is considered uniform.

4.1 Material Description

The self-made preform can be defined as a fibreglass mat. The production process of the preform includes a compaction stage, in which the preform achieves the initial properties. The initial thickness of the preform mat is 5 mm, with a fibre volume of 35% and a estimated permeability of $5x10^{-10}$ m^2. The Resin considered is a low viscosity resin, for infusion process, with a viscosity of 0,25 Pa s. Vacuum pressure used is fixed to 97,5 kPa.

4.2 Compaction Behaviour

A specific bibliographic review had been done [12]-[13]-[14] searching for compaction behaviour of the considered materials. Special attention to the work of Kerang Han et al., [14] where bidirectional fibre mat (COFAB A118) and random fibre mat (COFAB M8610) are analyzed, equations (10) and (11) are given, being *h* the thickness of the fabric in inches and *p* the pressure acting on the fibre in psi.

$$h_{\ker ang1} = 0.00703 \cdot (e^{[2.3(1-0.38\log(p))]} + 1) \quad (10)$$

$$h_{\ker ang2} = 0.0093 \cdot (e^{[2.3(0.303-0.191\log(p))]} + 1) \quad (11)$$

Hammami [15]-[16] analyzed the behaviour of different configurations of dry Unifilo U850, a continuous filament mat from Vetrotex. The following equations are extracted from his work, being *h* the thickness in mm and *P* the pressure in MPa

$$h_{Hammami1} = -0{,}0005 \cdot \ln(p) + 0.0089 \quad (12)$$

$$h_{Hammami2} = -0{,}0004 \cdot \ln(p) + 0.0068 \quad (13)$$

The variation of thickness with pressure is represented in Figure 2 for expressions (10) to (13). As it can be seen in the figure, compaction behaviour can affect the final thickness of the preform notoriously and consequently mechanical properties can be affected.

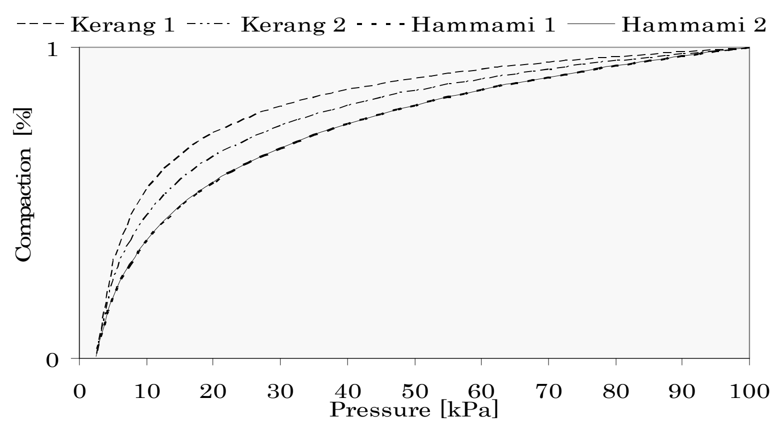

Fig. 2 Compaction behavior vs. pressures in a typical vacuum process

5.0 Simulation Results

All the compaction models were analyzed and fitted to the particular vessel considered in this study. Simulations were conducted including this compaction behaviour and compared with a typical RTM process. Figure 4 is a plot of a representative path of the vessel, where thickness reduction of 41 to 36% is observed, being the thicker parts near the inlets and the thinner parts near the vents.

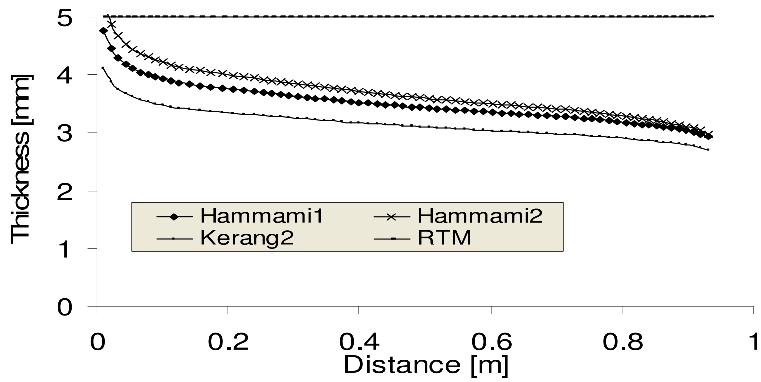

Fig. 3 Thickness variation through a vessel path . 0 at inlet, 0.95 at vent

The first compaction behaviour of the two described by Kerang et al. [13] at eq. (10) does not lead to convergence because the level of compaction achieved is higher than the maximum for the composite. Consequently, this compaction behaviour had to be discarded from the analysis

Results lead to the conclusion that in VBM processes the compaction pressure clearly affects the final thickness of the part. Compaction behaviour results in a thickness decrease of about 36 to 41%. This implies a fibre volume increase of about 46 to 37%.

Permeability is also affected due to compaction resulting in a slower infusion process. Actually, flexible mould processes are known to be typically slower than RTM; and this is why ancillary material such as race tracking channels or high permeability layers are commonly used in order to reduce infusion time. In Figure 4, filling time of the vessel is plotted versus linear distance from inlet to vent. The compaction effect represents an increase in time of 12, 5 to 23, 4%

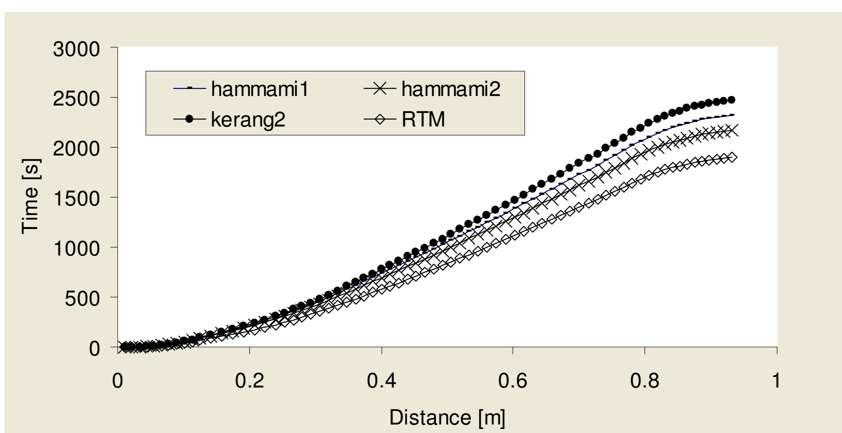

Fig. 4 Filling time through the geometry of the filter from inlet (0, top) to vent (0.95, bottom)

6.0 Conclusion

The Simulations conducted lead to the conclusion that, without auxiliary goods like flow channels or flow enhancement layers, VBM process can be considered a slow process. Despite being attractive due to a lower cost level in comparison to RTM, the planning of manufacturing vessels using VBM has been proven not suitable due to a dangerous reduction in thickness that can affect the mechanical properties of the vessel. Also, in terms of productivity, the VBM does not fit time requirements.

Acknowledgement

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EXPERIMENTAL ANALYSIS OF PROPERTIES OF MATERIALS FOR RAPID PROTOTYPING

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Abstract

***Rapid prototyping* (RP) can substantially shorten the time and reduce the cost of developing a new product from the initial idea to production. Rapid prototyping can help in recognizing the basic defects whose subsequent correction may prove very expensive, especially if they are made already when the product is ready for production.**

There are also many restrictions of RP procedures primarily in the number of available materials and their properties, which may differ significantly from the properties of end product materials.

In the work, based on the stipulated standards on the machines for *3D printing* (*ZPrinter 310 Plus*) and hybrid *Polyjet* technique (*Objet Eden 330*), adequate test specimens were made and with adequate equipment, the analysis of the dimensions, roughness of surfaces, and mechanical properties of prototype test specimens was carried out. Then, based on the data obtained by testing of properties, a critical commentary has been provided regarding the data stipulated by their producers.

Keywords: *3D printing,* hybrid *Polyjet* technique, roughness of surface, mechanical properties of materials.

1.0 Introduction

Rapid prototyping (RP) is a procedure of producing models. There are various methods of rapid prototyping. The main advantage lies in the speed of producing physical prototypes, and almost unlimited complexity of geometry. However, compared with CNC processing, the main drawback of these processes is that they are currently limited to fewer materials. The objective of the work was to find out the actual possibilities of RP procedures and materials for achieving maximal precision and accuracy of prototype dimensions.

2.0 Experiment Scheme

The test specimens were made by 3D printing procedures on the *ZPrinter 310 Plus* machine and by *Polyjet* procedure on the *Objet Eden 330* machine. The materials used for the test specimens made on the *Objet Eden 330* are *VeroBlack*, *VeroBlue* and *FullCure 720*, and on *ZPrinter 310 Plus* powder *zp 102*, binding agent *zb 56* and reinforcers glue *Loctite 406* and *Loctite Hysol 9483 A&B*.

In determining the dimensions of the test specimens the digital calliper "Mitutoyo", with the measurement range 0 – 150/0.01mm, was used.

A "Perthometer S8P" instrument was used to test the surface roughness. The surface roughness is determined perpendicularly to the direction of production. Measurement is performed at three places (at the beginning, in the middle, and at the end of the test specimen).

To determine the mechanical properties the tester "Messphysik Beta 50 - 5" shall be used. Tests were performed at a temperature of 20°C.

3.0 Shapes and Materials of Test Specimens

The flexural properties of rigid and semi-rigid polymers in defined conditions are determined according to standard ISO 178: 2001.

Three-point testing is applied, i.e. the test specimen (Figure 1) has to be supported by two supports and loaded in the middle by force *F*, until the test specimen fractures or until the deflection reaches certain values. [1]

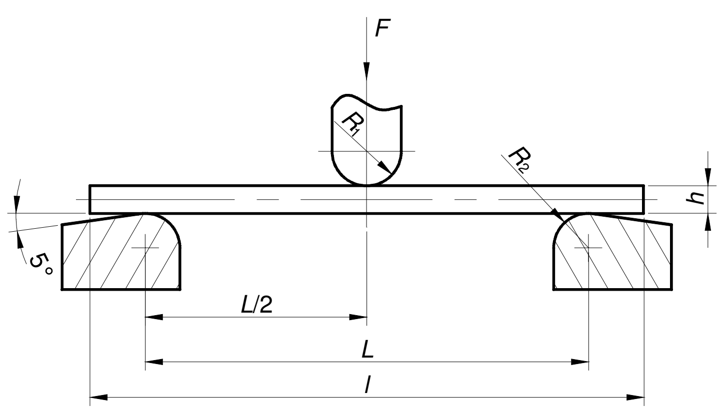


Fig. 1. Shape of test specimen for flexural testing [1]

Dimensions of test specimens stipulated by the standard is length l = 80 ± 2 mm, width b = 10 ± 0.2 mm, thickness h = 4 ± 0.2 mm, loading radius R_1 = 5 ± 0.1 mm and support radii R_2 = 5 ± 0.2 mm. [1]

The tensile properties of rigid and semi-rigid polymers are determined according to standard ISO 527: 1993. Dimensions of tensile test specimens is total length l_3 = ≥150 mm, length of the narrow parallel part l_1 = 80±2 mm, radius r = 20÷25 mm, distance between expanded parallel part l_2 = 104÷113 mm, width at the end b_2 = 20±0.2 mm, width of the narrow end b_1 = 10±0.2 mm, thickness h = 4±0.2 mm, measurement length L_0 = 50±0.5 mm and initial distance between the machine jaws L = 115±1 mm. [2]

For measuring the elasticity modulus, the testing speed has to be 1 mm/min. Figure 2 shows the shape of the test specimen for tensile testing.

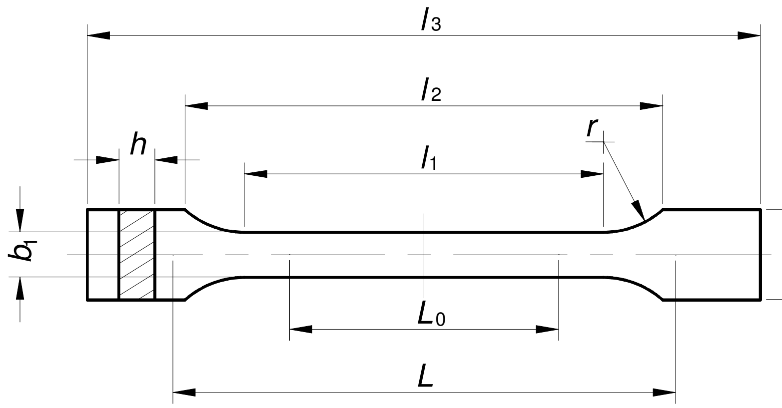


Fig. 2. Shape of test specimen for tensile testing [2]

Test specimens made by 3D printing technique using machine *ZPrinter 310 Plus,* have been made of powder *zp 102*, binding agent *zb 56* and reinforced by adhesives *Loctite 406* and *Loctite Hysol 9483 A&B*. The time necessary for printing of test specimens was 31 minutes, and another 45 minutes for cleaning and reinforcing. The white test specimens have been reinforced by cyanoacrylate *Loctite 406,* whereas the yellowish ones by epoxy resin *Loctite Hysol 9483 A&B*.

Test specimens produced by *Polyjet* technique using the *Objet Eden 330*, are made of the material produced by the company *Objet*: *VeroBlack* (black test specimens), *VeroBlue* (blue test specimens) and *FullCure 720* (transparent test specimens). The time necessary for the production of all test specimens of a single material is about 1 hour and 10 minutes, and another 10 minutes for cleaning.

4.0 Results of Analyzing the Rapid Prototyping Materials Properties

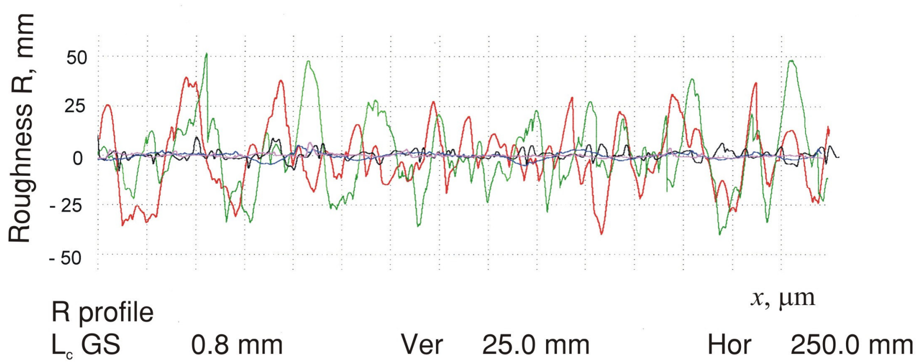
Table I presents the dimensions of test specimens for flexural testing and for tensile testing.

Table I: Dimensions for determining flexural and tensile properties of test specimens

3D PRINTING								
FLEXURAL PROPERTIES				TENSILE PROPERTIES				
	l[mm]	b[mm]	h[mm]		l_3[mm]	h[mm]	b_1[mm]	b_2[mm]
406 1	80.84	10.86	4.45	*406* 1	150.87	4.41	10.82	20.91
406 2	80.95	10.78	4.38	*406* 2	150.91	4.44	10.81	20.91
406 3	80.92	10.84	4.30	*406* 3	150.10	4.41	10.73	20.82
406 4	80.91	10.85	4.46	*406* 4	150.87	4.45	10.75	20.83
406 5	80.99	10.71	4.33	*406* 5	150.77	4.26	10.83	20.95
406 6	80.86	10.76	4.47	*406* 6	150.90	4.49	10.81	20.80
$\bar{x}$	80.91	10.80	4.4	$\bar{x}$	150.74	4.41	10.79	20.87
S	0.056	0.06	0.073	S	0.316	0.079	0.04	0.061
Hysol 1	80.56	10.62	4.37	*Hysol* 1	150.57	4.28	10.56	20.59
Hysol 2	80.66	10.66	4.25	*Hysol* 2	150.53	4.20	10.60	20.62
Hysol 3	80.71	10.57	4.35	*Hysol* 3	150.61	4.27	10.66	20.68
Hysol 4	80.69	10.70	4.30	*Hysol* 4	150.65	4.30	10.59	20.62
Hysol 5	80.66	10.63	4.33	*Hysol* 5	150.51	4.28	10.56	20.68
Hysol 6	80.62	10.61	4.28	*Hysol* 6	150.55	4.29	10.59	20.66
$\bar{x}$	80.65	10.63	4.31	$\bar{x}$	150.57	4.27	10.59	20.64
S	0.054	0.044	0.045	S	0.052	0.036	0.037	0.037
POLYJET TECHNIQUE								
VeroBlack 1	80.12	10.13	4.02	*VeroBlack* 1	150.28	4.03	10.08	20.04
VeroBlack 2	80.18	10.11	4.02	*VeroBlack* 2	150.28	4.01	10.04	20.04
VeroBlack 3	80.15	10.12	4.02	*VeroBlack* 3	150.29	4.02	9.99	20.07
VeroBlack 4	80.12	10.11	4.02	*VeroBlack* 4	150.27	4.00	10.06	20.01
VeroBlack 5	80.16	10.12	4.03	*VeroBlack* 5	150.26	4.00	10.12	20.08
$\bar{x}$	80.15	10.12	4.02	$\bar{x}$	150.28	4.01	10.06	20.05
S	0.026	0.009	0.005	S	0.012	0.013	0.048	0.028
FullCure 1	80.22	10.07	3.97	*FullCure* 1	150.18	3.99	9.99	19.97
FullCure 2	80.19	10.04	4.03	*FullCure* 2	150.22	4.01	10.01	20.01
FullCure 3	80.23	10.06	4.01	*FullCure* 3	150.19	4.02	10.00	20.02
FullCure 4	80.25	10.05	3.98	*FullCure* 4	150.15	4.01	9.99	19.99
FullCure 5	80.27	10.05	3.98	*FullCure* 5	150.22	4.00	9.98	19.99
$\bar{x}$	80.23	10.05	3.99	$\bar{x}$	150.19	4.01	9.99	19.99
S	0.03	0.012	0.025	S	0.03	0.012	0.012	0.021
VeroBlue 1	80.12	10.08	4.01	*VeroBlue* 1	150.17	4.01	10.01	20.00
VeroBlue 2	80.10	10.08	4.01	*VeroBlue* 2	150.19	4.00	9.98	20.03
VeroBlue 3	80.11	10.09	4.02	*VeroBlue* 3	150.21	4.00	10.00	19.98
VeroBlue 4	80.13	10.09	4.01	*VeroBlue* 4	150.21	3.99	10.00	19.97
VeroBlue 5	80.10	10.09	4.02	*VeroBlue* 5	150.21	4.03	9.97	20.02
$\bar{x}$	80.11	10.09	4.01	$\bar{x}$	150.2	4.01	9.99	20.00
S	0.013	0.007	0.007	S	0.018	0.016	0.017	0.025

The obtained results of measurement (Table I) show that the values of the dimensions obtained on *ZPrinter 310 Plus* (*Loctite 406* and *Loctite Hysol*) are greater than on *Objet Eden 330* (*VeroBlack*, *VeroBlue* and *FullCure*), because the machine *Objet Eden 330* produces layers of 16 µm, and *ZPrinter 310 Plus* of 89 µm. For length l the deviation of 80 ± 2 mm is stipulated and the length l_3 can be ≥ 150 mm , which means that all the dimensions are within tolerance limits, whereas the width b (10 ± 0.2 mm), b_1 (10 ± 0.2 mm), b_2 (20 ± 0.2 mm) and thickness h (4 ± 0.2 mm) on *Loctite 406* and *Loctite Hysol* test specimens exceed the tolerance limits. Such deviations occur since the material is rougher (i.e. powder particles), but the assumption is that they will not affect further testing of mechanical properties.

On *Loctite 406* test specimens the arithmetic mean $\bar{x}$ of the mean arithmetic deviation of profile R_a = 15.68 µm, and of *Loctite Hysol* is R_a = 13.99µm, which means that the level of roughness is N10. Substantial difference is noticed already in *VeroBlack* test specimens. Here is R_a = 1.64 µm, which is by 88% lower than R_a *Loctite Hysol* test specimen. The level of roughness is N7. The roughness parameters in *VeroBlue* test specimens are even lower, which can be seen also in Figure 3. The level of roughness is the same as in *VeroBlack* test specimens N7. *FullCure* test specimens show the best roughness of surface. The mean arithmetic deviation of profile R_a = 1.00 µm, which is in comparison with the test specimens made by *3D printing* an as much as 94% lower value. The roughness level of N6 is determined according to R_a (Figure 3).



Index: red – *Loctite 406* test specimen, green – *Loctite Hysol* test specimen, black – *VeroBlack* test specimen, blue – *VeroBlue* test specimen, pink – *FullCure* test specimen
Fig. 3. Surface roughness of all test specimens

Test specimens of powder *zp 102* fractured during bending, whereas this was not the case with other materials, so that flexural stress at break σ_{fp} and flexural strain at break ε_{fp} are not calculated for them. *Loctite 406* and *Loctite Hysol* test specimens fractured before deflection stipulated according to standard ISO 178: 2001 of $S_c = 1.5 \cdot h = 6$ mm, so that the flexural stress at conventional deflection σ_{fC} is not determined for them. The testing was done at a speed of 2 mm/min. Table II show the flexural properties of the test specimens, whose are calculated according to the standard ISO 178: 2001[1].

Test specimens made of powder *zp 102* break at strain ε_{fp} from 0.5 to 1%. Test specimens made of materials *VeroBlack*, *VeroBlue* and *FullCure* did not fracture to deflection $S_c = 1.5 \cdot h = 6$ mm stipulated by the standard, but rather the specimen falls in between the supports at: σ_{fp} = 33.7 MPa, ε_{fp} = 17.6 % and deflection S = 30 mm.

Tensile properties is calculated according to the standard ISO 527: 1993 [2]. Table III to present the calculated values of tensile properties of test specimens.

Table II: Flexural properties of test specimens

	E_f[GPa]	A_0[mm^2]	F_{max}[N]	σ_{fM}[MPa]	ε_{fM}[%]	S_{max}[mm]	σ_{fp}[MPa]	ε_{fp}[%]
406 1	2.791	48.33	32.60	14.55	0.684	1.050	14.36	0.75
406 2	2.505	47.22	30.35	14.09	0.716	1.117	13.04	0.822
406 3	2.840	46.61	36.00	17.24	0.881	1.399	16.15	0.982
406 4	2.928	48.39	33.75	15.01	0.678	1.037	14.54	0.743
406 5	2.616	46.37	29.25	13.98	0.671	1.058	13.43	0.769
406 6	2.179	48.10	40.50	18.08	0.892	1.363	17.08	0.911
$\bar{x}$	2.643	47.50	33.74	15.49	0.754	1.171	14.77	0.83
S	0.275	0.893	4.093	1.739	0.104	0.166	1.565	0.097
Hysol 1	3.230	46.41	33.70	15.95	0.531	0.829	15.95	0.571
Hysol 2	3.168	45.30	25.85	12.89	0.404	0.648	12.34	0.436
Hysol 3	2.929	45.98	24.75	11.88	0.511	0.802	10.08	0.558
Hysol 4	2.534	46.01	28.10	13.64	0.539	0.855	12.01	0.547
Hysol 5	2.718	46.03	31.50	15.17	0.520	0.820	14.62	0.564
Hysol 6	3.337	45.41	28.10	13.88	0.524	0.835	12.77	0.538
$\bar{x}$	2.986	45.86	28.67	13.90	0.505	0.798	13.08	0.536
S	0.315	0.421	3.385	1.482	0.050	0.076	1.876	0.05
	E_f[GPa]	A_0[mm^2]	F_{max}[N]	σ_{fM}[MPa]	ε_{fM}[%]	S_{max}[mm]	σ_{fc}[MPa]	
VeroBlack 1	2.430	40.72	133.8	78.46	4.856	8.246	68.58	
VeroBlack 2	2.493	40.64	132.7	77.97	4.848	8.233	68.07	
VeroBlack 3	2.294	40.68	134.9	79.22	5.067	8.604	68.65	
VeroBlack 4	2.234	40.64	132.7	77.97	5.082	8.630	66.75	
VeroBlack 5	2.326	40.30	136.1	80.45	5.161	8.742	68.48	
$\bar{x}$	2.355	40.57	134.04	78.81	5.003	8.491	68.11	
S	0.105	0.171	1.469	1.048	0.142	0.235	0.791	
VeroBlue 1	2.475	40.42	148.4	87.92	5.272	8.975	73.95	
VeroBlue 2	2.524	40.42	145.1	85.94	4.902	8.346	73.95	
VeroBlue 3	2.565	40.56	147.4	86.75	5.041	8.561	74.83	
VeroBlue 4	2.527	40.46	146.2	86.50	4.834	8.229	74.52	
VeroBlue 5	2.479	40.56	147.4	86.75	4.858	8.250	74.83	
$\bar{x}$	2.514	40.48	146.9	86.77	4.981	8.472	74.42	
S	0.037	0.071	1.273	0.722	0.181	0.310	0.444	
FullCure 1	2.628	39.98	158.6	95.93	4.908	8.439	81.63	
FullCure 2	2.596	40.46	164.2	96.67	4.962	8.405	83.43	
FullCure 3	2.639	40.34	155.2	92.10	4.738	8.066	80.09	
FullCure 4	2.754	39.80	159.7	96.79	4.916	8.431	81.79	
FullCure 5	2.798	39.80	159.7	96.79	4.962	8.511	81.79	
$\bar{x}$	2.683	40.08	159.48	95.66	4.897	8.37	81.75	
S	0.088	0.308	3.22	2.020	0.092	0.175	1.183	

Table III: Tensile properties of test specimens

	E [GPa]	A_0 [mm^2]	F_m [N]	R_M [MPa]	R_p [MPa]	ε_K [%]	ε_p [%]
406 1	3.645	47.72	321.6	6.740	6.693	0.353	0.537
406 2	2.708	48.00	304.8	6.349	6.349	0.152	0.387
406 3	3.623	47.32	275.5	5.822	5.798	0.138	0.298
406 4	4.463	47.84	343.0	7.169	7.169	0.260	0.421
406 5	3.078	46.14	262.0	5.679	5.630	0.157	0.341
406 6	2.935	48.54	307.0	6.325	6.279	0.322	0.537
$\overline{x}$	3.409	47.59	302.3	6.347	6.32	0.230	0.420
S	0.638	0.816	29.66	0.557	0.568	0.094	0.100
Hysol 1	3.897	45.20	218.1	4.827	4.827	0.058	0.182
Hysol 2	2.902	44.52	257.5	5.784	5.784	0.095	0.294
Hysol 3	2.515	45.52	238.4	5.237	5.212	0.078	0.285
Hysol 4	2.472	45.54	253.0	5.556	5.507	0.089	0.312
Hysol 5	2.497	45.30	246.3	5.436	5.411	0.097	0.314
Hysol 6	2.819	45.43	219.3	4.827	4.827	0.103	0.274
$\overline{x}$	2.641	45.262	242.9	5.368	5.348	0.092	0.296
S	0.203	0.425	15.03	0.362	0.357	0.009	0.017
VeroBlack 1	3.612	40.62	1868	45.98	33.00	7.047	7.960
VeroBlack 2	2.794	40.26	1826	45.36	33.24	6.090	7.280
VeroBlack 3	2.905	40.16	1859	46.29	33.82	6.466	7.630
VeroBlack 4	2.796	40.24	1842	45.77	33.25	6.524	7.714
VeroBlack 5	2.723	40.48	1875	46.31	34.42	5.610	6.875
$\overline{x}$	2.966	40.35	1854	45.94	33.55	6.347	7.492
S	0.367	0.191	19.94	0.396	0.574	0.535	0.422
VeroBlue 1	2.7	40.14	2088	52.02	37.59	5.626	7.019
VeroBlue 2	2.726	39.92	2057	51.52	38.96	5.130	6.559
VeroBlue 3	2.505	40.0	2049	51.22	41.94	4.347	6.022
VeroBlue 4	2.459	39.9	2042	51.18	39.29	4.780	6.375
VeroBlue 5	2.699	40.18	2077	51.69	36.35	5.828	7.175
$\overline{x}$	2.618	40.03	2063	51.53	38.83	5.142	6.630
S	0.125	0.127	19.32	0.348	2.097	0.606	0.471
FullCure 1	2.561	39.86	2196	55.10	40.0	4.820	6.382
FullCure 2	2.832	40.14	2210	55.05	36.56	5.904	7.195
FullCure 3	2.073	40.20	2224	55.33	40.20	4.527	6.465
FullCure 4	4.174	40.06	2198	54.88	36.41	6.7	7.572
FullCure 5	2.416	39.92	2200	55.10	40.25	4.717	6.384
$\overline{x}$	2.811	40.04	2206	55.09	38.68	5.334	6.8
S	0.810	0.144	11.61	0.161	2.010	0.934	0.550

Loctite Hysol test specimen 1 features very large deviations and is therefore eliminated from further analysis.

Test specimen of powder, binding and reinforced by cyanoacrylate (*Loctite 406* test specimen) shows slightly better properties than with epoxy resin (*Loctite Hysol* test specimen).

The analysis of flexural properties (Figure 4) and the analysis of tensile properties (Figure 5) shows that the best properties belong to the test specimens made of *FullCure* materials. Compared to the properties declared by the producers [3] flexural strength σ_{fM} is somewhat higher, whereas flexural modulus E_f is higher by an average of 100 MPa. Tensile strength R_M is a bit lower, whereas the modulus E is approximately the same. Tensile strain at break ε_p [4] is much higher than the one obtained by analysis (ε_p = 6.8%).

In case of *Vero* material the producer guarantees in *VeroBlack* the highest flexural modulus. The performed analysis shows that in this group of materials the flexural modulus is the lowest. In *VeroBlue* materials the values guaranteed by the producers almost match with the obtained ones, except in case of tensile strain at break ε_p which is much higher (ε_p = 15 – 25%) than obtained by the analysis (ε_p = 6.63%). *VeroBlack* material has the highest tensile modulus E = 2966 MPa in the group of materials made by *Polyjet* technique.

The lowest flexural and tensile properties are featured by the test specimens of powder made by *3D printing* (*Loctite 406* and *Loctite Hysol* test specimens). In comparison with *FullCure* and *Vero* materials the flexural strength σ_{fM} is very low, as low as σ_{fM} = 15 MPa, but the flexural modulus E_f is similar. Tensile strength R_M and tensile stress at break R_p are substantially lower than in *FullCure* and *Vero* materials, but the elasticity modulus E in *Loctite 406* test specimens is the highest of all the materials. It should be noted that their properties depend on the hardening agent which has been added to the powder and binding agent. Better properties are featured by the reinforcing agent cyanoacrylate.

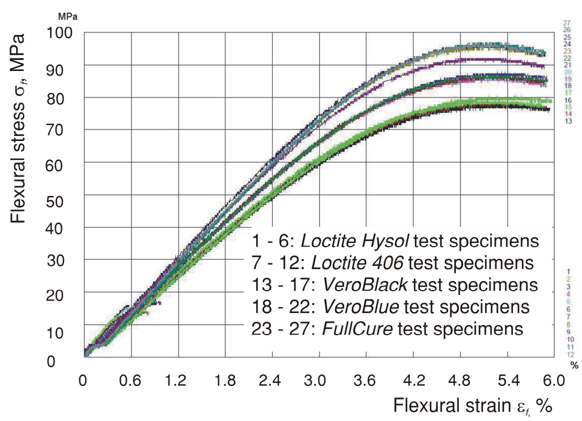


Fig. 4. Diagram of *flexural stress - strain* of all materials

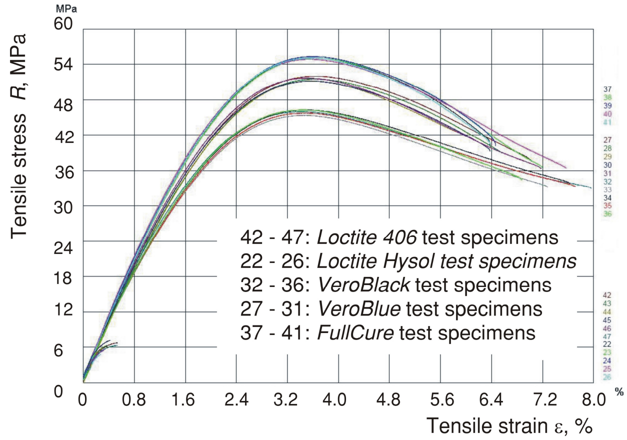


Fig. 5. Diagram *tensile stress - strain* of all materials

5 0 Conclusion

Rapid prototyping allows production of parts of very complex shapes the production of which, until the occurrence of these techniques, had been limited. The rapid prototyping techniques have been developing intensively from day to day. Here, the limiting number is of the available materials and their properties, which substantially differ from the properties of materials of final products. Therefore, it is necessary to know the properties of the prototypes materials.

The results of measuring the dimensions of test specimens show that the instrument *Objet Eden 330* is more precise in production than *ZPrinter 310 Plus*.

The surface of test specimens made of powder *zp 102,* binding *zb 56* and reinforced by cyanoacrylate *Loctite 406* or epoxy resin *Loctite Hysol 9483 A&B* is rougher than *VeroBlack* and *VeroBlue* material. *FullCure* material shows the lowest value of surface roughness.

The best mechanical properties belong to test specimens made of *FullCure*. For *Vero* material the producer stipulates that *VeroBlack* has the highest flexural modulus, and still the analysis results show that it is the lowest one. In *VeroBlue* materials the producer's guaranteed values almost match the obtained ones. The worst mechanical properties are featured by the test specimens made of powder. However, their properties depend on the reinforcing agent which is added to powder or binding. Cyanoacrylate features better properties than epoxy resin.

Manufacturer's estimates of the properties and properties obtain by the experiments is approximatelly the same. It is only recommended to change tensile strain at break to ε_p = 15 – 25%, as well as flexural modulus to E_f = 2400 MPa, specially for *VeroBlack* materials. For materials *406* and *Hysol* some parameters may be changed such as e.g., position of the model in the work space, layer thickness, ratio of saturation by binding etc., which also influences the properties of prototypes (strength, roughness, dimensions).

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Advanced Manufacturing Systems

ADVANCED PRODUCTIZATION REFERENCE MODEL

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Abstract

Productization can be understood as all those actions and operations that ensure the process from an idea to a product that sells well. Productization is a business process in companies. How well this process works basically defines the future success of the company. Products today are complex and people from several different knowledge disciplines are needed to do their part and communicate with each other before an idea becomes business. The required steps in productization are neither simple nor standard. Depending on the idea, the product in mind, the specific scenario, set-up and involved parties, the process can take multitude of forms. Ever shorter time requirements on turning an idea into a ready product set additional challenges for all the involved parties.

This paper proposes a new type of reference model for industrial productization. Reference models and reference architectures are already used in many other disciplines. The proposed model targets similar goals to existing reference models in other disciplines. The proposed model will take an ontological format. Academic and business people who are involved in productization through a variety of roles can realize the benefits of developing and using such model.

Keywords: Reference model, operations, management, productization, process, ontology

1.0 Introduction

Every year lots of good ideas are born. Most of those ideas never become good business. According to a very recent study conducted by Sitra, the Finnish Innovation Fund shows that around 80% of new ideas in Finland never become products that sell well. At universities, this percentage is still much higher. According to

Tuominen productization refers to everything between an idea and a successful product (a product that sells well) [1]. We can see that idea generation is not a problem in Finland but something must be wrong in how the productization is understood and utilized in practice. Understanding the concepts in the productization domain must be the basic requirement for all stakeholders. How well productization works in practice is based on people's perceptions on those concepts case by case, since people act and decide according to their perceptions.

The approach described in this paper looks at the low success rate in productization in a new way. Firstly, the idea is to clarify the real concepts in a productization domain. Secondly, to make empirical research based on the "clarified" concepts in order to find out how to improve the implementation of those concepts in real life. Thirdly, provide practical guidelines and decision support for managers.

In this research the concepts in the productization domain are explicitly specified and organized so that they form a structure of classes and sub-classes. When concepts are organized that way, they form an ontology. After the ontology is specified, it forms the conceptual framework for the productization research and practice. Then, the empirical study towards the real cure for low success rate in productization can begin. Each class (concept) alone refers to some cure, but most importantly they together show a holistic way what to do. The bottom-line is that all parties involved in productization should work, develop and manage the actual and timely concepts. This can only be achieved by utilizing productization ontology as a base for all activity. Such ontology naturally evolves when the world is changing. This research project is conducted at the University of Turku, Product Development Research Group. The goal is to build a generic model that can be used in any productization discipline. Similar ontology based management methodology has successfully been applied to Human Resource, Investment, Business and Organizational process management in Finland, Poland, Spain, South Korea, UK and US [2]. The motivation for this research is to increase the success rate in productization. If it can be done, there will be significant benefits for the academia and business.

2.0 Reference Models

First, we need some basic terms. A process is a systematic series of actions directed to some end [3]. A process in a business context is understood as a business process, which is defined as a series of steps designed to produce a product or service [4]. According to the Random House Webster's Dictionary, the meaning of a reference is: the act of referring; a source of facts or information [3]. Not many definitions for a reference model can be found in the literature, but with common sense we can understand that a reference model is a conceptual representation of a process or a system. Since reference models have such a fundamental role, they can serve as the conceptual basis to develop specific models and applications. These specific models and applications are used by practitioners and academics. In the next paragraph some known reference model are briefly explained.

- **SCOR** (Supply-Chain Operations Reference) model describes the business activities associated with all phases of satisfying a customer's demand. The SCOR model has three main pillars: process modeling, performance measurements, and best practices (plan, source and deliver) [5]. SCOR users can address, improve, and communicate supply chain management practices within and between all the interested parties. SCOR model is developed by the Supply Chain Council members on a volunteer basis [6].

- **OSI** (Open Systems Interconnection) model is a basic reference model for a communications and computer networking design. The reference model has seven layers: 1. Physical, 2. Data link, 3. Network, 4. Transport, 5. Session, 6. Presentation, and 7. Application.

- **FEA** (Federal Enterprise Architecture) is a collection of reference models that are being developed by the US government [7]. The FEA's foundation is the business reference model which describes the government's lines of business and its services and provides a common framework for improvement in key areas such as: budget allocation, information sharing, performance measurement, budget/performance integration, cross-agency collaboration, e-government, and component-based architectures. The goal is to simplify processes and unify work across the agencies. The goal is more citizen-centered, customer-focused government that maximizes technology investments to better achieve mission outcomes [7].

All the different kinds of reference models described above target similar goals: improve processes, communicate and co-operate better, enable application development, and serve customers better. For the productization reference model described in this paper the goals are the same.

3.0 Ontologies

Ontology is defined as the specification of the conceptualization of a domain [8]. Conceptualization is the idea of (part of) the world that a person or a group of people can have [9]. Ontology defines the common words and concepts (meanings) used to describe and represent an area of knowledge [10]. Ontologies represent a method of formally expressing a shared understanding of information [11]. The main parts of ontologies are classes (concepts), relations (associations between the concepts in the domain) and instances (elements or individuals in ontology) [9].

Using ontologies can have several benefits, such as interoperability, browsing and searching, reuse and structuring of knowledge [12]. Ontologies also enable the computational processing of information. Ontologies are becoming increasingly important in fields such as knowledge management, information integration, co-operative information systems, information retrieval and e-commerce [13]. When applied they serve needs such as storage, exchange of data corresponding to an ontology, ontology-based reasoning or ontology-based navigation [14; 15]. Ontologies promise a shared and common understanding of a domain that can be communicated between people and application systems [16]. In addition, ontologies enable computer processing to retrieve and use information in many other ways. The two above mentioned aspects, combined with opportunities provided by contemporary Internet programming technology, makes ontologies a very attractive approach to tackle productization problems in real life.

Ontologies have an important role in defining the concepts and their relations for application development. The reference model of a business process works as the basis for more specific ontology development in that domain. The developed ontologies form a solid base for management, development, communication and operations in the domain - productization domain in this case.

4.0 Advanced Productization Reference Model

People are "connected" to productization process through many different kinds of roles, such as operational roles, developer roles, management roles and academic roles. It is crucial that the people in these roles are able to be part of the productization process to the best they can [17]. However, this is very difficult without an independent and reliable source of the concepts in the productization process. Now, we can see that actually ontological approach is truly needed. Such ontology enables good participation in the process in each case from the perspective of the different roles.

Typical way to use ontology is to create first a top-level ontology that specifies the most important basic concepts and their inter-relations in the domain, Figure 1. Based on the top-level ontology, more specific domain ontologies can be specified. In this context, we can call these more specific domain ontologies as Productization Ontologies (POs). They define the basic structure for application development. The developed applications serve management, (process) development, communications and operations [17], Figure 1.

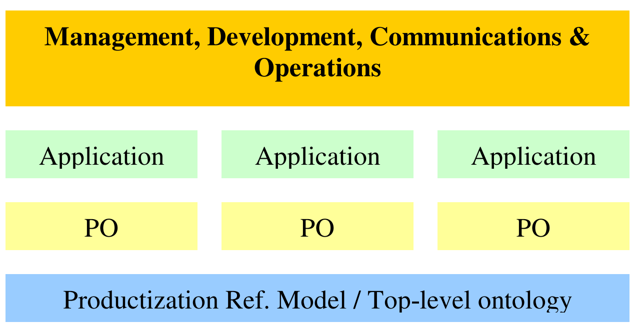

Fig. 1. The productization reference model serves as a base for ontology development. Specific ontologies (POs) form the base for application development for management, development, communication and operational purposes.

The approach shown on the Figure 1 also enables all the stakeholders in all the above mentioned roles to "speak the same language" when doing the productization work.

Management must take into account stakeholders' perception of productization cases during their life-cycles. Perception plays a very important role in an organization's management, since people think and act based according to their perception. People also envisage the future of each productization case. This is a very important element to consider, since this tension between current reality and envisaged future indicates the direction for peoples' thoughts and actions regarding the case in the future [2]. An individual's perception is composed of such things as accumulated knowledge and experience, individual's situation, values and attitudes regarding the specific case. Therefore, a perception of a productization case combines an individual's body, mind, vision, PO, perception of the PO, context and time. Modern on-line tools enable people to globally give their perception on productization cases for collaboration and management purposes [2].

The output of effective planning is an ever-changing plan, one that reflects the continuous learning and adaptation of those who prepare it [18]. This means that also the management of productization projects must be realized in periodic cycles that are not too long. Continuous planning requires a continuous process. Such ontology based management process is shown on Figure 2[2]. According to this process, all objects specified as POs can be managed in a similar way by utilizing instances through the following main steps:

1. Collecting instances within a set time window.
2. Validating (in workshops) the perceived impact of previous development plans (if existing) and fitting them together.
    A. Unique instances, and
    B. Focus areas coming from the strategy of an organization and local conditions, and
    C. Explicit knowledge about POs
3. Making targeted development plans for the productization case.
4. Taking action according to the plans.
5. Returning to Step 1 after each development cycle (1/2/3/6 months).

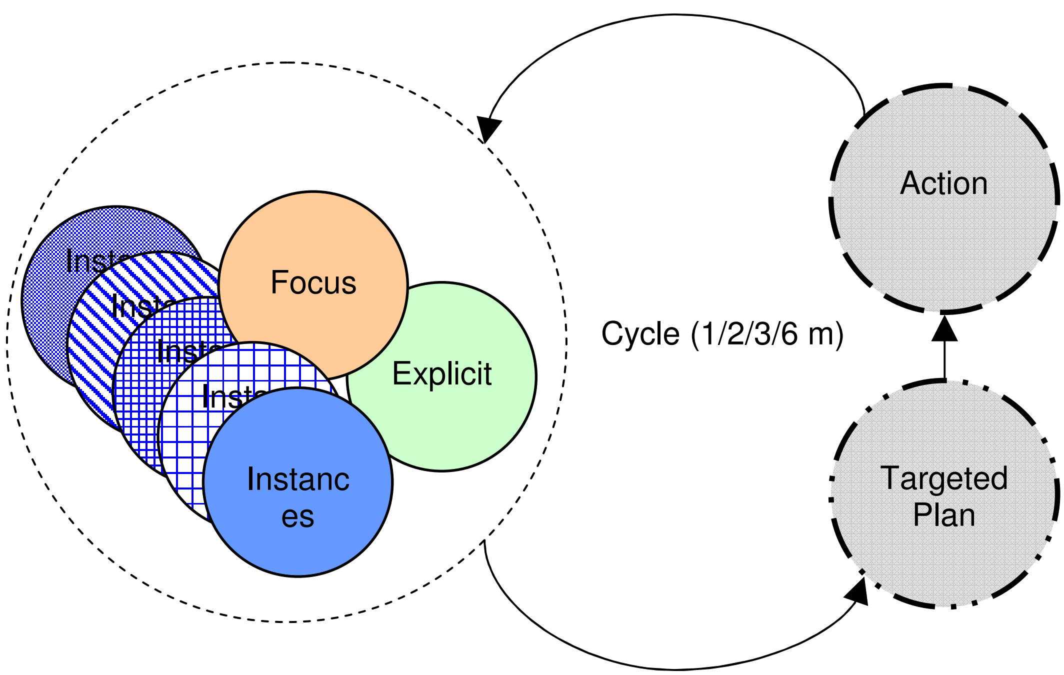

Fig. 2. Ontology based management framework by Kantola [2].

These steps are generic and independent from the content of PO. A PO may contain only a couple of sub-classes, tens ob sub-classes and more or less hierarchy, but still instances are collected in the same way, which allows for the visualization of the perception of POs. Every cycle can be seen as different, and all cycles can, in principle, be handled in a uniform way.

When we take one step upwards in decision making, we can consider each productization case as an entity in a certain context. The context is defined by: country, business area, company size, case type, consortium, etc. In order to understand these cases and find meta-knowledge (knowledge of knowledge) for improved decision making, we need a large productization case bank where the cases are stored. Then, the cases in the case portfolio can be examined against the case bank. Therefore, each case can benefit from the accumulated experience of all cases, and proactive heuristic measures can be taken in order to steer and manage each case towards success.

The proposed productization reference model serves many purposes:

- Improve the efficiency and effectiveness of the productization process.
- Improve communications and co-operation between:
    - Academic – Academic
    - Academic – Business
    - Business – Business
- Improve communications and co-operation between stakeholders in productization cases.
- Serve as the best practices database.
- Show the variations in productization process steps.
- Provide the base for measuring of productization operations.
- Serve as a basis for specific ontology development.
- Serve as a basis to develop more specific models and applications.
- Enable better development and management of the process than previously.
- Provide documentation.
- Visualize the concepts related to the productization process.

5.0 Conclusion

The proposed reference model can be seen as a base for productization work in academic and business sectors. In addition to such reference model, a management process that realizes the benefits of building and developing POs is necessary.

Now we can see that the success in productization cases actually becomes a management question. By applying ontologies for "collecting" the perceptions of productization cases for management and stakeholder co-operation and decision making we should be able improve the success rate. The approach described in this paper makes managers and other stakeholders more capable to do their work.

Academics and practitioners can realize the benefit of developing and using the proposed reference model. Without applying such a model, the risk of failing in productization cases is significant. This article is a proposal and an invitation to other parties to join in this effort. Should you be interested in this research, please contact us.

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PRODUCTION SCHEDULING IN THE CORRUGATED INDUSTRY: CHALLENGES AND SOLUTIONS

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Abstract

Production scheduling is a crucial and deterministic process to the performance of manufacturing industries. Most companies focus on optimising this process and making it as efficient as possible. This is to lower manufacturing costs, increase production efficiency and capacity utilisation but also to improve customer satisfaction by delivering on time and in full. In this way, huge efforts have been focused on conducting research to improve production scheduling and several solutions proposed however they do not alone fully satisfy industry expectations. Moreover, research studies related to the corrugated industry in this area are scarce.

This paper aims to identify production scheduling issues and practices in the corrugated industry that might be solved and improved through the development of a decision support tool. Significant improvements and economies could be achieved through the support and assistance of human schedulers in making more effective scheduling decisions in order to generate better solutions in terms of cost and customer satisfaction.

The investigation of a case study revealed the existence of challenges faced by the corrugated industry during the scheduling process. Several industrial visits were conducted in the form of observation sessions, interviews and workshops with the human schedulers and the shop floor operators in order to gather the relevant data necessary for this research project. The analysis of these data showed the existence of differences in the human scheduling practices and sometimes the absence of standards related to some scheduling tasks. The case study illustrates that several decisions involved in the search and selection of jobs to build a work mix of customers orders for the corrugators machines such as: the evaluation of the paper trim percentage,

deckle size, upgrading costs, target run lengths and sequencing of the set of orders work mix, constitute challenging tasks that require the support of a decision tool to produce better scheduling solutions.

Keywords: Manufacturing; Corrugated Industry; Production Scheduling

1.0 Introduction

Production scheduling is all about clever and effective handling of information to make the right decisions related to the efficient assignment of tasks to available resources over time [1]-[2] while satisfying production constraints and minimising costs. Interest in studying production scheduling initiated about half a century ago from a general perspective and within limited disciplines [2]-[3]-[4]. However, research in this area soon expanded to embrace more disciplines and adopt a more specific and detailed investigation approach. Tough extensive research studies have been done on production scheduling yet studies related to the corrugated industry in this area are scarce.

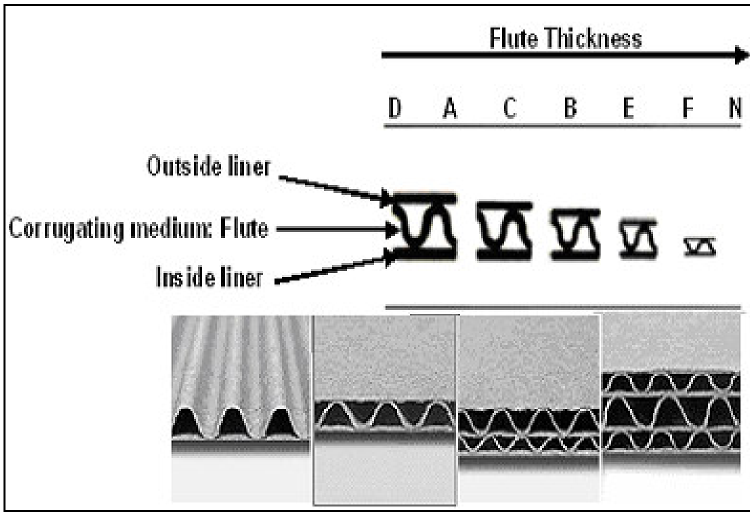
Today's highly competitive environment made the corrugated industry a fierce and challenging business where organisational and strategic skills became key words of success. In addition to the highly demanding customers, there are a number of constraints faced by the industry on day-to-day basis. These constraints are mainly related to the large variety and quantity of products ordered, the machine failures, the unpredictable customer's ordering behaviour, and the complex multi-stage production process [5]. With all these challenges, the corrugated board industry is still required to demonstrate a high degree of flexibility and to guarantee on time and in full (OTIF) delivery to its clients. Therefore, it is necessary to keep a certain balance between satisfying customer requirements and maintaining the business competitive advantage. In this way, special attention is to be given to the investigation of the production scheduling process in an attempt to improve and optimise it. This will boost the corrugated industry's competitive advantage while enabling it to satisfy its clients' requirements. In this way, this paper will investigate a case study from the corrugated industry to determine the major issues related to the scheduling process and identify solutions to cope with these.

An exploratory approach based on the qualitative research technique was adopted and the concept of deduction was relied on in the research process. It involved the conduct of literature review, design of a questionnaire, conduct of interviews as well as observation sessions for information gathering mainly from the industrial case study but also from academia. This provided enough information to understand the production scheduling process at the case study company and identify major issues faced with the production scheduling system.

2.0 Overview of the Corrugated Industry

In this paper, we refer to the corrugated industry as the corrugated paperboard that has been in production since the 18th century. It is a composite material that consists, in its basic form, of a three layers structure as illustrated in Fig.1. It is composed of an outside and inside liner holding together a corrugating medium or flute in the middle. These three major components control the characteristics of the final corrugated board based on the type and thickness of the papers as well as the height and number of corrugations used. The corrugating medium is a key component in making corrugated boards. The various flutes are combined with the linerboards in different ways resulting in four major forms of corrugated boards (as illustrated in fig1):

- Single face: is made by gluing one sheet of linerboard to another sheet of corrugating medium.
- Single wall: consists of two sheets of linerboard glued to each side of the corrugating medium.
- Double wall: consists of three linerboards and two flutes glued in the following sequence: an outside liner, a flute, a center linerboard, a flute and an inside liner.
- Triple wall: this form of corrugated board could be described as tree single walls glued together. It consists of four linerboards and tree corrugating mediums.



Type of Flute	Thickness (mm)
A	4.1 – 4.8
B	2.2 – 2.9
C	3.2 – 3.9
D	6 – 6.5
E	1.2 – 1.8
F	1 – 1.3
N	0.6 – 0.9

Fig. 1. Corrugated paperboard components

One of the main applications of the corrugated paperboards is packaging boxes. A multi-milliom dollar machine called corrugator is used to take wide rolls of paper, corrugate one unwinding roll and glue the other two unwinding rolls to the fluted paper in the case of a single face board. Then takes place the slitting and scoring of the paper lengthwise in order to cut them to the specified measures according to clients' requirements [6]. For instance, the case study company offers conventional boards that consist of 600 different combinations of paper grades and flutes both in single and double wall, as well as speciality boards that are made of special materials to provide a clay-coated surface. It differentiates itself through the provision of a wide product range on a very short lead-time that can reach 12hours. This is made possible through the exact and efficient scheduling of its 6 world-class corrugator machines.

Despite the use of an automatic scheduling system, the intervention of human planers remains essential. Hence, making manual and automatic scheduling complementary to each other in order to for the business to preserve its competitive advantage and satisfy its clients' requirements. In fact, keeping a certain balance between satisfying customer requirements and maintaining the business competitive advantage is necessary as expressed by Georges Schepens, a founding partner at OM partners: "Your customer is king, but he is not the emperor" [6].

3.0 Critical Parameters in the Scheduling Process

A first review of industrial documents and available literature review helped draw a general high level view of the different parameters involved in the production scheduling process in the corrugated industry along with the outputs that are expected as shown in Fig2. In fact, successful automated production scheduling has to provide an effective tool for the human schedulers to help them better manage and act upon available data and information in order to facilitate rapid and efficient decision-making [7]. This is in part due to the fact that there will always be some orders –referred to as exceptions in Fig2- which do not completely satisfy scheduling rules and hence cannot be processed automatically.

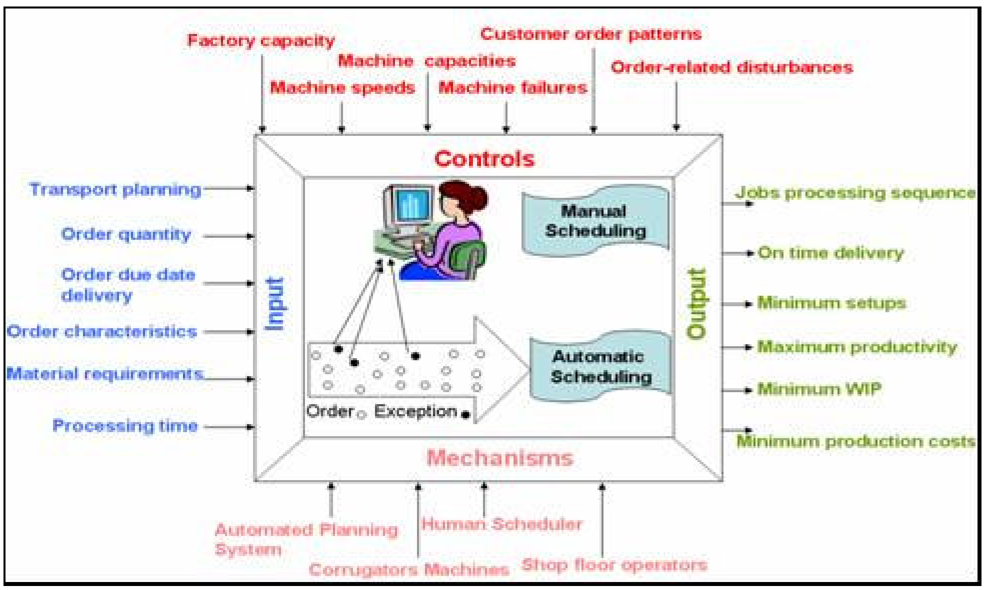


Fig. 3. Automated production scheduling parameters

At the present day, 80% of the scheduling activity at the case study company is done by three human schedulers with the help of a system that pulls similar orders together. Hence the workmix attributed to each corrugator machine is done automatically. The planners then manipulate the categorised orders in order to produce the best scheduling solutions in terms of cost and service requirements based on their own judgement and experience [8]. The existing off the shelf production scheduling software packages are inappropriate for the company's business because of the use of six corrugator machines, where boards of 1200 grades of any size and length with scores in any position are produced for next day delivery in England. The available software packages do not offer the possibility of scheduling more than one corrugator at a time.

In this way, in depth study of the production scheduling system at the case-study company aims at identifying the key parameters used by the human planners in order to construct scheduling solutions and determine major issues encountered during this process. This will help in the formulation of recommendations and solutions to improve automated production scheduling in the corrugated industry. The investigation of the scheduling system involved the study of the process followed to schedule four corrugator machines. The scheduling process of the normal orders consists of two main stages as illustrated in Fig.3:

1) **Order allocation**: is performed by the Bespoke System and consists of assigning every order to a given corrugator mainly based on the match between orders' characteristics and corrugators' characteristics in terms of flute type, width, chop length, and grade.
2) **Orders sequencing and programmes formation**: this stage is carried out by the human planners and involves the manipulation of the assigned orders in order to build the best scheduling solutions.

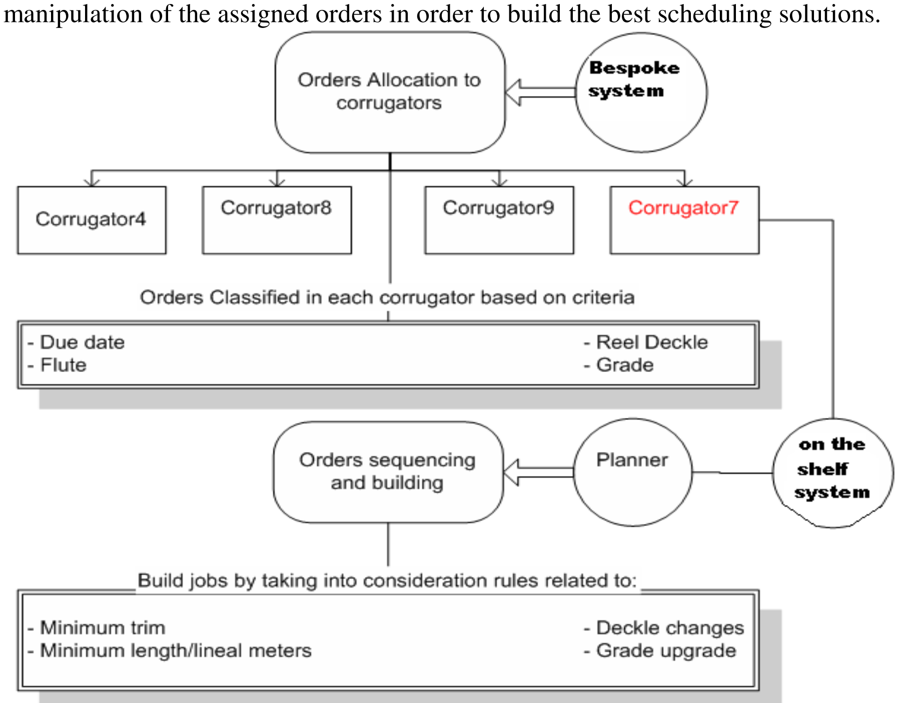


Fig. 3. Overall view of the scheduling system phases for the case study

It is important to note that during the first stage, the filtering of orders, performed by the Bespoke System, consists of grouping similar orders together under a particular programme number. Pulling orders into the same programme number is based on a number of different criteria:

- Reel size or width of paper to be used based on the order width.
- Flute type.
- Order due date.
- Grade: each corrugator runs particular grades which can be part of the same programme.
- Characteristics of the corrugators in terms of minimum and maximum widths, maximum number out, trim, minimum lineal meters per deckle.

During the second stage, the human planners need to go through the first filtering performed by the Bespoke System in order to make necessary amendments as required depending on the situation. For instance, they may need to transfer some jobs to another corrugator to ensure equal distribution of work between the machines. They may also need to move orders forward to build either the lineal meters of a specific grade or the total lineal meters of the whole programme. The main objective consists of making sure the corrugators are efficiently, cost effectively and fully utilised by taking into consideration the following criteria:

- Minimum number of deckle changes.
- Minimum percentage of trim.
- Use of narrow paper widths.
- Start with large widths first to avoid problems with line ups of papers.
- Run heavy grades first.

The main problem here is that some of the goals and rules for scheduling are contradictory or sometimes impossible in certain situations. It is therefore important to provide support to the human planners in delicate decision making situations to allow them to select the best and most cost effective options [9].

4.0 Major Scheduling Issues Identified

As mentioned in the previous section, human planners face the problem of contradictory goals. For instance, achieving both a minimum number of paper size changes and minimum percentage of side trim is very difficult. Practically, the only way to achieve minimum side trim with different combinations of order widths is to change roll sizes. Moreover, observation sessions and interviews conducted with the different planners at the case study company enabled the researcher to:

- Identify the major decision making situations encountered by the planners when performing the scheduling.
- Determine the rules and constraints taken into consideration when dealing with each decision making situation.
- Identify differences in decision making between the different planners.

Following the analysis of the data collected from the observation sessions and the interviews, a set of decision making situations has been identified as illustrated in Table4:

Decision Making Situation	**Description**
Corrugator scheduling priority	Corrugators are scheduled based on the types of orders available and the availability of machines
Assignment of exception orders	Orders which do not obey to the company standards are not automatically allocated to corrugators. They are stored in an

to corrugators	exceptions file waiting to be approved and assigned by schedulers.
Sequencing of orders within the same programme	Schedulers need to follow a number of rules such as avoiding small orders at the start or end of a programme in order to insure orders are run smoothly at the shop floor level
Sequencing of programmes	Schedulers need to choose the deckle sizes to run in such way that they start with a similar deckle as the last one finished on and they introduce deckle jumps to allow time for paper change at the shop floor level
Searching for jobs to build programmes	The schedulers need to perform a careful and complete search of all the orders stored to select appropriate orders and avoid upgrading orders that contribute to increasing the overall costs

Fig. 4. Corrugated paperboard components

One of the main issues noticed within most of the decision making situations is the non existence of standard rules applied by all the planners which was noted at the shop floor level when receiving different scheduling solutions. In fact, in most cases each planner follows his own experience when confronted to critical choices and which does not always lead to the best solution. Another issue is related to the searching approach adopted by the planners to find appropriate jobs necessary to build programs. If the searching procedure is not efficient it may lead to omissions of potential jobs. This may induce the planner to the easy solution of upgrading jobs to build programs which results in additional costs that could otherwise be avoided. Another issue related to the searching procedure and the selection of inappropriate jobs is the high number of grade and flute changes that affect the quality of the scheduling solutions. In fact, the higher the number of grade and flute changes the higher the percentage of paper breaks and hence the amount of waste. Last but not least, the schedulers tend to underestimate the importance of selecting the appropriate sequenced combination of jobs' chop lengths. This is extremely important because Different chop lengths restrict the running speed of the corrugators.

5.0 Conclusion

Most of the reviewed literature related to production scheduling, emphasised the following issues [10]-[11]-[12]-[13]:

- Computer-based solutions to manufacturing production scheduling are rarely successful in satisfying industry requirements.
- The importance of the investigation of the domain of integrated human and computer-based scheduling systems.

In fact, more research is to be directed towards the human factor and the development of efficient and tailored decision support tools to assist human planners in the generation of cost-effective scheduling solutions in the corrugated industry in particular. Indeed, Production scheduling in the corrugated industry has not received enough attention and consideration from researchers compared to the more general domain of manufacturing. It is therefore critical to determine the appropriate and required computer-based support to make production scheduling in the corrugated industry more efficient and cost-productive.

Acknowledgement

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AN INDUSTRIAL IMPLEMENTATION OF A METHODOLOGY FOR THE OPTIMISATION OF PRODUCT DESIGN TOLERANCES

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Abstract

Today, the key to commercial success in manufacturing is the timely development of new products that are not only functionally fit for purpose but offer high performance and quality throughout their entire lifecycle. In principle, this demands the introduction of a fully developed and optimised product from the outset. To accomplish this, manufacturing companies must leverage existing knowledge in their current technical, manufacturing and service capabilities. This is especially true in the field of tolerance selection and application, the subject area of this research. Tolerance knowledge must be readily available and deployed as an integral part of the product development process. This paper describes a methodology and framework, currently under development in a UK manufacturer, to achieve this objective.

Keywords: CAD, design, knowledge, tolerance analysis, optimisation.

1.0 Introduction

An important design resource in any manufacturing organisation is the ability to leverage the historical knowledge contained within the entire organisation. Figure 1 illustrates the different domains this knowledge can originate from, and whether the sources are internal or external to the manufacturing organisation. Sources of information outside the company include trends of product sales and marketshare between competitors. Product analysis is important to identify which features are responsible for commercial success - and equally which attributes can lead to poor sales. The other socio-political drivers in Figure 1 are the environmental impact of the product and its manufacturer (either actual or perceived) and whether there are any ethical issues associated with the product or its manufacture. This kind of high-level information can set the key characteristics of a product such as target performance and size, and also set certain lifecycle attributes such as service intervals and overall length of use.

Figure 1 also shows the three key downstream domains within a company, the manufacturing, inspection and service functions. These can yield important lifecycle information that could be used in the front end design process, and deployed in new product design or incremental product redesigns. In contrast to the external

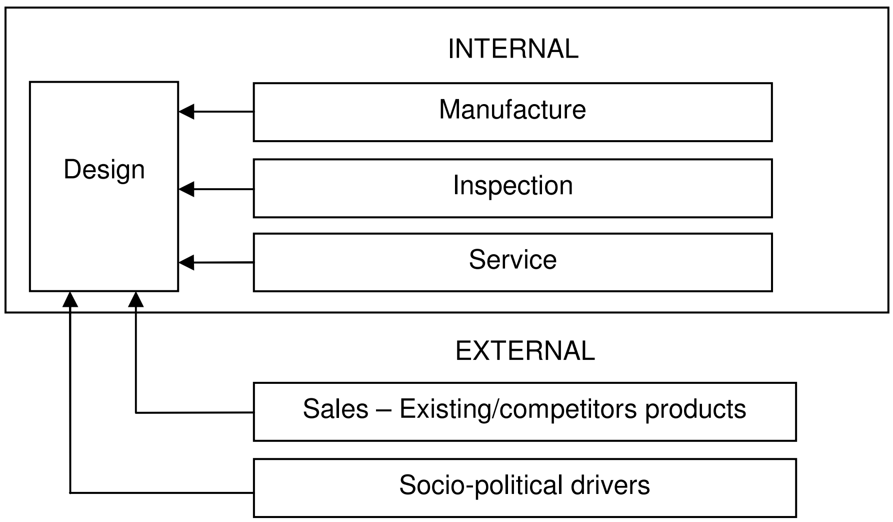

Fig. 1. Internal and external knowledge sources

sources of design information, these internal sources can be used to refine and optimise the design against existing manufacturing and service capability. Essentially, the goal should be to close the design-to-manufacture-to-inspection loop, and to return as much useful experience to the design domain as possible. The *quality* of 'what' is fed back is important. Merely providing raw information back to the design domain is not sufficient - the knowledge must also be *filtered* and *matched* to the context in which it is being used. Ideally, existing tools should be useable, the methodology should be complement tolerance analyses capabilities already deployed within the design function [1]. Also important to what is fed back, is the question of 'how', 'when' and 'how often' – in other words the timeliness and frequency of the information is crucial to its effective utilisation.

2.0 Methodology

The subject of this research programme is the creation and implementation of a tolerance optimisation methodology for the design environment with particular use of the internal sources of design information. A preliminary methodology is illustrated in Figure 2. Establishing a Design Knowledgebase is central to the methodology, and comprises two key elements: design tolerance knowledge and design context knowledge. The design tolerance knowledge is represented by a set of generic features created from relevant manufacturing processes such as injection moulding, sheetmetal forming and metal machining and fabrication. The knowledgebase also holds the various design contexts applicable to the definition of a product or subassembly. These design contexts may hold design representations at different levels of abstraction, from a two-dimensional basic part or product layout to a three-dimensional fully defined geometric part or constrained assembly. As Figure 2 shows, the Design Knowledgebase must support the use of actual manufacturing tolerance data obtainable from various manufacturing sources whether from in-house production or from the supply chain. In addition, the Design Knowledgebase must receive product assembly, build or test data (recording the performance attributes of a product). In addition to tolerance and performance data available from the original assembly of a new product, the equivalent data from remanufactured and serviced products should be made available to the knowledgebase. This gives the option to optimise part tolerance specification from new product build and test data only; from remanufacture and service data only; or from an aggregate of new product and service data. The inclusion of tolerance data from products with a service history is important for new product tolerance optimisation. Wear of critical components or features may affect product performance over time – hence dimensional control of additional features to offset worn componentry maybe appropriate – or recommending shorter service intervals to replace worn parts.

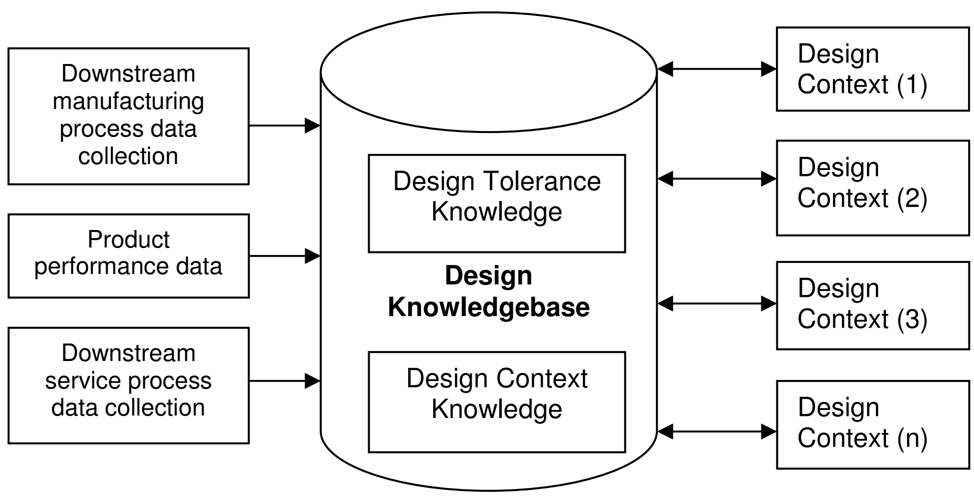

Fig. 2. The Research Methodology

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The developed methodology must enable the design contexts stored in the knowledgebase to be used transparently be adaptable to the specific product development task. Each design context should provide the user with a representation of the features or dimensional tolerances relevant to a particular engineering or product scenario. The use of a particular context from the knowledgebase should act as a high level filtering mechanism to offer a minimal dataset of retrieved information. The context therefore creates a sophisticated set of criteria to retrieve the required information from the knowledgebase. This approach is central to the widespread adoption of the methodology, and should be viewed as an integrated step within the design process. If the methodology has to be used as a separate 'mini project', this could limit its utilisation and the overall benefit in the process. 'Usability' is therefore a major requirement. The architecture of the Design Knowledgebase must support the chronological addition of both design tolerance knowledge and design contexts, as new and existing products are developed, tested and serviced. The Design Knowledgebase will evolve and mature over time as both the quality and quantity of the accumulated knowledge increases. The ability to understand the maturity of each knowledge source would be useful as a confidence level check, indicating how much additional data are required and the extent to which they have been filtered into a context-useable format.

3.0 Knowledge Infrastructure Support

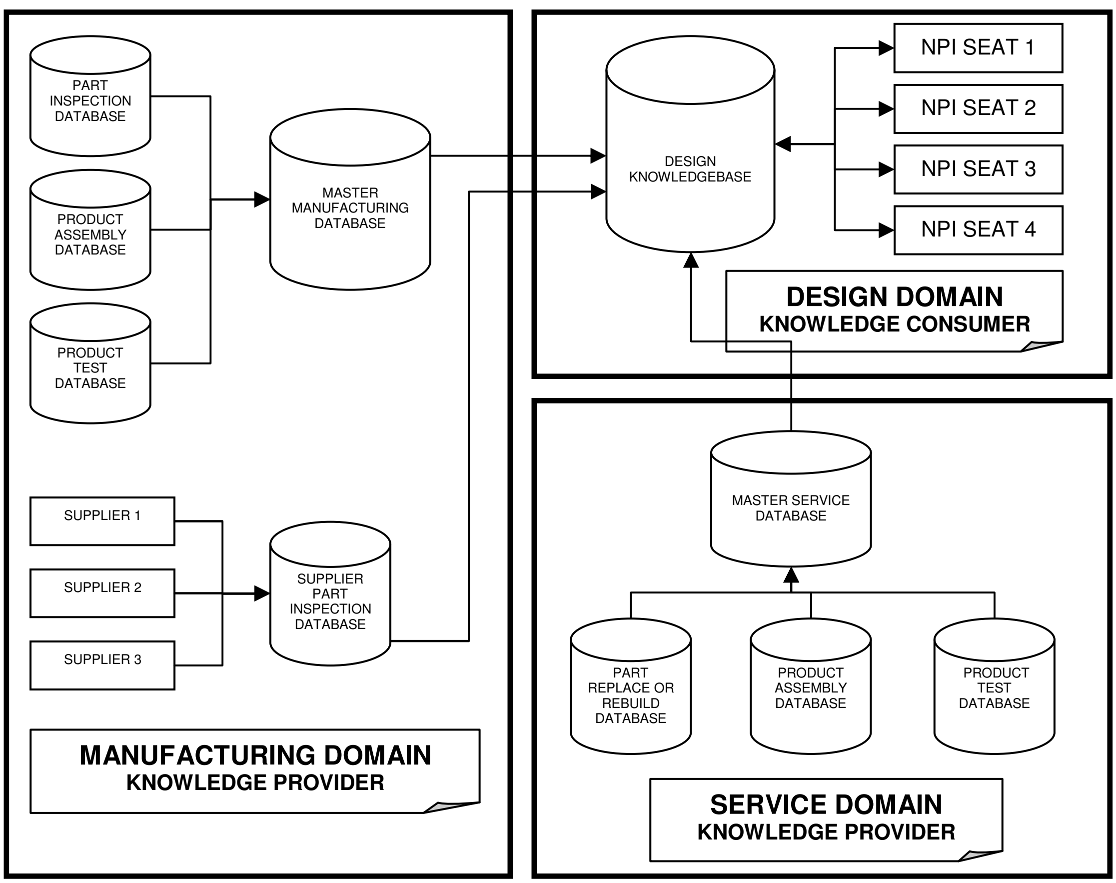

Fig. 3. Scope of domain data collection

An information collection and propagation strategy is required to meet the needs of the domains and the upstream manufacturing and design functions consumers. The framework shown in Figure 3 shows how this could be enabled, and comprises design, manufacturing and service domains [2]. In the manufacturing domain, there are three databases: the single part inspection database, the product assembly database and the product evaluation (or test) database. Also shown within this domain is the database storing the dimensional data from components manufactured by suppliers (e.g., in a multi-tiered supply chain). There are also three databases shown in the service domain: the part replacement or rebuild database, the product assembly database and product test database. The data is optionally consolidated into a master service database, although this would be an operational refinement. The Design Knowledgebase is the recipient of the data available from the manufacturing and service domains. The next step is to describe how this information is deployed with the design domain. An important principle in the use of downstream data is whether the information is 'pushed' by the manufacturing domain or if it is 'pulled' by the CAD application where the tolerance selection process is undertaken. Another consideration is whether the use of this data is influenced by the context of the design scenario in which they are used and whether the use of the information is driven interactively by the designer, or is an 'off-line' data retrieval process. Using the design context to control the nature of the query to the Design Knowledgebase is a way of filtering the mass of available information.

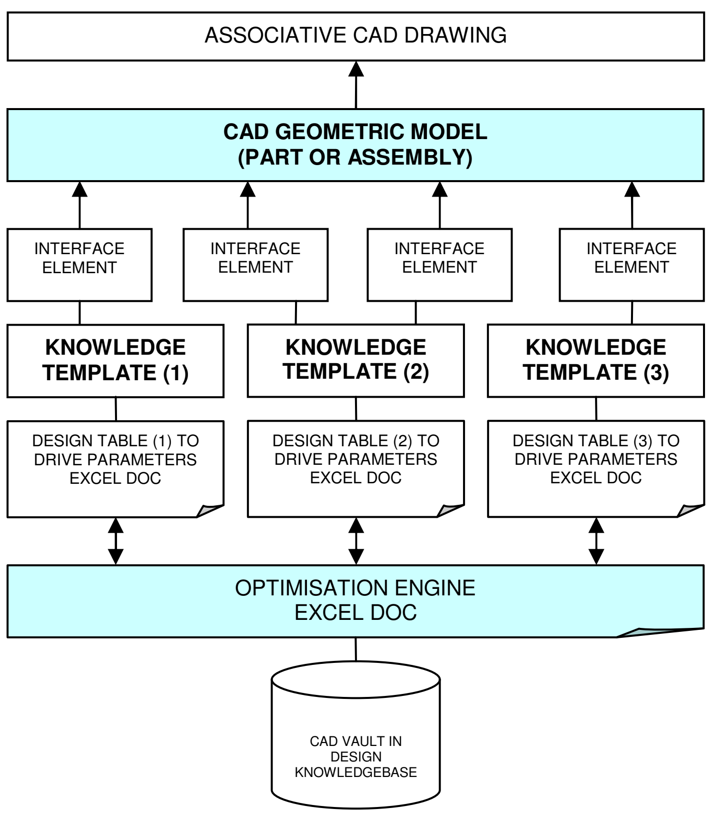

Fig. 4. Use of knowledge templates

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4.0 CAD Knowledge Templates

The retrieved dataset can then be passed directly into the geometric model or drawing. To achieve this, each generic product design configuration is captured as a knowledge template in the CAD application. Each template comprises simple geometry, such as wireframe elements or simple volumes to represent the semantic layout of design. Figure 4 illustrates how a knowledge template is used as a basis for the geometric elements of a new design. The template and the new design are linked using specific geometric elements which are exposed or made accessible to enable the association of geometric or linear constraints. These interface elements are used to enable the knowledge template to drive the features in the new parts and assemblies in the same system. The designer is able to link the new design into all the features in the knowledge template or may opt to only choose specific features of interest, and may decouple some of the associations if required. The use of the appropriate template establishes the parameters of any query to the knowledgebase. This is achieved by using the design table interface which captures the required size and tolerance parameters, which in turn is linked to a query engine. This is a spreadsheet environment from where queries are complied to obtain information from the knowledgebase to facilitate analysis of process capability, experimental design and process test data, used by the designer to optimise the design. The returned dataset information is used to update the design table, which updates the knowledge template, and hence the final design. The design table can contain a flag on the parameter that has been modified using the knowledgebase data. The new geometric design model is driven by the knowledge template via the interface elements, while a design table, held in an Excel spreadsheet, is used to drive the tolerance parameters.

5.0 The Optimisation Engine

The optimisation engine shown in Figure 4 is a key part of the methodology, and is shown in more detail in Figure 5. Essentially the optimisation process is conducted within a configured excel workbook the most appropriate software tool to accommodate the process. The first worksheet within the workbook stores the tolerance chain imported from the design table document - these initial dimensions and tolerance values are stored as reference values. Worksheet 1 also stores the output (from the other worksheets). The second worksheet is a query environment, the main purpose of which is for the user to gain an understanding of the impact of current process capability on the critical clearances. The tolerance chain is copied into this worksheet from the first worksheet. For each contributing tolerance in the chain, the potential (CP) and process capability (CPk) indices [3] are calculated, and each tolerance is modified to reflect this process capability. The overall clearance, now taking into account process capability, is calculated and can be compared with the initial clearance values. The dotted arrow back from worksheet 2 to worksheet one in indicates that these revised tolerances and dimensions may be captured and stored as a configuration, ready for use in the knowledge template if required.

In worksheet 3 allows the use of Monte Carlo analysis of the tolerance chain to obtain an output distribution [4]. This is in contrast to the analysis offered on worksheet 2 which was limited to a single clearance value and a tolerance. It is proposed that the analysis could be performed in two ways – using an assumed distribution, where the population was statistically normal and 99% of the output was within tolerance, or using the actual sample distributions available from the Design Knowledgebase. The output distribution would therefore more accurately represent a typical product run because realistic statistical distributions were used as inputs. The user would also enjoy a contribution analysis, displaying the impact of each tolerance in the chain - those tolerances with minimal impact could be relaxed to reduce cost, while the justification for imposing tight tolerances on specific features can be made. As before the dotted line depicts the capture and storage of this tolerance chain back to the summary sheet. Worksheet 4 is where the optimisation process occurs, and comprises a combination of correlation and goal seeking of the available manufacturing and performance data accumulated in the Design Knowledgebase. Most products are factory performance tested prior to shipping to ensure the product will perform as intended for the customer, and some of these performance metrics will be affected by certain key attributes in the assembly of the product. It is proposed to use the Spearman Rank correlation coefficient as means of identifying those critical assembly attributes (and their numerical values) which correspond to the best performing products. For each critical assembly condition contributing to 'good' performance, the tolerance chain can be represented with the assembly (clearance) condition being the required 'goal'. By imposing constraints derived from the available manufacturing capability, the goal seeking algorithm in Excel can be used to allocate tolerance values to the remaining elements in the chain. Figure 5 shows that once the tolerance chain has been optimised in this way, the results are passed back to the worksheet 1, offering the user the choice of updating the design table parameters with the suggested tolerance values. This in turn updates the dimensions and tolerances in the knowledge template which (through the interface elements) will update the detail design parts and drive any required drawing updates.

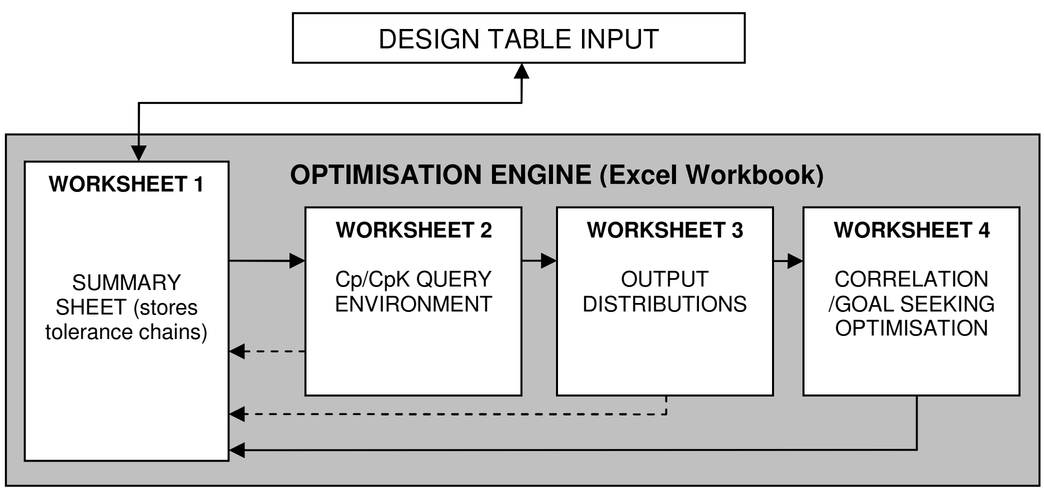

Fig. 5. Structure of the optimisation environment

6.0 Case Study

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A case study is currently being conducted to validate the proposed methodology in a manufacturing company. Edwards Vacuum designs and manufactures vacuum pumps and exhaust abatement systems for the semiconductor and chemical industries. The company machines core pump components in-house, but suncontracts less critical sheetmetal and plastic ancillary items.

The data collection phase is currently underway, with the collection and synthesis of pump build data (critical internal clearances) and performance data (ultimate vacuum, peak pumping speed and peak power consumption). The identification of the existing downstream databases will be identified, followed by a recommended database implementation which will be simulated to enable the capture of manufacturing data from both in-house and supply chain sources.

The product knowledge templates will then be modelled (as seem in Figure 4), in this case, a representation of the pump assembly. These drive derivates of the generic design (represented as geometric models), and are linked to the optimisation engine.

FEATURE	CONFIG0			CONFIG1			CONFIG2			CONFIG3			CONFIG4		
DESCRIPTION	DIM	TOL+	TOL-	DIM	TOL+	TOL-	DIM	TOL+	TOL-	DIM	TOL+	TOL-	DIM	TOL+	TOL-
	5	0.5	0.5	5	0.7	0.7	5	0.7	0.7						
	3	1	1	3	1.2	1.2	3	1.2	1.2						
	2.5	0.2	0.2	2.5	0.2	0.2	2.5	0.2	0.2						
	8.5	0.5	0.5	8.5	0.5	0.5	8.4	0.8	0.8						
TOTAL	**19**	**2.2**	**2.2**	**19**	**2.6**	**2.6**	**18.9**	**2.9**	**2.9**						

Fig.6. Summary worksheet

The optimisation engine (Figure 5) is a key element in the case study - elements of which have been developed and tested in isolation (such as process capability query) and now require integration within an Excel application. Figure 6 shows the first worksheet within the optimisation engine which stores the tolerance chain imported from the design table document. The initial dimensions and tolerance values are stored as reference values (Config0), while the modified tolerance chain, returned by the optimisation process is stored as a specific configuration (Config1,2,3, etc). The user of the system can select which of the stored configurations are to be uploaded to the design table, which as previously described, is used to drive the knowledge template within the CAD system. Ultimately, the component drawings which are associative to the geometric model can be driven by this optimisation process.

7.0 Conclusion

- This paper has highlighted the importance of marshalling engineering knowledge from the different domains within a manufacturing company principally from manufacturing, inspection, production testing, service and the supply chain. It has shown how this information should be centralised in a Design Knowledgebase as a means of defining knowledge templates which can be used as a means of controlling the representation of new or incremental designs, and hence ultimately the manufacturing drawings most systems are required to output. The proposed optimisation engine provides a means of optimising the tolerance chain using existing design and manufacturing knowledge. It provides several analyses options for the user to enrich the design with existing pertinent tolerance knowledge.

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INDUSTRIAL ROBOTICS IN THE LEAN ENTERPRISE – A CASE STUDY

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Abstract

The globalization and the increasing challenge from low-wage competitors highlight the need for European industries to enhance their ability to develop and manufacture products competitively. Meeting customer demands requires a high degree of flexibility, low-cost/low-volume manufacturing skills and an ability to offer short delivery times. In order to stay competitive, many manufacturing industries are trying to implement the unique management principles and practices of the Toyota Motor Corporation's with many different names as e.g. "The Toyota Production System" or "Lean production". One question and debate within industry, during the transformation towards lean manufacturing is whether traditional robot automation fits the principles and practices of lean? This paper presents a case study which has investigated if industrial robot automation has a place in *a* manufacturing company pursuing the lean philosophy. The case study is based on one manufacturing company in Sweden that is currently implementing a transformation towards a lean-based production system. The case study was performed using interviews at the company, observation at the manufacturing plant, and workshops together with key-employees at the company. The results from the case study show that there is a need to align the company's present robotic equipment and machinery towards lean principles. The lean transformation within the company is based on increased availability, controlled buffers, a more open layout, and flow-based manufacturing with reduced batch sizes which all effect the equipment and machinery. In order for the robot automation to fit lean principles and practices there is a need for development of robotized working cells with increased availability, reduced set-up times by improving the ability for easily reconfiguration, and improved information design to clearly present visual information and options to the operators.

Keywords: Lean Production, Industrial Robotics, Case Study.

1.0 Introduction

An increasingly global market and a business environment that is becoming harder are driving companies to become more competitive. The needs to reduce waste and create production systems that are streamlined towards producing products at lowest possible cost push companies into changing their production set up. Many manufacturing companies are transforming their production systems towards the *lean production* philosophies. Case studies shows that companies that implement what is called lean manufacturing principles or just-in-time (JIT) production can reach competitive advantage over those that does not [1]. However, these transformations are more or less successful depending on how much the internal structure and culture of the company is changed [2]. Many western companies have realized that just trying to imitate the *Toyota Production System* will not give them the competitive advantages they are looking for. An increasing amount of companies are realizing that they need more than just a lean transformation of their production systems; they need to implement *lean organizations*; they need to become *lean enterprises* [3]. This means that the whole company will have to change, both in working methods and in a business cultural sense.

The term lean means using less human effort in the factory with less manufacturing space, less investments in tools, less engineering hours to develop a new product in shorter time, keeping less inventory, fewer defects in production, and production of a greater and ever growing variety of products [3]. Lean practice has primarily two objectives: "*eliminate waste*" and "*create value for end-use customers*". Companies that adopt to lean manufacturing principles or JIT production have been shown to gain competitive advantage over those that does not [1]. Studies show the more comprehensive the adoption of JIT is at a company, the greater are the overall returns [4].

The lean production philosophies introduce extra demands on the production systems and the workstations that are parts of the systems. Many companies automated as many workstations as possible in order to reduce the manual labour cost in each product. This have historically, in some cases, ended up with what is called monumental automation; meaning that companies have automated too much and their production systems became rigid and vulnerable to changes. Today, many companies are doing the opposite and are removing the automation in order to become as flexible and robust as possible. When conducting interviews at companies one can receive comments like: "*Automation and industrial robotics creates complexity*" or "*Robotics and lean does not fit together; they rather contradict each other*". Further, many companies in Sweden regards automation, and especially industrial robotics, as unfit it lean production systems. The general belief is that working stations including industrial robots becomes too rigid and thus creates production systems that are inflexible and cannot adapt to changes. In many cases the movement towards removing automation is motivated with a reference to Toyota as a company that does not use advanced manufacturing technologies. This, however, is often a mistake since Toyota is a technology-based company that are among the most sophisticated users of advanced manufacturing technologies in the world [5].

This paper presents a case study performed at a large manufacturing company in Sweden. The company is undergoing a large "lean" transformation and the question whether industrial robotics is a desirable tool in the workshop was raised. The case study aimed at mapping the current usage of industrial robotics in the factory, and find out why the current robot installations did not perform as well as they should in order to fit into the new, more productive, production system.

2.0 Method

The case study is a preferred research method when the researcher is looking for answers to “Why?” and “How?” questions [6]. The case study may also contain a wide spectrum of rich data, in the form of documents, interview results, notes from observations, etc. The case study performed in this research had two main purposes: (1) map the current state of industrial robots at the case company, and (2) propose how the company should proceed with using industrial robotics in their new lean production system. These goals of the study could then be divided into a set of questions to answer:

Q_1 – How was industrial robot automation used at the company before the lean transformation?
Q_2 – Why is there a reluctance to use industrial robotics at the company?
Q_3 – How can the robotic working cells used at the company be changed/improved in order to make industrial robot automation more accepted at the company?

A literature study was performed in order to set the theoretical foundation of the research. During this literature study online searchable databases was used to find relevant scientific papers, as well as books.

The case study contained four different phases, shown in Table I: (p_1) pilot study carried out over one month containing interviews and observations at the factory, (p_2) workshops/brainstorming, (p_3) intensive study at the company, and (p_4) workshop/brainstorming with project team and key-employees at the company. The project team from the university consisted of: (1) professor in innovative production, (2) PhD-student within the area of applied industrial robotics, (3) PhD-student within the area of strategic manufacturing maintenance, and (4) research assistant within the area of applied industrial robotics.

Table I: Summary of the different phases in the case study.

Phase	**Purpose**	**Participants**
P_1 - Pilot study	Initial background study, in-depth study of one cell	Project team; interviewees at the company
P_2 - Workshop 1	Building a vision and overall goal for the project	Project team
Workshop 2	Building a vision and overall goal of the project	Key-employees at the company: project manager for transformation process, purchasers/managers of production equipment, production manager; project team as moderator
P_3 – In-depth study	In-depth study of how industrial robotics is used at the company	Project team, primarily two master thesis students; interviewees at the company
P_4 – Workshop and follow-up meetings	Deciding suitable concept solutions for how to better utilize industrial robotics at the company	Project team; key-employees at the company: project managers for purchasing projects, employee responsible for production development.

The five phases described in Table I was performed in sequence and built on the results from previous phases. The pilot study (P_1) was intended to investigate the need for a research project that was to focus on how to integrate industrial robotics in a lean production system. The pilot study resulted in a set of suggested improvements for the case company, as well as a proposal for a research project in collaboration between the case company and Mälardalen University.

The objective of the first workshops (P_2) was to get a common understanding in the project group of what it means to have industrial robotics in a lean production system. A set of questions had been prepared beforehand and the group used brainstorming on a whiteboard in order to answer the questions in sequence. The questions were: (1) what is the overall goal of the lean transformation at the company?, (2) What does it mean to become lean?, (3) How will the company become lean?, and (4) Which requirements does lean pose on the equipment used in the production system (with focus on industrial robots)? The results were in the form of bullet lists where some of the bullets were considered more important. Two workshops was carried out, first one with the project team from the university, and then one with key-employees from the company. The results from the two workshops were later compared to see if there were any differences in the results.

The third phase (P_3) was performed by two master thesis students who's main objective was to make a more in-depth study of the company's production system, and how industrial robotics was applied in that system. This phase had a time-span of almost six month, starting in the spring of 2007 and ending during the fall. The result of this phase was a masters' thesis containing a theoretical framework, a mapping of the current state of production, and a proposal of checklists that can be used by the company as guidelines for investment projects.

The final phase (P_4) was a workshop and brainstorming session where the project team and key-employees from the company worked together to identify which areas that was of greatest importance to the company. The background material used in this workshop included: the literature collected in the earlier phases, the results of earlier phases, the results of a measurement of stops in the robotic working cells performed by the operators, and the results that a lean consultant agency had provided after an extensive investigation performed during 2006.

The case company is a large manufacturing company supplying drivelines to automotive industry. The company has several production plants world-wide and this study was performed at one plant in Sweden. The case study was delimited to a certain segment of the manufacturing system where industrial robots were used for material handling and tending CNC-machines. The product produced at this production segment was gears used in gearboxes. The company is currently undertaking a large lean transformation where a whole production facility is being re-arranged and adapted to lean production philosophies. The company is part of a large group that have developed its own clone of TPS, which is near to identical to TPS. The company initiated the transformation in order to meet with a higher demand of their products, which was not supported by its current production facilities.

3.0 Automation and the Lean Enterprise

Womack et al. [3] identified in their MIT study that many automotive companies had a lot of automation, but the Japanese companies that had the highest productivity also had the lowest level of automation. However, they also believed that the automotive industries would automate almost every operation in the factories in the future [3, p. 102]:

> *"by the end of the century we expect that team-assembly plants will be populated almost entirely by highly skilled problem-solvers whose task will be to think continually of ways and means to make the system run more smoothly and productively."*

This prediction that Womack et al. did has not really come true but it is still possible, and even likely, that it will happen in the future.

Traditionally within the lean enterprise, e.g. Toyota, low-cost automation has been utilized [7], while companies that are not traditionally lean have used the more high-technology automation [8]. This type of low-cost automation is implemented to take the needs of the whole system into account, and thus becomes subordinated to the rest of the system. This kind of automation is considered to be in line with lean production philosophies [8]. However, there are several motivations for using more high-technology solutions such as industrial robotics, the flexibility and re-programmability of a robotic arm, for example. The industrial robot is a very versatile machine that can be used in many different applications.

One of the driving forces for using automation within industry is reduction of cost. Within the automotive industry there is a noticeable difference between companies that reside in countries where there is a high labour cost and those in countries with a lower labour cost. In the Daimler-Benz Mercedes A-Class series factory in Germany the body shop is almost 100 per cent automated, whilst Skoda's Octavia body shop in Czech Republic, where labour costs are low, is only 15 per cent automated [9]. In the Octavia body shop "*the strategy is to use a manual solution wherever possible, unless quality or productivity factors dictate otherwise*" [9, p. 136].

The term *lean automation* has been defined in different situations. Some pharmaceutical industries been looking to make their production more efficient through the use of automation, and have in this context defined lean automation as [10, p. 26]:

> *"Lean automation is a technique which applies the right amount of automation to a given task. It stresses robust, reliable components and minimises overly complicated solutions."*

One of the pillars of the Toyota Production System is called Jidoka, which comprises autonomation, also known as "automation with a human touch" [11]. Autonomation means "[…] *making equipment or processes that are 'smart' enough to detect an undesired, abnormal state and stop so as not to produce a defective product* […]"[1] The concept of autonomation was developed since the Toyota Corporation saw a problem in that normal automation do not have any built in checking for quality problems. This may lead to hundreds of defect parts produced if automated production equipment is producing without human supervision. "*At Toyota, a machine automated with a human touch is one that is attached to an automatic stopping device"* [11, p. 6]. This stopping device described in [11] is not only a stopping device that is used to stop that particular cell or workstation, but it is a stopping device for the whole production line, i.e. a line stopping device. This means that autonomation is an important part of the Visual Control system, or *Management by Sight*, where it is important that the current state of production is always visible and any problems are brought to attention as soon as they occur [12].

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[1] Source: Babylon online dictionary, http://www.babylon.com/definition/jidouka/Japanese, visited: 2008-03-31

As a result of this, the equipment may produce unattended and without human worker presence until there is a defect or malfunction. The original meaning of jidouka was "Automation" as shown in Fig 1 (a). The sentence was later changed at Toyota into the spelling shown in Fig 1 (b), the pronunciation of jidouka was the same but they added two extra lines, spelling human. This was an important statement, meaning that the automation (or autonomation) should be working the same way as a human; it should be *intelligent*[2]. The three words in Fig 1 (a) spell out: "Self moving transformation", while the extra two lines in Fig 1 (b) adds the "human touch".

自動化	自働化
(a)	(b)

Fig 1. the Japanese word Jidouka; for (a) Automation and (b) Autonomation.

4.0 Case Study Results

The case study has been carried out over 16 month in total, with different activities as described in Section 2. The overall objective of the case study has been to investigate whether the industrial robot has a place in a lean manufacturing system, and if so, how it should be used. The study was initiated as the company itself felt rather unsatisfied with the industrial robot automation that was used at the company at the time. The pilot study (p_1) aimed at identifying why the industrial robot automation used at the company did not work in a satisfying manner. The objective subsequent workshops (p_2) was to get a consensus within the company, and between the company and research group, of what lean production means at the company and what demands lean philosophies puts on the production equipment used in a lean manufacturing plant. The in-depth study (p_3) aimed at doing a more thorough study of how industrial robotics is applied at the company, and proposes a method for how industrial automation should be integrated in the production system. The final phase in this study (p_4) aimed at identifying needs for how to make industrial robot automation more applicable at the case company.

The study was designed to answer the three questions posed in Section 2. The following part of this section will present the answers to the questions, based on the evidence collected at the case company.

Q_1 - *How was industrial robot automation used at the company before the lean transformation?*

The study focused on a part of the company's production system where the machining of gears and axes was performed. In this part of the production system industrial robots was used to tend CNC-machines. The usual robotic working cell contained a robotic working cell and three of four machines. The robot picked material from an EU-pallet using vision or laser guidance and moved the material between the machines before finally placing it in another pallet. Some cells where connected using conveyors or shuttles where parts where transferred between the cells.

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2 Source: Seminar with Hiroyuki Mikami, a TPS-expert originating from Toyota Corporation, 2007-04-27

One notable issue for the company is that several different external system integrators have been hired to do different installations. The different systems integrators have been provided with a *scope of supply* and a *technical specification*, but those documents have been rather loosely defined and left a lot of decisions open for the consultant. Thus, different system integrators have made different types of solutions, which mean that each installation is different from the others. This leads to that every installation at the company has different solutions for programming, user interfaces, and other technical solutions.

The company have also had a lot of consultants working for them when it comes to daily operation of the robotic working cells. The competence of the operators when it comes to robotics and programming is quite low and thus a lot of external expertise is needed when introducing new products in the cells, for example.

Q_2 - *Why is there a reluctance to use industrial robotics at the company?*

There are different issues that have been identified as reasons for the reluctance to use industrial robotics. One of the major reasons is that the production management argues that the robotic working cells have to low availability. There are several reasons for this; one is that the robotic working cells have a high number of operations incorporated into the same cell. If there are 5 machines in the cell, each having an availability of 98%, the cells overall availability will be ($0.98^{\wedge}4$) about 92.2%. This availability will suffer even more if each stop in the cell gets longer because of low competence of the operators, leading to situations where experts (internal or external) have to be requested to fix any problems.

The operators working on the factory floor (blue collars) is reluctant to use industrial robotics based on that they do not feel comfortable working with technologies they do not fully understand. The different solutions that are implemented in each installation make the inexperienced operator unable to efficiently and effectively interact with each cell.

Another problem was identified when a review of reports on production stops was conducted. The follow-up protocols used in the robotic working cells were not providing any real information on which types of problems that were experienced. When reviewing the reports for one cell, the most commonly reason for stoppage in a machine was reported as "*No Category*" with 45.0%. In another machine in that cell the most commonly reported reason for stops was "*Short stop*", with 67.3%. This type of follow-up of production is of course useless since no information about the reason for the stop is provided. A manual measurement of the stops showed that changeover was the most common reason for stoppage in the production process. The most common breakdowns reported was short stops where the robot was unable to pick up components, or dropped components.

Even though several issues with industrial robotics were reported in the study, the overall opinion of the operators was that the roboticized workstations worked rather ok. Interviews with the operators revealed that they where satisfied with the overall performance of the cells, even tough it was quite a lot of "quick fixes" and "fire distinguishing" reported. The overall opinion of the management was a bit different. They felt that the robotic working cells where not performing as well as they should, and that they brought on unnecessary costs.

Q_3 - *How can the robotic working cells used at the company be changed/improved in order to make industrial robot automation more accepted at the company?*

The objective of the last phase of the study was to identify different means for making industrial robotics more attractive and useful for the company. The results of P_4 were divided into four categories, with the overall goal at making the industrial robotic working cells more easy to use: (1) software used in the cells, (2) maintenance of the cells, (3) manuals for how to purchase, integrate, and manage the cells, and (4) visualization of the cells. The different categories in turn contain several issues to investigate/develop. Table II shows some examples of topics that fall into each category.

Table II: Summary of the content of the different categories for improvement.

Software support	**Maintenance**	**Manuals/checklists**	**Visualization**
- User interfaces - Cell programming - Interfaces between cell and surrounding IT-structure - Jidoka	- Operator maintenance - Preventive maintenance - Measurements in the cell - SMED	- Manual for operator - Manual for purchasers - Manual for integrators - Technical specification - Scope of supply	- Andon charts - Visualization of production flow - Visualisation of current state of production

5.0 Conclusions

This case study aimed at investigating whether traditional industrial robotics is applicable in a lean production system. There is, based on the case study, no reason to say that industrial robotics is not applicable. However, as companies strive to become *leaner* and eliminate waste, complex and complicated production equipment often gives disturbances due to rigid solutions. Continuous flow and reduced inventory highlight inefficiencies and poses some new demands on the equipment used in the production cells. Four main areas where the robotic working cells at the company can be improved have been identified.

As can be seen from the case study, the operators have little confidence in their ability to implement changes in the robotic working cells. Further, the managers feel discomfort in the fact that the company has to rely on outside experts in order to handle day-to-day activities, such as introducing new products or fixing small problems. Those issues are all incentives for the development of robotic working cells that are more easy to use than today's installations. Two of the proposed categories of development and improvements are focusing on this; the software support category and the visualization category. Those two categories are also very closely connected since the software support may be seen as an enabler for visualization.

Traditionally, research in the area of automation has had a long tradition on focusing on the user of automation technologies, trough concepts such as system/situation awareness [13], users feeling "out-of-the-loop" [14], and other consequences of different levels of automation [15]. This type of research has been focusing on large automation systems which may have fatal consequences in case of a breakdown; aviation, power plants, and air-traffic control for example. However, when the availability of production equipment becomes increasingly important, those research areas become more and more important within manufacturing technologies as well.

The automation technologies used in world class manufacturing plants have to comply with lean principles such as andon, jidoka, and visual control. This pose new demands on the production equipment, but also adds a lot of value since it brings clarity and transparency. If the system designers focus on ease-of-use and provide solutions for system- and situation awareness for the operators, the usage of industrial robotics will have potential to become more of a commodity in all types of companies and manufacturing systems.

This case study aimed at identifying the needs for further development of industrial robotic working cells that are to be used in lean production systems. The proposed four categories will be further investigated and developed in the Lean Robotics project as part of Robotdalen. One of the more hands-on developments that are planned is a Cell-PC where the theories of Jidoka and Visual Control will be implemented.

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AN ASSEMBLY LINE INFORMATION SYSTEM STUDY

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Abstract

Assembly line information systems are designed to provide assembly workers with appropriate information that allows the assembly of the product in good time and good quality. In this context product quality might be defined relative to the number of internal rejects or products which need some kind of reworking before being in a deliverable condition.

This paper describes a pilot study of a heavy diesel engine assembly line where considerable variety is presented to the assembly workers in the form of engines destined for trucks, buses, marine applications and stationary power generation each of which has to comply with a variety of national and international standards. Internal rejects might for example occur through the fitting of sub-assemblies that are unsuited to the eventual application, and although an extensive information system is currently in place the level of internal rejects is considered to be unsatisfactory. The objectives of the study were to understand how the assembly workers interact with information systems and the impact this has on product quality and productivity. A single line was studied for ten days during which 2600 engines were assembled. At four of the assembly stations the existing information system was changed to reduce the amount of information to be assimilated by the workers, the timing of its presentation and its location. The use of simple colour-coded cards and symbols resulted in the reduction of internal rejects by 40% on two of the assembly stations and to zero on the other two stations. It is believed that changing the information system has changed the workers' behaviour through a reduction in cognitive stress levels. The pilot study has provided useful insights into the basis for modifying information systems and a further study of the final assembly of heavy trucks is planned with an ultimate aim of determining a rationale for the design of information systems for use within the assembly of customised products.

Keywords: Production, Information usability, Cognitive ergonomics, Workplace design, Assembly quality.

1.0 Introduction

Volvo Powertrain in Skövde, Sweden manufactures heavy diesel engines destined for trucks, buses, marine applications and stationary power generation each of which has to comply with a variety of national and international standards**.** Engines are assembled using mixed-model production where a high volume product is assembled in the main flow but low volume products are also present. To handle this situation a dynamic information system is essential so that it can (for example) refer to parts to be assembled on a specific engine, information regarding how to assemble a particular engine, etc. In the plant studied the information system is implemented as an IT system mounted on the automatic guided vehicles (AGVs) that carry the engines down the assembly line. Earlier work [1] explored the relationships between attention, interpretation, decision-making and acting and how this relates to the information flow based on the idea [2] that the degree to which Active Information Seeking behaviour is supported/triggered has a large influence on the number of internal rejects. As an extreme example, if a trigger is not present or detected, then an active information seeking behaviour will not be present. In other words, the trigger is predecessor to active attention, and active attention is believed to be a state of mind that is crucial for successful use of data and information. If it is not possible to create attention, then it is not possible to start an interpretation, decision-making and acting process. Obviously, there will still be some kind of interpretation, decision-making and acting, and the assembly personnel will continue to assemble engines, but the risk of assembly errors increases if one fails to trigger the personnels' attention [3] at the right time and to the correct data source. "Structured translation of data into action" [4] to reach a specific goal must be the main focus for the assembly personnel. This requires that the information is available at the right time in the right place and that the assembly personnel have identified a need for the specific information. In the assembly environment there is evidence, internal rejects, that the personnel do not use the information system in the most effective way. Studies made on the shop floor have concluded that the support system, from a graphical point-of-view is well, but not perfectly designed, but the users do not use them in a way that was anticipated. Input from ongoing projects indicates that one the main reasons for this is the attention levels among the assembly personnel.

1.1 The Role of Information Triggers

The purpose of any rational action should be to achieve a goal [5, 6]. This should normally create a demand for information, which is triggered in some way. There are four situations regarding information need versus demand: (1) There is a need but no demand. An error will eventually occur, and a solution might be to introduce triggers to create the demand. (ii) There is a need and a demand. This situation is the preferred one with low risk of errors due to lack of information. It is still essential that information matches the need. (iii) There is a demand but no need. This situation can be frustrating for the personnel as they have identified a need and have a demand, but they are not provided with the information they feel they need. (iv) There is no need and no demand.

1.2 Models Relating Action to Information

The OODA loop (Observation, Orientation, Decision, Action) [7] is an example of a model relating the information process to actions. However, some researchers [8] have suggested that "Observe, Orient, Decide and Act" should be redefined to "Observe, Interpret, Decide and Act". This would create a more generic model more suitable for manufacturing purposes, and in this case make it possible to map "Attention, Interpreting, Decision making and Acting" to the OODA model in a better way.

1.3 Attention

Before it is possible to receive information, one must perceive its presence. Aspects of passive and active attention are believed to be major contributors to problems in the work environment [2, 9-11]. Active attention is connected to actively processing information. e.g. during skilled machining operations one actively seeks and processes information. In passive attention, such as a visual inspection task we may register data/information in our surroundings without processing it actively until something unusual happens. The assembly personnel studied seem to be aware of some data, and perform parts of tasks correctly, but at the same time missed other important issues connected to the same task, although all data/information is available in the context of the work station. In other words, attention plays an important role in how data is observed.

1.4 Interpreting

In this case "interpreting" refers to the process of transforming [12] data into information. One way to describe the difference between data and information is that data is ”a set of symbols in which the individual symbols have a potential for meaning but may not be meaningful to a given recipient" or ”a set of symbols in which the individual symbols are known, but the combination is meaningless" or "understandable symbols rejected by the recipient as being of no interest or value" [12]. Information however can be described as "a message that exists but that is not necessarily sent to, or received by, a given recipient" or "a message sent to a destination or received by a destination, but not evaluated or understood" or "a message understood by the recipient and which changes that person's knowledge base" or "an output of the process of converting received messages, data, signs, or signals into knowledge." [12]. This leads to a conclusion that there is a connection between interpretation, data and information. The definition of information [12] states that it is an output of a process. This output among other things, such as knowledge, is a base for decision-making and acting. From this it is possible to state that information in the assembly plant context could be a message that when **received**, **read**, **interpreted** by a recipient **creates** knowledge/**changes** the receiver's knowledge base so that an **action** can be committed by the receiver that is **predicted** by the sender.

1.5 Decision-making and Acting

Although the subject of linking acting to decision making is an interesting topic, within the context of this paper these two topics can be discussed as one. Decision-making can be seen from a process perspective as a "many-to-one mapping of information to responses" [13]. If one considers this visualization together with the "mapping" statement it is easy to see that there could be different data/information sources that provide assembly personnel with data/information. This of course can directly affect the decision-making process in a negative way.

1.6 The Importance of Triggers

A trigger is the signal that creates a change of state regarding attention, from passive to active, and preferably, from active to passive. The hypothesis is that on the shop floor much of the attention is focused on the assembly task, and not on gathering data/information. This selective attention [14] is a part of the human nature, so an information system should provide a possibility to focus the assembler's attention to the right place (there is evidence that at the specific plant, the personnel use data/information from non-reliable sources) and at the right time as the trigger and the data must be synchronised.. The information system should support a change of state between active and passive. As "it is the nature of the attention process to generate its own extinction" [15], a trigger must also contribute to the "resurrection" of the information demand. It is important that a trigger is used in a way that really supports the personnel. There is evidence at plant that misuse of quality support systems have created a feeling of irritation leading to misuse.

2.0 Pilot Study

The aim of the pilot study is to find evidence that supports the overall aim of the research which is to find or develop a prototype work method that supports the design of information flow based on product and process demands. Two hypotheses have been formulated: Hypothesis 1 - 'Information Seeking Behaviour' - *The degree to which Active Information Seeking behaviour is supported/triggered has a large influence on the number of internal rejects.* Hypothesis 2 – 'use of evaluation methods' *The use of an evaluation work method in the conceptual as well as in the design phase of an information flow will affect the internal rejects in a positive way.* The pilot study was aimed at gaining practical knowledge regarding how triggers, active attention and passive attention affect the internal reject rate, but it also gave knowledge regarding how the assembly personnel interact with the information flow present in their work context. It is hoped that the knowledge gained from the pilot will be useful in the next stage of the research which is the creation of a prototype work method.

2.1 Performance Indicator

To evaluate the value of the knowledge obtained it is important to identify a performance indicator. In this case the main performance indicator is the rate of internal rejects for which there is historic data. The historic data covers a period of about 9 months in 2006 and includes approximately 33000 records. This data includes: date and time which can be used to trace the error source, engine family and variant (the data includes data connected to 6, 7, 12, 13 and 16 litre engines). The engine families have different variants (known as "engine types") and approximately 500 variants exist), effect number (a code used for reject causes), part number and free text field (used to describe the cause of rejection - unfortunately not used reliably). The reject historic data process starts with a discovery of a divergence from the order specification. This is done at the end of the line and in the test zones. If a divergence is discovered it is saved in a database and problem is solved in a special reject area. The most common way of subsequently retrieving data from the database is via a Business Objects (BO) question. This data has to be prepared for viewing so that the reject information can be used as the basis of decision-making. In this case the data can be sorted to identify the engine family, the date and time (to establish a weekly reject rate) and the assembly station.

2.2 Experimental Assembly Environment

The actual production environment under normal operating conditions was used in the pilot study and was modified by changing the trigger from the screen-based alphanumeric approach. The new triggers were coloured magnetic rubber sheets attached to the Automatic Guided Vehicle (AGV) which is the carrier of the engine (figure 1). The sheets have five different colours - blue, pink, orange, green and black to act as triggers for the different situations.

Fig. 1. The AGV/carrier and its cargo, a diesel engine.

2.3 Quantitative Data

The results were evaluated by comparing the performance indicator before and after the pilot study. As mentioned earlier, this indicator is a part of the reject handling system and had previously been measured for approximately 9 months during 2006. The data gathered during the pilot study shows that the performance indicator for the period is at a mean level of 1.46% (figure 2). However, depending on the sorting of the reject data two more values with higher means of 2.77% and 3.12% must be considered. The performance indicator with value 1.46% ($H_{\alpha 0}$) includes only rejects with the effect numbers being studied (parts missing or wrong parts assembled). The performance indicator with value 2.77% ($H_{\beta 0}$) includes $H_{\alpha 0}$ and rejects that have a non-assembly related attribute. The performance indicator with value 3.12% ($H_{\gamma 0}$) includes rejects from $H_{\alpha 0}$ and $H_{\beta 0}$ as well as rejects connected to a series of categories that indicate leakage of oil and water. Parts missing or wrong parts assembled can, if not found earlier, lead to a leakage in the final test zone. If this happens the reject registration will not be in the category "parts missing" or "wrong parts assembled" and it will be "leakage" or "deviation from specification". Figure 3 shows the error distribution over the stations within the line during the nine month period before the pilot study. The workstations affected were stations 800 and 1100, and as there are parallel lines this makes a total of four workstations.

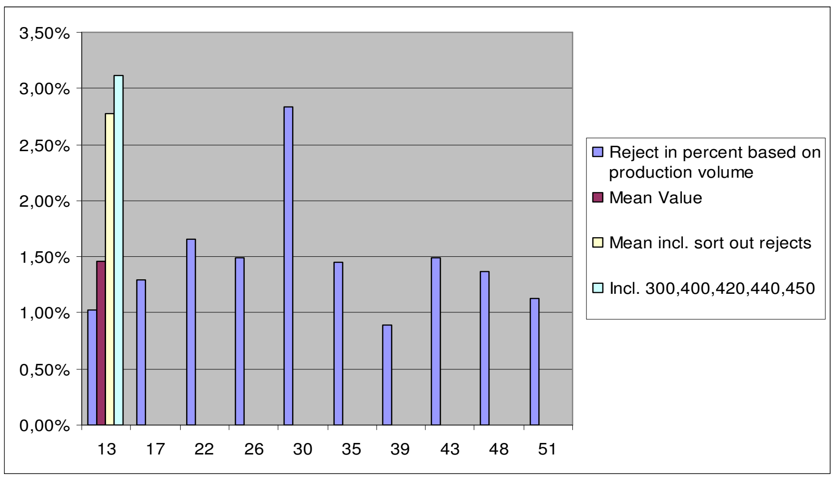

Fig. 2. Performance indicator sorted per week.

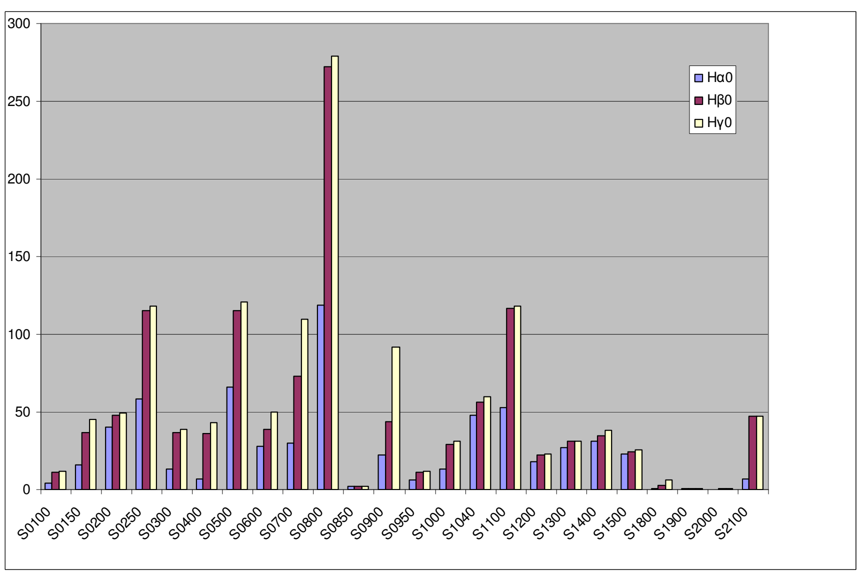

Fig. 3. Performance indicators sorted per assembly station.

2.4 Assembly Process AS-IS

The line studied contains twenty-four assembly stations and is balanced so that every station has approximately eight minutes of assembly time, i.e. the assembly personnel have eight minutes to accomplish the assembly task. The work process starts typically with an AGV/carrier arriving at an assembly station. The onboard information system would typically be displaying up to 19 lines of text to describe the assembly requirements. The subsequent steps in the assembly process are (1) identification of part to assemble. (not necessary where parts are identical on all engines), (2) retrieval of part to assemble (3) assembly of part onto engine. Steps 1 to 3 are repeated until all parts are assembled. (4) Confirmation of task - the personnel confirm via an IT system that they have completed all assigned tasks at the station. (5) Carrier departs from the assembly station to the next station. Step 1, "Identification", involves gathering of data/information. The data/information is presented to the personnel via a computer screen and is visible when the AGV/carrier arrives at that assembly station.

2.5 Assembly Process TO-BE (During the Pilot)

The TO-BE process is in a sense the same as the AS-IS process except in one important respect - that is the trigger. The trigger is a predecessor to "1. Identification of parts…..". No special arrangements influencing the production context were made, except for the handling of the triggers (the magnetic sheeting). This is to satisfy the objective of testing the hypotheses in a real assembly environment, and not in a controlled laboratory. MINITAB 14 was used to calculate the sample size (number of engine assemblies to be studied). And was calculated to be 2541. This, 2541, is approximately two weeks (ten twenty-four days) production. Therefore the experimental time frame within the production area was set to ten days. It was expected that this time frame would need updating during the experiment due for example to disturbances in production. In all experiments there is a possibility that the experiment itself influences the results. In this pilot three (four) experiment groups were used with the purpose to create an understanding of how this particular pilot might influence the personnel and thereby the results. The different experiment groups are divided by two different variables: A: Interaction: (A1:"High" , A2:"Low"), B: Trigger: (B1:Present or B2:Absent).

3.0 Results

The results can be categorized according to the subject groups. **Control group A2B2:** The results from this group are the historic data from the nine month period in 2006. This results are used as a reference value for the experiment groups. **Experiment group A1B1:** High interaction and trigger present. The experimenter was actively involved (asking questions, starting discussions about the work etc.) with the assembly personnel at their work stations and the new trigger was present. **Experiment group A1B2:** High interaction and trigger absent. As before the experimenter was actively involved with the assembly personnel at their work stations but the new trigger was not used **Experiment group A2B1:** Low interaction and trigger present. The experimenter was situated in the start of the assembly line and there was no or very little interaction between the experimenter and the assembly personal. The single line was studied for a period of ten days during which 2600 engines were assembled. At four (out of twenty-four) of the assembly stations the existing information system was changed to reduce the amount of information to be assimilated by the workers, the timing of its presentation and its location. The use of simple colour-coded cards and symbols resulted in the reduction of internal rejects by 40% on two of the assembly stations and to zero on the other two stations. On reversion to the original information system the rate of internal rejects rose to equal or surpass those before the study. Full details of the results can be found in [16].

4.0 Conclusions

It is believed that changing the information system changed the workers' behaviour through a reduction in cognitive stress levels. The pilot study has provided useful insights into the basis for modifying information systems and a further study of the final assembly of heavy trucks is planned with an ultimate aim of determining a rationale for the design of information systems for use within the assembly of customised products. The company expects to benefit in the long term through reduced rates of internal rejects brought about by more appropriate information systems that more closely match the assemblers' needs for information.

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ANALYSIS AND OPTIMIZATION OF ASSEMBLY LINES FEEDING POLICIES

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Abstract

Assembly line manufacturing systems require uninterrupted availability of components and subassemblies to feed the workstations. Three policies are typically available for materials delivery to the shop floor, namely line-stocking, kitting and kanban based (i.e. just in time supply). Each method has specific advantages and drawbacks also implying different performance levels in terms of work in process, material handling effort, space utilization, personnel requirements and costs. Policy selection is often a matter of qualitative judgement perhaps influenced by company-specific practices and tradition. In the paper descriptive models to design the components delivery system and compute required resources and performance metrics are developed for the three policies. This provides production managers some quantitative decision tools to help in properly selecting the components delivery method at an early decision stage, and explore trade-offs between the three feeding policies. The possibility of adopting a mix of the delivery methods is also examined and a methodology to develop and evaluate hybrid line feeding policies is presented.

Keywords: Assembly line feeding, line stocking, kitting, kanban, model.

1.0 Introduction

In assembly line manufacturing systems a decision has to be made about the way components and subassemblies are delivered to the shop floor to feed the assembly stations. Three policies are typically available, namely line-stocking, kitting and kanban based (i.e. just in time supply). The selection among such policies is often a matter of qualitative judgement perhaps influenced by company-specific practices and tradition. However, the choice of the component delivery policy strongly affects the performances of the assembly system in terms of work in process, material handling effort, space utilization, personnel requirements and costs. In order to provide production managers some guidelines and quantitative decision tools to help in properly selecting the components delivery policies, the paper at first develops descriptive models for the three policies. The models allow to design the components delivery system enabling the computation of size and number of containers for each policy, as well as the requirements of personnel, material handling and storage space. This allows to explore trade-offs between the three feeding policies for specific problem instances at an early decision stage in either single-product or multi-product settings. A comparison of cost (personnel and equipment) and performances (work in process) of the three methods is thus made possible. Subsequently, the possibility of adopting hybrid delivery methods including a mix of the above policies is examined. A methodology to develop and evaluate hybrid line feeding policies is then presented based on the ABC classification approach in order to properly associate the most suitable delivery policy to each component.

2.0 Overview of Line Supply Policies

In a kitting policy no parts inventories are kept at the assembly stations and the specific assortment of components required to perform the assembly operation are grouped together and placed into a kit container. Kits are prepared in a stockroom by the use of a pick list generated from the order's Bill of Materials and then delivered to a nearby assembly line according to the production schedule. In a kitting process, material is stored centrally which increases security in the control of physical inventory and also allows reduction of raw materials inventory at a given service level. Kitting allows better control and minimization of the work in process (WIP) and reduces manufacturing floor space utilization. Product changeover is simplified as only a change of the pick list is required and this supports small batch size operations with a large product variety, while obsolete materials can be readily removed from the inventory. This does not happen if the inventory is distributed on the shop floor. Material flow through the shop floor is simplified too as only the kits need to be moved to the assembly stations instead of individual components containers. Kitting offers opportunity for better quality and productivity as parts are readily available, checked and pre-positioned, and this supports the assembler's work. However, the kit preparation with the associated order picking is labor intensive and non productive (with little or no value added to the product) even if automated order picking is sometimes feasible. Kit preparation increases space utilization in the stockroom. Errors in kit preparation, defective parts included into a kit, or temporary shortage of parts may affect the assembly operations or the efficiency of kitting process. Procedures for management of exceptions are thus required. A thorough discussion of kitting operations and related advantages or drawbacks is given in [1], [2], [3],[4]. In case of no kitting (continuous supply), components containers may be stored along the line and resupplied in just in time fashion adopting a kanban-based policy. Otherwise, components containers in bulk quantities are simply stored along the line and periodically replenished (line-stocking). Respect kitting these two policies save the order picking labor but at the expense of a greater space utilization on the shop floor, an increased containers flows and a greater work in process. The just in time approach allows to somewhat reduce work in process respect line stocking but requires more frequent handling of components containers. The main drawback of both approaches is that parts are stored at their point of use meaning that a station has to store enough quantity of all the component that are utilized at the station for every product configuration, and that if the same component is used in multiple stations it has to be stored separatedly at each station. Finally, just in time and bulk line storage policies are not suited to variable product mixes. While kitting is an established practice in assembly industries [5], [6], the choice of materials delivery will largely depend on the structure of the assembly process and from parts size and cost, kits size and containers size (some parts are simply non kittable). Johansson and Johansson [7] state that a kitting process is suitable for assembly systems with parallelized flows, products structures with many part numbers, need for quality assurance and high value components. Kitting is considered most suitable for industries such as the electronic industry [8],[9], which deals with small parts and performs assembly tasks quite often. However, it is reported that even JIT systems dealing with larger parts can benefit from kitting [8],[10],[11].

3.0 Descriptive Models of Line Feeding Policies

Among the scarce literature existing on modeling material delivery to assembly lines, kitting has received the greater attention. However, most available models utilize queueing theory to analyse dynamic performances of kitting systems [12]-[15]. Nevertheless, these are not design methods and are scarcely useful when different component delivery methods have to be compared. Descriptive models useful for system design have been developed instead by Bozer and McGinnis [2] and Medbo [16]. Recently, Carlsson and Hendsvold [17] extended the Bozer and McGinnis model to compare kitting with just in time kanban-based line storage also allowing the possibility of arbitrarily choosing the delivery mode of each component. However, they do not take part size and weight into account. In this section specific descriptive models for resource sizing and performance estimation will be developed with reference to the three examined material feeding policies. Models development is partly inspired from the early work of Bozer and McGinnis [2] but several distinctive features have been included. Among the main differences Bozer and McGinnis do not explicitly take into account the human resources requirements and equipment cost or the economic value of WIP, as made in this work, and consider only kitting vs general line stocking policies without explicitly discriminating bulk with just in time line supply. This work instead includes a kanban-based just in time feeding model and also explores the possibility of mixed feeding policies. In this work all models are based under the hypothesis of one warehouse with a single I/O point, and a single-product assembly line consisting of M workstations arranged serially. However, multi-product cases can be incorporated adopting weighted averages of required data in order to reflect specific production mixes. The extension of the models to a multiple lines system is straightforward. The assembly line has a constant daily production volume and the considered time horizon is one day. Material handling personnel is distinct from line staff which is in charge only of assembly operations. Kits are prepared one at a time and delivered to the first station of the line. Materials composing a single kit may be put into one or more separate containers according to weight and space limitations. In kanban and line stocking systems each workstation has its own containers available and containers are not shared among multiple workstations. The same constant-speed vehicle or walking operator is used to transport kit containers and components containers. Empty containers are returned back to the central warehouse. Exceptional items, such as those very cumbersome and heavy requiring special handling care are not included in the analysis. For meaning of symbols please refer to the nomenclature section at the end of paper.

3.1 Kitting

A kit is here defined as a unit load holding all the components required to assemble a unit of the finished product. However, according to weight and size of its components a kit may be made up of one or more distinct containers or totes. In the kitting policy it is assumed that a single kit is prepared for each end product and is moved from the kit preparation zone located at the warehouse I/O station to the first station of the line. Multiple kits can be accumulated at the start of the line. In this work single kit preparation is considered (although batch kitting is allowed) and only traveling kits (which move along the line with the assembly) are utilized.

The number of separate containers making up a kit is $n_{cont\ kit}$ and it is determined on the basis of containers volume or their allowed weight. Unless the same container is reused twice or more each day, the total number of containers required to manage the daily production D (where D is the number of kits n_{kit} to be prepared and moved daily) is $n_{c\ tot} = n_{cont\ kit}\ n_{kit} = n_{cont\ kit}\ D$, while D is also the number of kits to be moved daily. The number of workers needed to operate the kit preparation and transportation is N_{op} as given in equation (2) where $2\ n_{c\ tot}/\omega$ is the daily number of material handling moves from the warehouse to the line with full containers and from the line to the warehouse with empty containers. Personnel cost is simply evaluated as $C_M = N_{op}\ C_{op}$. Equipment cost C_E is the sum of containers cost and transport equipment (i.e fork lifts, manual carts, tractor/trailers etc.) capital investment. The holding cost of the work in process is C_{WIP} (equation 4) considering that ω_k kits are simultaneously moved to the line and that $C_{std\ i}$ is the annual unit holding cost of i-th component. As far as space requirements on the shop floor (S) are concerned, the space occupied by the single traveling kit can be neglected, while in case multiple kits are transported and accumulated at the first station S is given by equation (5) where n_{sl} is the number of containers which can be stacked in a column and a_k and b_k are the length of the containers base sides.

$$n_{cont\ kit} = \max \left[\sum_{i=1}^{N} \frac{v_i\ n_i}{V_k}, \sum_{i=1}^{N} \frac{p_i\ n_i}{p_{max}} \right] \tag{1}$$

$$N_{op} = \frac{[t_{r/s} N + t_p \sum_{i=1}^{N} n_i] n_{kit} + [t_m k \frac{2}{\omega}] n_{ctot}}{\eta_{op} h_1} \tag{2}$$

$$C_E = n_{ctot} C_c + C_V \frac{\frac{2n_{ctot}}{\omega} L}{V_v h_1} \tag{3}$$

$$C_{WIP} = \left[\sum_{i=1}^{N} C_{std\ i}\ n_i \right] \frac{\omega_k}{2} \tag{4}$$

$$S = \frac{(a_k\ b_k) n_{cont\ kit}\ \omega_k}{n_{sl}} \tag{5}$$

3.2 Kanban (Just In Time)

According to this policy material is resupplied at each station with a lead time LT in separate containers dedicated to each component type. Let define n_{ij} as the number of items of the i-th component utilized at the j-th station per unit finished product ($n_{ij} = 0$ if component *i* is not utilized at station *j*), then the number of containers needed at station j to hold the material needed to avoid starving during the supply lead time (with zero buffer stock) is $n_{cont\ ij}$ and the total number of containers utilized is n_{ctot}. The total number of times that a single component container is to be refilled and moved to the line is $n_m = n_{c\ tot}$ /LT, therefore the workers requirement is N_{op} and 2 n_m/ω is the daily number of material handling moves from-to the warehouse. Personnel cost is computed as in the kitting case, while equipment cost is computed as shown in equation (3) but including the storage racks cost C_{SR}. This can be estimated as $C_{SR} = n_{c\ tot}\ V_c\ C_{SRU}$ where C_{SRU} is the rack cost per unit volume. The holding cost of the work in process is the holding cost of the average material amount in the kanban containers along the line (equation 9) and the shop floor space S occupied by materials containers along the line is given by equation (10).

$$n_{cont\,ij} = \frac{LT\,D\,n_{ij}}{\min\left[\frac{V_c}{v_i}, \frac{p_{\max}}{p_i}\right]} \tag{6}$$

$$n_{c\,tot} = \sum_{j=i}^{M} \sum_{i=1}^{N} n_{cont\,ij} \tag{7}$$

$$N_{op} = \frac{(t_{r/s} + t_{fr} + t_{m'}\,k\,\frac{2}{\omega})\,n_m}{\eta_{op}\,h_1} \tag{8}$$

$$C_{WIP} = \frac{1}{2}\left[\sum_{j=i}^{M} \sum_{i=1}^{N} C_{std_i}\,LT\,D\,n_{ij}\right] \tag{9}$$

$$S = \sum_{j=i}^{M} \sum_{i=1}^{N} \frac{(a_c\,b_c)\,n_{cont\,ij}}{n_{sl}} \tag{10}$$

3.3 Line Stocking

In line stocking each station holds a different container, periodically resupplied at time intervals which depend from the adopted containers capacity, for each separate component it uses. The total number of containers along the line is n_{ctot} (equation 11). The number of material handling workers is computed by equation (8), but since the number of replenishments is not dictated by the lead time but from the size of containers, n_m is expressed as given in equation (12), and 2 n_m/ω is the daily number of material handling moves from-to the warehouse. Personnel and equipment costs are computed as shown for the kanban feeding policy. The holding cost of the work in process is the holding cost of the average material amount in the containers along the line and is expressed as equation (13). Line storage containers in general will have a larger size than the corresponding containers utilized in the just in time policy. The shop floor space occupied by materials containers along the line is then computed according equation (14).

$$n_{c\,tot} = \sum_{j=i}^{M} N_j \tag{11}$$

$$n_m = \sum_{j=i}^{M} \sum_{i=1}^{N} \frac{D\, n_{ij}}{\min\left[\frac{V_c}{v_i}, \frac{p_{\max}}{p_i}\right]} \tag{12}$$

$$C_{WIP} = \frac{1}{2}\left[\sum_{j=i}^{M} \sum_{i=1}^{N} C_{std_i} \min\left[\frac{V_c}{v_i}, \frac{p_{\max}}{p_i}\right]\right] \tag{13}$$

$$\mathrm{S} = \sum_{j=i}^{M} \frac{(a_c\, b_c) N_j}{\mathrm{n_{sl}}} \tag{14}$$

4.0 Analysis of Hybrid Feeding Policies

Utilization of the above models allows to compare the performances of the three line feeding policies in order to choose the best solution for any given scenario. However, the underlying assumption is that once the policy selection is made all the components, apart from exceptions, are supplied with the same method. Nevertheless, improved results can be sometimes obtained when the feeding policy is selected at single componente level, meaning that hybrid feeding policies may be adopted where the entire set of component is partitioned into homogenous classes and a specific feeding policy is assigned to each class. While several partitioning criteria can be conceived, i.e in multi-product lines components can be classified according to their commonality level with respect to the end products variants, in most cases a Pareto ABC classification referring to the economic value of the components can be appropriate. In this case, defining the economic value of a component as its unit cost times the demand, components can be ordered according to diminishing values of the economic values and class A may group components having a cumulative economic value about 80% of the total (this class will group about 20% of components). Class B will group remaining components having a cumulative economic value of about 15% of the total (usually around 30% of components), while class C will comprehend the remaining 50% of components responsible for the residual 5% of overall economic value. Therefore, class A components will have a greater relevance and will be responsible for the greatest flows, WIP and holding costs, class C components will be scarcely relevant components with minimal flows or negligible holding costs, while class B components will represent the intermediate case. A hybrid delivery policy can be then identified by the string X/X/X where the sequence of "X" indicates the policy associated to A, B, C classes respectively and X may assume the following values: KI = kitting, KA = Kanban-just in time, LS = Line storage. As an example the string KI/KA/LS means that A class components are managed with a kitting policy, class B components utilize a kanban based policy and class C components are resupplied with a line storage policy. Within this framework one can choose three distinct policies for any of the three components classes, meaning that overall 27 options are available. Neglecting the "pure" policies where the same method is used for all components, one has 24 theoretical hybrid policies. However, some are unfeasible or meaningless in practice. For example, the LS policy is not advisable for class A components as it would cause excessive WIP and holding cost, while a kitting policy is not justified for class C components because their low holding cost allows high WIP to be tolerated and its reduction can not offset the added cost of manual kit preparation. It follows that only the following options are likely to be considered for each class: Class A (KI, KA), Class B (KA, LS), Class C (KA, BL). This reduces the number of practicable hybrid policies to eight. Nevertheless, one can consider that if KI, KA, and LS represent policies with a progressively reduced degree of WIP control and workforce effort, while ABC represent classes of reducing economic relevance, it is of no use to increase degree of control and effort while passing from class A to C. Therefore, the choice can be further simplified if, beyond the three pure policies, one narrows the options to the following most promising hybrid policies only,

- **Policy I: KI/KA/LS.** This policy strictly controls WIP and holding cost by managing A class codes by kitting, while relaxes the control on Class C items which are less influencing. Class B codes are managed by kanban to reduce WIP but without imposing an excessive order picking burden.
- **Policy II: KI/KA/KA.** Most relevant codes are still managed by kitting but kanban control is extended to class C codes to pursue overall WIP reduction. Commonality of Class B and C policy improves operational efficiency even if the handling effort is increased.
- **Policy III: KI/LS/LS.** In this policy attention is focused on Class A codes only and control is relaxed on Class B and C items. It is a trade off policy with lower workforce cost than the previous policies and intermediate WIP.
- **Policy IV: KA/LS/LS.** Control is fairly relaxed except for Class A components which are managed in just in time fashion. Pursues minimization of workforce cost while maintaining a degree of WIP control over most relevant components.

Therefore, a strategy for selecting the optimal material handling approach would include the following steps repeated for the three pure policies and the four selected hybrid policies. A multicriteria rating of the computed performance indicators, properly weighed according to the specific scenario, will then allow a comparison of the policy options and may help plant managers to make an informed decision.

1. ABC classification of materials according to economic value
2. Resource sizing (workforce and equipment) according to the above developed models
3. Performance estimation (WIP, holding cost, handling flows, personnel expense)

5.0 Conclusions

Kitting, just in time and bulk line storage are different options to supply components and subassemblies to the workstations of assembly lines. Not a single technique may represent the appropriate approach in any assembly situation, each having specific advantages and drawbacks,. However, to identify the cases where each approach is most suitable or to select the preferred method in a given scenario, is a challenging task especially owing to the lack of literature models allowing comparison on a similar basis. As a results the selection of assembly lines feeding method is often a matter of qualitative judgement and common practice. In this paper descriptive models have been developed for all of the three solutions enabling a plant manager to compare on a quantitative basis the respective performances considering WIP, holding cost, equipment and workforce requirements and intensity of containers flows. Moreover, a procedure has been presented to enable a systematic analysis and comparison of hybrid policies where a components classification is carried out at first and a specific material delivery method is associated to each class. This allows to rapidly explore mixed solutions which can be more suited to specific scenarios.

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Nomenclature

C_c	Container unit cost	n_m	Number of daily replenishment and transport cycles of a materials container
C_E	Equipments capital cost	n_{sl}	Number of stackable containers on the shop floor
C_M	Personnel annual cost	nc_j	Number of different components utilized at station j
C_{op}	Annual cost of a worker	N	Number of different components in a finished product
C_{SR}	Cost of storage racks	N_j	Number of different components assembled at j-th station
C_{SRU}	Cost of storage rack per unit volume	N_{op}	Number of operators
$C_{std\ i}$	Unit holding cost of i-th component	p_i	Weight of the i-th component
C_V	Vehicle unit cost	p_{max}	Maximum allowed weight of a container
C_{WIP}	Holding cost of the work in process	q_i	Quantity of i-th component moved replenished in batch
D	Daily demand finished products	S_j.	Set of component codes utilized at the j-th workstation
h_l	Daily working hours (hours/day)	t_{fr}	Time to fraction bulk component cartons in warehouse
i	Component identification index	t_m	Warehouse to assembly line kit containers trip time
j	Workstation index (j = 1 to M)	$t_{m'}$	Warehouse to assembly line containers trip time
k	Number of operators to move a kit	t_p	Picking time for a single item
L	Length of one way transport route	$t_{r/s}$	Time to locate and reach components in the warehouse
LT	Containers lead time in kanban policy	v_i	Volume of the i-th component
M	Number of workstations	V_c	Volume of a components container (a_c x b_c x c_c, being a_c, b_c, c_c the dimensions of the container)
$n_{cont\ kit}$	Number of separate containers in a kit	V_k :	Volume of a kit container (a_k x b_k x c_k, being a_k, b_k, c_k the dimensions of the container)
N_{ctot}	Total number of containers	V_V	Transportation velocity
n_i	Mukltiplicity of i-th components in a finished product	η_{op}	Average workers efficiency

n_{ij}	Number of items i utilized at station j per each unit of finished product	ω	Number of containers transported simultaneously
n_{kit}	Daily number of kits to be moved	ω_k	Number of kits simultaneously moved to the line

DECISION SUPPORT SYSTEM FOR PALLET UTILISATION IN THE SHEET FEEDER INDUSTRY

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Abstract

The sheet feeder industry is a business that provides a wide range of cardboard sheets to its customers. Pallet utilisation in such industry sector has a direct impact on the cost and time related to the preparation and delivery of the product. This paper presents a decision support system for pallet utilisation in the sheet feeder industry. The developed system comprises a knowledge – based system, material handling modules, databases and user interface. Furthermore the system encompasses pallet database, truck database and material features databases. It also takes into account several factors that affect directly the pallet loading problem. Cardboard sheet size, type of flute, type of paper, cardboard sheet configuration, customer restrictions and type of lorry for the product delivery are the key factors that have been considered to maximise customers' orders onto the pallet. These data has been gathered by semi-structured internal interviews and questionnaires within the sheet feeder industry and visits to the shop floor.

The developed system has the capability to estimate the number of corrugated cardboard sheets that should be loaded per pallet as well as number of stacks per pallet. Additionally the system predicts the number of sheets per stack and the type of pallet that should be used. The system provides the shop – floor operators with an effective tool for pallet utilisation in order to reduce their decision time. Therefore, the developed system provides cost and time savings in terms of improvements of the pallet and vehicle volume utilisation for the preparation and delivery of the corrugated board product.

Keywords: Sheet Feeder Industry, Pallet, Cardboard Sheet, Transport, Logistics, Decision Support Systems.

1.0 Introduction

In the last few years, corrugated industry has undergone different mergers and acquisitions, hence the cardboard business is immersed in a very competitive market where each company fights for being the best in terms of service, product quality and cost. As a result of this, nowadays companies are making a lot of effort in optimising the different tasks that are involved in their business: from the management of an order to the distribution to the customer. The customers of this industry sector are very demanding because they require a very specific cardboard sheet sizes. Morabito et al. [1] stated that “The mission of optimisation is to get the right goods or services to the right place, at the right time and in the desired conditions, while making the greatest contribution to the company”.

However, in the sheet feeder industry some improvements have been done in the reduction of waste material. A cardboard is a lightweight and sensitive material, so many cares should be taken into account for its transport. Sheet feeder industry is manufacturing cardboard sheets of many sizes which require different pallet sizes for their delivery. A pallet is a factor in the material handling line and any small improvement in its use will have a big impact for the company. The less pallets the company uses, the less time will be use to manage and transport the products. This is traduced in time and cost saving.

Deciding the optimal height for a pallet is not an easy task because customers sometimes have their own requirements. Furthermore, the pallet has its own restrictions as well such as maximum weight and height. The transport vehicle is another very important factor in this decision. The maximisation of the space available in the truck is another concern. Many pallets size is proportional to the space available in a truck. But for those pallets that have a specific size, because they are customers’ bespoke pallets, the optimal use of the space in the truck is an issue.

The developed decision support system aims to provide the shop – floor operator with the necessary information to manage customers’ orders in the most efficient way. Many variables are involved in this system such as the weight of the cardboard. The system presented in the paper improves the current system to distribute customers’ orders onto pallets. Less number of pallets will be used for the delivery of an order which means cost and lead – time reduction

2.0 Literature Review

A pallet is a portable, horizontal, rigid platform used to store, stack and hand loads as a single mass [2, 3]. Trebilcock [4] and Fornicio [5] explain that the pallet is the most used item to transport products from one point to the other. The users of pallets are expected to buy the same number of pallets or more year by year. The most used pallets are made from wood and plastic. However, wooden pallets are down slightly in the last few years [6]. Different aspects of these items for the transport are looked when they are bought, like: durability, purchase price, availability, etc.

As well as being different materials to make a pallet, there are different pallet sizes in the market. The pallet dimensions are made in a way that they are submultiples of the place that will be used to transport the pallets [7]. Nowadays, there are two normalized pallet dimensions: the Europallet (1200mm x 800mm) and the universal pallet (1200mm x 1000mm). Apart from the standard pallets that can be found, nowadays there is a tendency to make a pallet for new products. This makes an increase in the cost of pallet management and this variety causes less efficiency in the distribution chain. Trade costs increase too because those products that should be transported from one country to another (countries that have different pallets standards) at the border are unloaded from the initial pallet to the second one [2]. Morabito et al. [1] argue that another disadvantage is the lack of well- accepted standard pallets and compatible trucks designs for these standards that has as a consequence an undesirable empty space of the cargo loading.

There is an option to fill these pallets when the customer makes an order to fill a pallet with few material, this is called mixed pallet. Instead of increasing or decreasing his amount of products of the order to fill a pallet, a pallet with products of different customers' products is loaded. But the use of this pallet may complicate the logistics. Firstly, the manufacturer needs to know how the products should be loaded onto that pallet; this decision is taken every time a customer order is placed. This pallet design should be efficient in terms of pallet space and it also should be stable. Because if the load is not stable enough the material can be damage and this is the main reason [8]. Therefore, the design of these mixed pallets is a time consuming task. Hoffman [9] reports that if the stability is improved, the productivity too, including the reduction of damage in transport. It could be found three groups of designers in the material handling field: designers of handling equipment, designers of the pallet and the designers of the packaging ([10]. White et al. [3] point out that a cost reduction in the pallet will save money in those activities associated with the movement of products between the seller and the customer. For example, some designers invest efforts in redesigning the pallets because pallet interacts with other components of the supply chain like: vibration interactions during the loading and conveying, shock transferences while the forklift is handling the material, etc. In spite all of this, there is a special concern in saving transport costs.

3.0 Methodology

A combination of research methodology approaches has been employed in this research study. Firstly, a familiarisation stage has been conducted through comprehensive literature review and visits to the sponsoring company. The second phase was to conduct semi - structured interviews with the shop-floor operators and operations directors to have a better understanding of the business needs. This was combined with measurements of the trucks and the pallets and internal documentation from the company. In this stage, the researcher also distributed questionnaires to other sheet feeder companies to know if the system could be applied also to more companies. In the third phase, the data gathered were analysed for the subsequent development of the system. Then the system has been developed following the logic rules obtained by analysing the data. Finally, the developed system has been validated, through real – life case studies and expert opinions.

4.0 Overall Structure of the Developed System

The aim of the Decision Support Systems is not making decisions. These systems should give a serial of assessment decision tools to improve the results of the decision [11]. The developed system has the aim of improving the management of customers' orders onto pallets. The overall structure of the prototype system is shown in Figure 1.

The system consists of three databases. These databases have data of the different pallet and truck sizes and material features that are in the company. All these data interact with the user interface.

It has been developed some logic rules and equations that with the data inserted and the databases give a decision to the shop – floor operator. This decision provides information about: how many sheets per pallet should be loaded, how many full pallet are used, if there is any part pallet and which pallet size should be used for the product delivery.

5.0 System Implementation and Scenario

The system has been developed by means of the VBA programming language. This language which embedded in Microsoft Excel which was seen as an ideal medium for achieving the goals of this research.

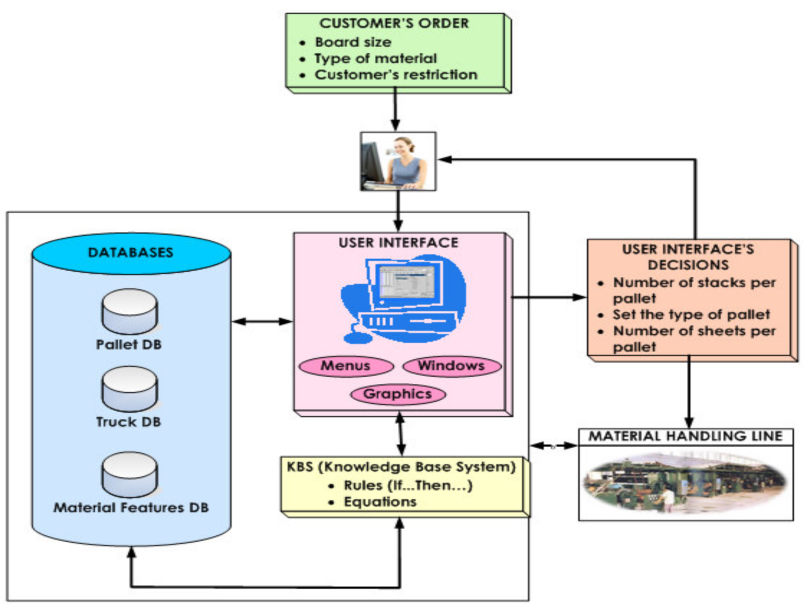

Fig. 1. Overall structure of the developed system

Figure 2 illustrates the system scenario and screenshot where the user of the system should interact to input a customer's order. Firstly, the various data of the customer requirements are input to the system. The system prompts the user if the customer has specified the number of sheets per stack. If this the case, the user has to input the specified number of sheets which should be loaded per stack. Therefore the shop-floor operator has to follow the customer requirements.

The user has to specify if the number of stacks per pallet was a customer requirement. Otherwise, the planning department decides the number of stacks per pallet. The number of stacks per pallet is detailed. More customers' restrictions are required in the system. The overhang is a factor to consider because it affects to the system when it has to choose the size of the pallet for the customer order. If the customer allows overhang the system takes a pallet some centimetres smaller than the size of the cardboard. The value of these centimetres varies regarding the type of flute that the cardboard sheet is made of.

Another customer restriction is the possibility of applying over sheets to the number of cardboard sheets that are loaded onto the pallet. Some customers want a specific amount of sheets in their orders. If the customer allows over sheets a tolerance can be applied. This tolerance varies regarding the customer and the overall quantity of cardboard sheets per order. This tolerance adds an extra percentage of number of cardboard sheets to the overall quantity of the order. In another field of the system, this tolerance it is asked. So, that the system knows the tolerance that should be applied.

The last field to fill in the customer requirements section is if the customer requires a specific pallet to use. If that is the case, it is asked which are the dimensions of the pallet that he wants and if it is a standard or bespoke pallet. In this situation, the system checks if the pallet that the customer has specified fits properly with the order. If not, the system shows a message to the user advising him to ask the customer to require another type of pallet. The reason why it is important to ask if the pallet is standard or bespoke is because there is a difference of thickness between them. This difference of thickness it is traduced in the number of cardboard sheets that can be loaded per pallet. The thickest the pallet is the less number of cardboard sheets can be loaded. On the other hand, if the system has the freedom of selecting the type of pallet that can be used only standard pallets will be taken into consideration. The reason for this is because only standard pallets are known beforehand. Bespoke pallets are only considered when the customer requires them. Bespoke pallets are purchased when the customer asks for them. The second reason is that standard pallets are the ones that best fit into the truck because their dimensions are proportional to the dimensions of the truck.

Secondly, the features related to the order itself are required. In this section the first thing that the system requires is the overall quantity of cardboard sheets of the order.

Next, the dimensions of the cardboard sheets are introduced: the width and the length. If the customer does not specify the type of pallet to use the system compares the width and length of the cardboard sheet with the width and the length of the twenty four pallets available in the warehouse. And if the customer requires a specific pallet, the system compares these dimensions with the dimension of the cardboard sheet.

The flute is also specified because the type of flute affects to the thickness of the cardboard. Consequently, to the number of sheets that can be loaded per pallet if the system has the option of making this decision.

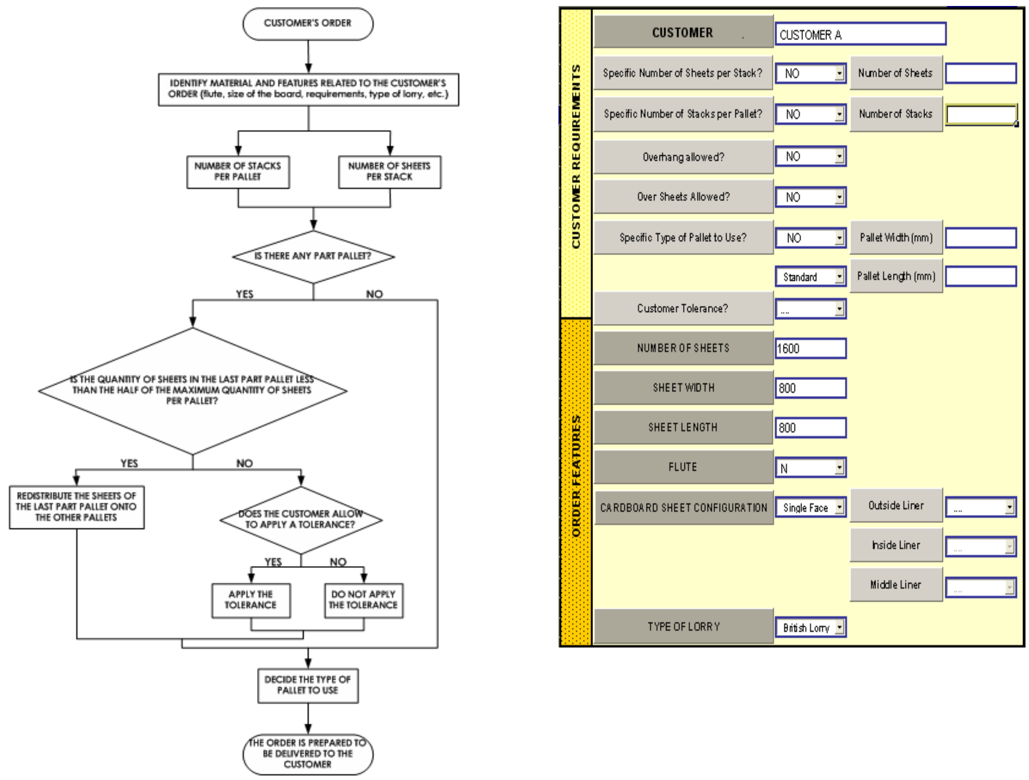

Fig. 2. Overall system scenario and an example of input window

The cardboard configuration and the type of paper used for the manufacturing of these cardboard sheets are asked by the system. These factors affect directly to the weight and the height of the cardboard. For example, if the cardboard sheet required by the customer is single face, this kind of cardboard sheet will lighter and thinner than a double wall cardboard sheet. The reason for this, it is because this kind of cardboard sheet is made of less number of papers. It influences the type of paper used for the manufacturing of the cardboard as well because not all the papers weight the same.

Finally, the type of truck used for the product delivery is another factor included in the system. Regarding the truck, more or less space will be available for the product delivery. There four types of trucks in the company and they have different sizes.

After completing all the required fields, the system automatically creates the decision for pallet utilisation. Figure 3 shows an example of the outputs generated by the developed prototype system. The system provides the pallet width and the pallet length if the customer does not require a specific type of pallet. It matches the 24 standard pallets in a company to find out which pallet fit properly with the customer's order. The reason is that these standard pallets dimensions can fit with the dimensions of a truck.

In the system is detailed as an output the number of full pallets that are used. It is called full pallet to a pallet filled to the 100% of its maximum capacity. It also specifies if there is any part pallet. It is called part pallet to a pallet filled less than the 90% of its maximum capacity.

As it has been mentioned before, if the number of cardboard sheets in the last part pallet is less than the half of the maximum capacity that can be loaded, a redistribution action is done. This means that the system redistributes these sheets onto the other full pallets. So, this last part pallet is removed. If in the last part pallet there are more sheets that the half of the maximum number of sheets that can be loaded per pallet, this last part pallet is kept. And the customer's tolerance is applied if it is possible. After applying the tolerance, the system details the quantity of cardboard sheets that are in the last part pallet.

If the system does not make the redistribution there will be only full pallets and it could be part pallets too. The number of cardboard sheets per stack and the number of sheets per pallet in the full pallets are specified.

Figure 3 shows the system output window. It can be appreciated that there are two outputs namely "Number of Sheets per Stack 1" and "Number of Sheets per Pallet 1". They represent the number of cardboard sheets per stack and the number of sheets per pallet. The overall number of stacks of the full pallets is defined by the button "Number of Stacks Type 1".

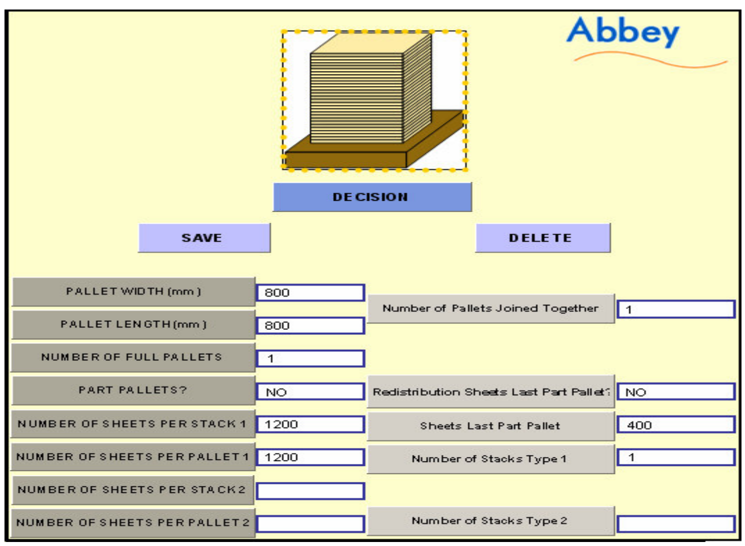

Fig. 3. System output window

If the redistribution action is not carried out the system reports the user if there is any part pallet and the number of sheets in the last part pallet. If the system makes the redistribution action there will be two kinds of full pallets. The reason why there will be two kinds of full pallets is because the system proceeds to redistribute equally onto the other pallets those cardboard sheets of the last part pallet removed. So, it will add one cardboard sheet more per stack in the full pallets until there are no more cardboard sheets to distribute. So, some full pallets will have one sheet more per stack comparing to the rest of full pallets.

6.0 Conclusion

It may be stated that the system presented enhances the production line and the planning department. Moreover, the author believes that there is not a standard way to choose the most suitable pallet for each order. Nowadays, sheet feeder companies have a shop – floor that makes this decision. So, it can be stated that this system is the first step done for the standardisation of the pallet selection task.

The weight is a new factor to consider into the business of the sheet feeder industry. The conventional cardboard is a lightweight and strong material but with the new trends of material (microflute) appearing in the sheet feeder industry, the weight plays an important role. The microflute cardboard is a very delicate material and if the pallet loads too much quantity of this kind of material, the material can crash itself.

The developed system will improve the current practise giving the following benefits: a maximisation of pallet and truck utilisation, a reduction in the overall number of pallets used, cost and time reductions in the preparation of customers' orders.

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SCHEDULING OF NON-REPETITIVE LEAN MANUFACTURING SYSTEMS UNDER UNCERTAINTY USING INTELLIGENT AGENT SIMULATION

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Abstract

World-class manufacturing paradigms emerge from specific types of manufacturing systems with which they remain associated until they are obsolete. Since its introduction the lean paradigm is almost exclusively implemented in repetitive manufacturing systems employing flow-shop layout configurations. Due to its inherent complexity and combinatorial nature, scheduling is one application domain whereby the implementation of manufacturing philosophies and best practices is particularly challenging. The study of the limited reported attempts to extend leanness into the scheduling of non-repetitive manufacturing systems with functional shop-floor configurations confirms that these works have adopted a similar approach which aims to transform the system mainly through reconfiguration in order to increase the degree of manufacturing repetitiveness and thus facilitate the adoption of leanness. This research proposes the use of leading edge intelligent agent simulation to extend the lean principles and techniques to the scheduling of non-repetitive production environments with functional layouts and no prior reconfiguration of any form. The simulated system is a dynamic job-shop with stochastic order arrivals and processing times operating under a variety of dispatching rules. The modelled job-shop is subject to uncertainty expressed in the form of high priority orders unexpectedly arriving at the system, order cancellations and machine breakdowns. The effect of the various forms of the stochastic disruptions considered in this study on system performance prior and post the introduction of leanness is analysed in terms of a number of time, due date and work-in-progress related performance metrics.

Keywords: Lean Manufacturing, Just-in-Time, Scheduling, Shop-Floor Control, Non-Repetitive Manufacturing, Job-Shops, Performance Modelling, Intelligent Agent Simulation

1.0 Introduction

The lean manufacturing paradigm devised by Toyota grew into a global phenomenon which is still attracting the undiminishing attention of both the industry and the academia [1]. Lean production scheduling and shop-floor control are exercised through a set of key lean concepts, techniques and tools integrated under the umbrella of Just-in-Time (JIT) pull production. Nonetheless, the majority of these critical enablers were developed in line with the design and operational characteristics of flow-shop layout configurations found in repetitive production systems in which leanness was originally introduced. This consequently led to only scarce attempts to implement the lean paradigm in the scheduling of non-repetitive manufacturing environments.

Group Technology (GT) and layout reconfigurations have been proposed in the limited attempts reported in the literature to increase the degree of manufacturing repetitiveness and facilitate the implementation of lean scheduling in complex non-repetitive production settings. Whilst the majority of these studies report satisfactory improvement in system performance resulting from the adoption of leanness they fall short to address the full size and complexity of real-life applications. More specifically they employ solution methodologies that downsize the scheduling problem considered or address a simplified version of it which often ignores the openness of the system and merely deals with its deterministic version.

Scheduling problems particularly those which are good approximations of real-life systems are highly complex combinatorial problems the optimisation of which is classified as NP-hard. The large number of input parameters, their interdependencies as well as the stochastic nature of many of these parameters calls for modelling methodologies which offer high level representation and can manage efficiently the complexity and volume of interactions pertaining ever-evolving scheduling systems. Constant advancements in computer technology coupled with the rapid evolution of simulation and artificial intelligence however, call for the issue of the transferability of leanness into the scheduling functions of complex non-repetitive manufacturing systems to be revisited. This research employs state-of-the-art agent-based simulation to extend lean pull production control to the scheduling of dynamic non-repetitive manufacturing job-shops which are subject to machine breakdowns and unexpected variations in customer demand.

The remainder of the paper is organised as follows: Section 2 presents a brief review of the literature focusing on the implementations of leanness in the scheduling of non-repetitive production systems as well as on applications of agent-based simulation in lean scheduling. Background information on job-shop scheduling and shop-floor control is presented in Section 3 along with a brief introduction to the push and pull production policies considered in the framework of this study. Section 4 gives an overview of the two agent-based architectures built to model the operation of the job-shop scheduling system under investigation and to test its performance under push and tight pull control. The section also presents the functionalities added to the agents of both architectures to model uncertainties related to unexpected demand changes and machine breakdowns. The parameters determining the experimentation setting in which the simulation runs were performed are analysed in Section 5. The simulation output from the various experimentations and comparisons drawn on the system's performance under push and the proposed lean pull shop-floor control are summarised in Section 6 which also presents brief concluding remarks on the performance of the proposed modelling methodology.

2.0 Literature Review

In spite of the general consensus in both the academia and industry that the lean paradigm is applicable merely on repetitive production systems and the subsequent lack of support to its transferability, a review of the literature reveals a small number of research works investigating the extension of leanness in the scheduling of non-repetitive production environments.

2.1 Implementations of Lean Scheduling in Non-repetitive Manufacturing Contexts

Earlier works studying the extension of leanness into non-repetitive production environments share a common point of departure. They recognise the non-repetitive nature of the manufacturing operations performed in these facilities as the strongest impediment to the application of critical lean scheduling and shop-floor control enablers. To this end, they propose functional layout adaptation or reconfiguration to increase the degree of manufacturing repetitiveness in these systems and thus facilitate the introduction of leanness into their scheduling functions. One of the first research works highlighting the need to reform job-shops into more lean-friendly shop-floor configurations is presented in [2]. The author proposes a move towards the reconfiguration of functional layouts into cellular layouts, Flexible Manufacturing Systems (FMS) or job-shop "islands". The utilization of MRP as a higher level planning and inventory management system and the implementation of JIT shop-floor control at the lower level combined with the rate per day schedules and back flushing are introduced in a reconfigured production system to support its lean transformation in [3]. Stockton and Lindley [4] propose process sequence cell layouts as an alternative to GT cells to enable the material flow to be controlled by kanbans in High Variety Low Volume (HVLV) production environments. Hybrid push/pull dual-card kanban control is implemented in different shop-floor configurations in order to study the effect of various contextual factors e.g. batch size, material handling mechanisms etc and of their trade-offs on system performance in [5].

With no prior adaptation or modification of any form to alleviate the serious restrictions imposed by certain design and operational characteristics of non-repetitive manufacturing functional configurations, early studies investigating the direct introduction of leanness into the scheduling functions of the former focused on applications not representative of the size and complexity of real-life problems. Despite their limitations these studies confirm an optimised performance resulting from the adoption of leanness. One of the first comprehensive attempts to implement leanness in a non-sequential however simplified context, is presented in [6]. In a similar study, Gravel and Price [7] employ simulation to test the performance of a job-shop under kanban control and a selection of dispatching rules developed in the framework of their work. The effects of pull control introduced in two alternative modes, i.e. tight pull and CONWIP on the performance of a Small-to-Medium Enterprise (SME) job-shop operating within a broader Make-To-Order (MTO) supply chain are modelled and analysed in [8]. A HVLV job-shop setting with stochastic arrival and processing times is considered in [9] whereby the results of the agent-based simulation showed that tight pull control exercised by kanbans outperformed the initial push system. A basestock pull control policy is introduced in a job-shop setting in [10]. No machine breakdowns or unexpected variations in demand are considered in the agent-based modelling methodology employed to test the system performance after the introduction of pull control.

2.1 Applications of Agent Based Systems in Lean Scheduling

In their majority, the applications of multi-agent systems and modelling methodologies in lean scheduling to date study the implementations of leanness in repetitive manufacturing settings utilising flow-shop layout configurations. An agent-based approach to address the problem of minimising the JIT earliness/tardiness weighted deviation in a parallel machine setting with stochastic order arrivals is proposed in [11]. An autonomous decentralised system for minimising intermediate and end product storage costs, changeover costs and due date penalties for JIT scheduling is presented in [12]. The performance of the proposed system is tested by considering a multi-stage flow-shop and experimentation results confirm the effectiveness of the proposed system in meeting the aforementioned JIT scheduling objectives while achieving considerable savings in computational time. Frey et al [13] develop a multi agent system for production planning and control which they compare with other conventional centralised approaches. The benchmarking scenario adopted in their study considers the case of a multi-level assembly where material flow is controlled by Kanbans. In a recently published study, Papadopoulou and Mousavi [14] adopt a multi-agent modelling approach to apply lean scheduling and shop-floor in a non-repetitive functional layout with particular focus on controlling the constant work-in-progress in the system. Their study considers a job-shop with dynamic order arrivals and processing times but does not account for other stochastic factors affecting the system as it assumes negligible machine downtime, order cancellations and rush order arrivals.

3.0 Lean Scheduling and Shop-floor Control in Job-shops

Job-shops are the dominant shop-floor settings in non-repetitive manufacturing environments. They employ functional layout configurations whereby equipment carrying out the same type of processing is grouped together and positioned in distinct areas of the shop-floor. Following the introduction of lean manufacturing, the two prevalent production control modes are push and pull with their names pointing to the way the system responds to actual customer demand. A job-shop operating in push mode typically comprises a number of disconnected production stages (workstations). In front of every workstation there is input buffer with theoretically infinite capacity. When actual demand information is received for a certain product type production is triggered at the first stage of its process routing. If the first station in the process sequence of this job is busy the job joins the queue of waiting jobs in the input buffer in front of the workstation. Jobs completing their processing at one workstation are pushed to the input buffer of the next workstation in the sequence without any consideration of its demand or workload.

Each production stage in a job-shop operating in pull production mode can be viewed as a production-inventory station comprising an input buffer, one or more machines and an output buffer. Apart from the movement of parts, other types of entities that move within a pull production system are demand and production authorisations. A part is released from the output buffer of a preceding stage into the input buffer of the subsequent stage in the sequence only if authorisation for the release of this specific product type is available. In contrast to the physical movement of parts downstream, the movement of customer demand takes place only logically and in the opposite direction (upstream). Production authorisations can be either physical cards (kanbans) or logical signals generated by a software scheduler.

Whilst the implementation of push production control is quite straightforward, pull production control is more complex and can be exercised by adopting various alternative pull production control policies [15]. Figure 1 below illustrates the basic principles of operation of the Kanban Control System (KCS) adopted in our study in the case of a simplified manufacturing system with two production stages in series.

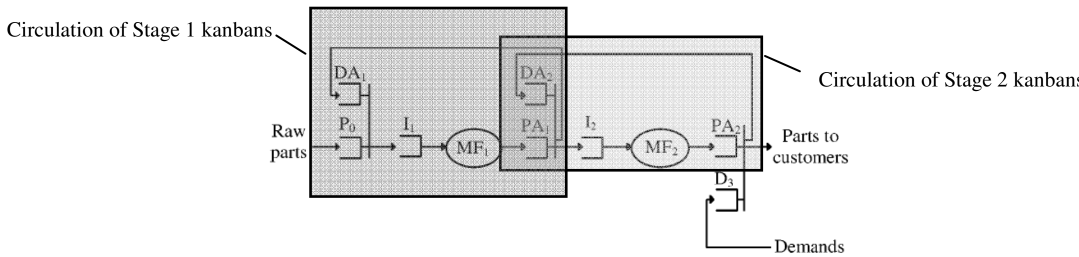

Fig. 1. KCS queuing network with synchronisation stations, case of two serial stages [16]

Queue PAi in the output buffer of stage i contains pairs of stage i processed parts and stage i production authorisations whereas queue DAi+1 denotes pairs of demand and production authorisations for the production of new stage i+1 parts. Queue Ii represents the input buffer of stage i whereas the raw material buffer and customer demand are represented as queues Po and D3 respectively.

4.0 Intelligent Agent Modelling and Simulation

The agent-based simulation models developed in the framework this study, were built using JACK Intelligent Agents™ [17]. JACK™ is a third-generation commercial framework for building and running industrial and research multi-agent applications. The framework benefits from the underlying JAVA infrastructure and multi-threading environment which offer high levels of performance, concurrency and efficiency. A multi-agent architecture is designed to model the operation of the scheduling system prior to the introduction of leanness and to benchmark its performance. This architecture is then modified to simulate the system's operation after the introduction of lean kanban-pull production control, Figure 2. Both architectures incorporate uncertainty expressed in the form of high priority orders arriving at the system unexpectedly, order cancellations and machine breakdowns.

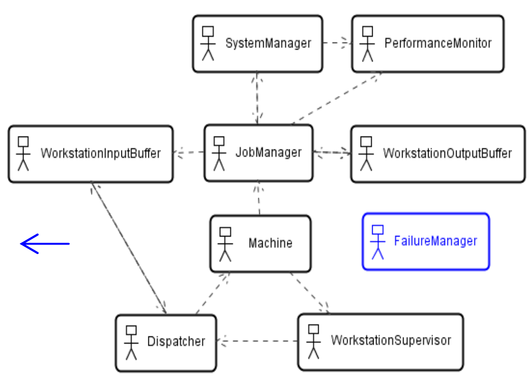

Fig. 2. Multi-agent architecture of the pull system

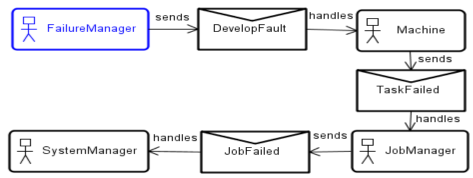

Fig. 3. Interface of the FMA

In the architecture of the initial push model the System Manager Agent (SMA) is responsible for creating the different job types processed in the modelled system. It assigns a workstation to each process step in the job's task list and sets the associated processing time. The Job Manager Agent (JMA) carries all necessary information about the job including the data determined by the SMA and other time-related data collected during its processing. The JMA manages the job's flow through the system by routing the job from one workstation (forward scheduling). When the processing of the entire job is completed, the JMA provides the job's data to the Performance Monitor Agent (PMA) which calculates the performance metrics generated in the simulation output. The input buffer queue in front of each workstation is represented by a Workstation Input Buffer Agent (WIBA). Each WIBA is responsible for exchanging information with the JMA and for updating its list following the addition/removal of jobs to/from the input buffer it manages. The Workstation Supervisor Agent (WSA) holds information on machine identification and status, i.e. busy/idle and is responsible for assigning jobs queuing in the workstation's input buffer to the machines available in the workstation. The change of machine status is communicated by the Machine Agent (MA) to the WSA whenever the machine's status changes. The last agent type available in this architecture is the Dispatcher Agent (DA) which performs the selection of the next job to be processed by employing a number of dispatching rules.

In order to model the proposed pull production system, the agent-based architecture of the initial push model is modified by introducing a new agent type, i.e. the Workstation Output Buffer Agent (WOBA). These agents exchange information with the JMA on the availability of inventory and update their databases whenever inventory is added (removed) to (from) their lists. At system initialisation their inventory lists contain pre-determined levels of zero due date inventory for all the different job types processed at the respective workstation. Further modifications to the initial model concern additional functionalities performed by the JMA. Following the arrival of a new job, its JMA requests information on the availability of a fully processed (zero due date) job from the last WOBA in the job's task list. If confirmation is received, the JMA replaces the zero due date of the already available job with the actual due date of the newly arrived job which then removes from the WOBA's database. After exchanging information with the PMA, the job agent updates the job's data by replacing its original due date with a zero due date and releases the now "zero due date" job to the system by breaking down the job's task list and executing it sequentially but in reverse order (backwards). However, if no confirmation is received, the JMA logs its request for fully processed job with the WOBA of the last workstation in the job's task list and puts the release of the job on hold until inventory is finally available.

Modelling machine breakdowns requires the introduction of the Failure Manager Agent (FMA), Figure 3. If the failure takes place whilst work is in progress without any damage caused to the part, the processing of the job will be resumed after the downtime period. However, in case of the work-in-progress being damaged, its JMA will remove the job from the machine and report back to the SMA and its life will be terminated. The cancelled job will re-enter the system and start its processing again and for that the SMA will generate a new job with a new due date to compensate for the time lost. Under pull production control a breakdown on a busy machine can only affect the zero due date replenishment jobs. A machine failure resulting in the damage of the replenishment job being processed would require the JMA to remove the affected (damaged) step of the job from the system and instigate the procedure for its replacement by a new part. In order to achieve its replacement, its JMA will simultaneously log a request for a processed part with the WOBA of all the stages in the job's process sequence preceding the stage where the breakdown occurred.

Rush orders arriving at the system unexpectedly carry a special "tag" indicating that they are high priority jobs. The functionality of the DA is modified slightly so that it initially checks whether there are any high priority jobs which it releases first before performing its prioritising functions. Under pull production control, high priority orders are filled from the available inventory immediately by treating the time of their arrival as their due date and thus as the time they need to be released to the customers. If there is no sufficient inventory to satisfy a high priority order, a request will be logged with the last WOBA in the job's sequence and will be satisfied once its inventory is replenished. A cancellation of order prior to the job's due date will result in the removal of this job from the system and the termination of the life of its JMA.

5.0 Experimentation Setting

The simulated job-shop comprises 10 machines and is processing 10 jobs with diverse process routings and number of steps between 8 and 18. The time between the arrival of jobs follows an exponential distribution with μ=0.6 hours. Processing times are generated using a uniform distribution with min=3 min and max= 10 min. The due dates are calculated using the Total Work Content Method and with the due date tightness coefficient set to 2. The dispatching rules considered are: First Come First Served (FCFS), Shortest Total Processing Time (STPT), Earliest Due Date (EDD) and Work Content in the Queue of the Next Operation (WINQ). In order to ensure the comparability of the output of the 8 simulation runs, three faults are introduced at time 5, 12 and 18 hours, with durations of 6, 4 and 5 minutes affecting the first, fifth and eighth workstation respectively. The probability damage is set to 100% for the case of workstations one and eight and 0% for workstation five. Two rush orders arrive at the system at time 10 and 15 hours and one order is cancelled at time 22 hours. The system's performance is evaluated in terms of Mean Flow Time, Mean Time in Queue, Mean Absolute Deviation (MAD) of Earliness/Tardiness, Number of Tardy Jobs and WIP.

6.0 Analysis of Simulation Output and Conclusion

In terms of the number of tardy jobs, the kanban-pull system performed better than the push system with the EDD dispatching rule producing the best results, Figure 4. However, in terms of the average number of jobs in the system at any time (WIP) the proposed kanban-pull system was significantly outperformed by the initial push system for all the dispatching rules considered and with the best of its performance observed under the WINQ rule, Figure 5. This is due the high levels of inventory maintained in the system to facilitate the operation of the kanban-pull system and achieve a satisfactory fill rate.

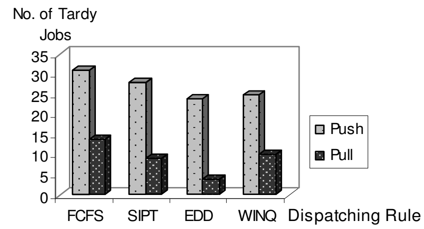

Fig. 4. Tardiness performance of push/pull systems

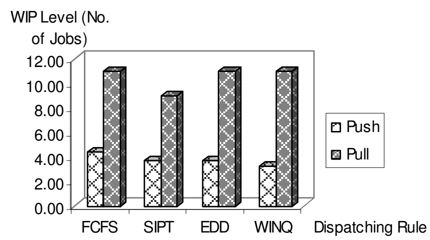

Fig. 5. WIP performance of push/pull systems

As illustrated in Figure 6, with regards to mean time in queue the best pull performance was observed under the WINQ rule whereas the EDD rule produced the least MAD of Earliness/Tardiness. Kanban-pull produced the same output in terms of mean flow time for all the dispatching rules and was outperformed by the push system which produced the best output when the WINQ rule was employed. The consistent performance of the kanban-pull system in terms of the mean flow time is attributed to the way the pull logic is implemented i.e. jobs in the available inventory are held until actual demand releases them from the system at their due date.

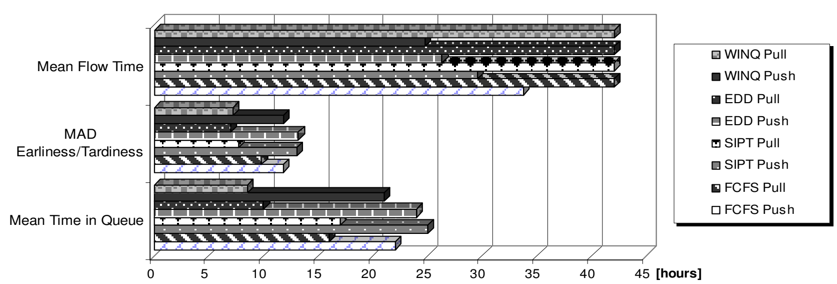

Fig. 6. Time-related performance of push/pull systems

Concluding, the employed agent-based simulation managed the complexity and stochastic nature of the scheduling system efficiently by offering high level representation and performing well in terms of computational time requirements.

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SAFETY CULTURE CHANGE IN A HIGH-RISK INDUSTRY

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Abstract

In a modern society, inside an organizational culture there is, or we are able to create a safety culture. However, in several cases safety culture is considered too static, not being able to adjust its action to the external and internal changes of a predominant business environment. Therefore, we need active and dynamic models in order to respond to the changes of an organization, and especially to the safety risks seen in the future. Furthermore, the ultimate goal for an organization is to successfully harness, organize and steer human beings toward the center of safety culture, and also toward an awareness of health, security and environment (HSE) within an organization. The current study derives from the lack of hands-on safety culture applications for managing this important organizational concept. The main purpose of the study is to find those safety performance drivers and characteristics, by which we are able to both understand and create a safety culture ontology in a long run. Secondly, the aim is to verify whether soft-computing is suitable technology in order to utilize constructed safety culture ontology in a dynamic business environment.

Keywords: Safety, Safety Culture, Ontology, High-risk industry, Soft-computing.

1.0 Introduction

Based on several safety reports, it is estimated that every year organizations confront approximately 1 million accidents, which converted into euros stands for 1.3-1.6 billion economic total costs to Finland [3]. Such economic figures illustrate that some organizations have faced severe deficiencies regarding safety programs. But have some organizations achieved higher safety level than others? Furthermore, is it possible that organizations that are lacking a distinct safety culture program are able to learn from the pioneers? Based on the study by Juha Miettinen [7], the question is how to improve a safety culture within an organization. According to that study, in order to reach affirmative safety figures, we have to enhance our safety programs. Already some eligible results have been gained through safety development processes, laws on industrial safety and training associated with an industrial safety card. However, study notes that there is still a lot to do, mainly because a safety culture is a fuzzy concept and developing organizational structures have its own effect.

An organization's safety culture is seen as a way based on values and attitudes to carry out safety matters in an organization. It is noteworthy that all the related subsystems can be measured. In a safety culture survey an organization tries to clarify values and basic assumptions, which have a great influence on improving safety in daily work. Furthermore, during development processes, engineers try to produce tools for management and personnel, by the means of which an organization gets its safety culture to a desired level. Since the benefits of technology in this field have not been entirely exploited, novel kinds of theoretical frameworks, methods and empirical testing are required to clarify the influences of the development work of information technology, as well as the exploitable possibilities to capture tacit knowledge (users). That is why this study thesis aims to improve an organization's ability to create, use and distribute new kind of knowledge in such a way that this knowledge would be effortlessly available from a safety culture viewpoint.

2.0 Cultural Approach

Organizational culture creates a basis for forming a safety culture. It consists of structures and contents, which must be explored through humane, strategic and technical dimensions. Specifically, the technical dimension has become one of the important factors among organizations operating in the nuclear, maritime and aviation industries. Although, organizations have paid a lot of attention to technical safety, the researcher wants to note that safety should be seen as a socio-technical matter, in which case also a social dimension has a significant role in fostering an organization’s safety performance. Therefore, it is essential also to bring alongside a humane approach, which attest that organizational culture is basically the personality of an organization. By means of assumptions, values, norms and tangible signs (artifacts), members of an organization will soon come to sense the particular culture of an organization. Furthermore, both understanding the culture, and being able to transform it are considered vital skills for management trying to achieve strategic outcomes. Therefore, first an organization must create a good organizational culture, after which it is able to base the same relationship to create a sub-culture, which focuses on safety.

2.1 Safety Culture

Safety culture is not merely a organization’s safety program, policies and procedures, but the incorporation of safety into the informal and formal parts of the organization. Therefore, safety must be integrated into every aspect of “the way of doing business”, requiring strong commitment from its leaders, as well as showing continuously that working in a safe manner and maintaining a safe workplace are truly the core values within an organization. According to Shaw [12], especially through strong leadership an organization is able to ensure that the necessary support and training are always available, that is creating effective communication, providing recognition, actively both gathering input and involving employees in decision-making, regularly touring the plant, and attending safety meetings. Above all, an organization’s safety culture must be seen as one of the boosters that gives appropriate priority to safety. Organizations have increasingly realized that safety must in the first place be managed just like other business areas. Still, this concept confuses a lot of people. They often use this concept without understanding the idea or the means of its possibilities. The safety culture and risks are often understood in a technical way, in which case it mystifies people. Thereby, many people are unaware of the safety culture’s human side. Safety culture includes all proper personnel attitudes and commitment to safety matters. This way, alongside with a technical approach, an organization is able to shape a good plan for a viable safety performance.

We are able to find from literature several different kinds of safety ontologies. However, the researcher wants to stress that the safety culture concept has about as much definitional precisions as a cloud, which are at the same time both fuzzy and incongruent which each other. Therefore, it is common that some concepts are normally lacking something that other concepts might have. Although, there are lots of safety cultural structures, the core for safety consists of following features [8]:

- *Culture dimension*
- *Human behavior dimension*
- *Management dimension*

Especially, when dissecting safety through a cultural dimension, it can be divided into four main features: organizational safety accountability, safety conscious work environment, organizational learning and work planning [13]. Nonetheless, we must observe that none of these ontologies are exactly dynamic and variable, but more static. Furthermore, they don't gather information in any form, but are only considered as specifiers, which are quite hard to exploit for organizations' purposes. In order to aggregate, the researcher wants to point out that safety culture ontologies are hard to operationalize, since forming these ontologies will stay on a conceptual level, rather than on a level based on magnitudes or meanings. Therefore, the researcher states a question: "*Since just awareness of a safety culture is considered inadequate, is it possible for an organization to operationalize and convert cultural precisions into dynamic intelligence, in which case readiness for change through a continuous process of change can be executed*?"

3.0 Measuring Safety Performance through Cultural Dimension

Organizations' actions can be developed in several ways. It is essential to recognize development areas, as well to observe how they are able to succeed. One way for finding paths between target areas and ways of action is to create a self-evaluation tool for an organization's purposes. [5] Organizational safety performance has been established on the foundation of "defense in depth". This creates a basis for an organization's safety philosophy, through which ensuring its safety performance is guaranteed. Furthermore, it enables a practical methodology for safety assurance, in which safety provisions are made in three completely different dimensions. The first level of safety addresses the prevention of accidents through the intrinsic design features of the physical working environment. The second level, correspondingly, aims at providing reliable protection through effective devices and systems. The third level of safety supplement the first two through features that add margins to the environment, as well as plant design to deal with events that are postulated to occur under extremely unlikely and foreseen circumstances. [11] To crystallize this notion, overall safety and its performance can be dissected through two different variables: attitudes, systems and environment. [10]

Still, it is not possible to graft a safety culture onto an organization, as each organization being unique, and the best safety systems failing without a supportive culture. Therefore, the researcher experiences that an organization must create such a method or a tool, through which it is able to measure attitudes, both personal and organizational, because of both crucially, affecting the development of a safety culture in a workplace. According to safety experts [10], the environment where people work and the systems and processes in an organization create a basis for a safety culture. Each organization needs to consider all of these aspects in developing and nurturing a safety culture that suits the organization and the individuals within it.

More and more organizations are trying to measure the intellectual capital, such as awareness of safety, and value of human beings in the area of conscious and knowledge. Currently the success of organization depends on how it is able to measure these two indicators in order to effect improvements. To do this, managers are anxious to find ways to measure the core competencies of their employees. Furthermore, there is a coercing need for organizations to learn to measure the influences of business and capital profit, as well as management continuity, customer relations and the company's influence on society itself.

While measuring know-how, there is no single all-purpose indicator that is adequate to accurately portray an organizations current and future level. The very nature of field work and action create an impact of how an organization will measure and determine its know-how level. A few comprehensive indicators can give a quick impression, but this can hardly be considered to be waterproof. Therefore, it is appropriate that a wide array of indicators are used simultaneously in order to get more precise and deeper knowledge giving picture of an organization's entire business environment.

Indicators based on intellectual capital measure competencies of both the organization's and its employees' capabilities. According to Rylatt [9], due to the fact that culture cannot be managed, nor owned, researchers have engaged in extensive debate on whether culture should be experienced as capital. Nonetheless, several reports claim that staff's attitudes and presumptions regarding an organization and its customers deserve particular attention. Many spokesmen feel that a so-called weak culture has a crushing impact on knowhow and innovation in any team or business concept. Rylatt [9] shares this opinion, and remarks that in such situations everything gets more difficult in an organization. It is little wonder he experiences that culture should be considered as measurable intellectual capital.

Safety has traditionally been measured through statistics associated with accidents, disasters and injuries albeit subsequent to the incident. However, currently in addition to measuring external observable factors, organizations have created indicators, which share a purpose of measuring internal, psychological factors as well. In such kind of measurement organizations are first and foremost interested in reconciling employees' attitudes, skills and knowledge. Based on these results, the purpose is to construct methods, by which organizations pursue changes relating to attitudes and tacit expectations. The figure below illustrates the measurable factors of a safety culture. [2]

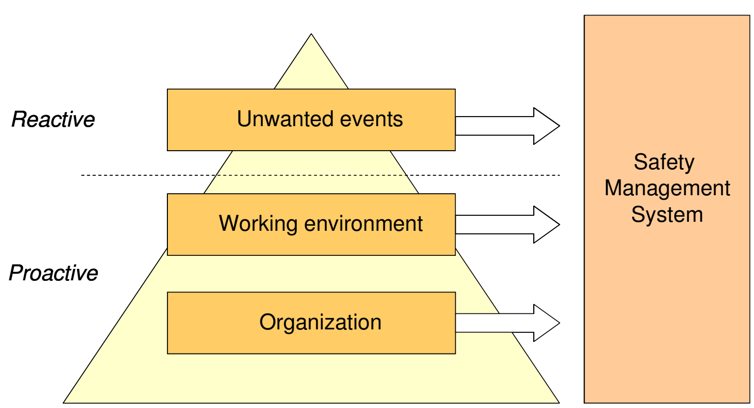

Fig. 1. The Measurement of Safety Performance [2]

Unfortunately many indicators merely measure factors based on external characteristics, a tendency which is common with reactive organizations. Although, the results of quantitative indicators are easy to follow, there is a possibility that while following statistics that represent accidents that have already occurred, an organization will never achieve a proactive stage. The common assumption is that statistical data from every adverse incident can be used to improve safety performance, but this means that an organization does not focus on factors which relate to avoidable incidents.

Henttonen [2] stresses that it is inadequate to evaluate organizational safety only by the means of aberrations, because such factors are considered flawed in characterizing the true stage of organizational safety. Therefore, an organization must use qualitative indicators along with quantitative ones. There is indeed a clear goal to shift from reactive measuring to proactive measuring, in which case along with measuring undesired events an organization must create indicators that are capable of measuring both the working environment and the organization itself. [2, 8] To simplify, Henttonen [2] has outlined safety measurement into four different segments as follows:

- *Technical systems*
- *Safety culture*
- *Management systems and courses of action*
- *Undesired events*

Every organization must choose applicable indicators based on its own needs. Measuring safety related to technical systems can be carried out through risk management, malfunctions and usability. Safety culture, on the other hand, accentuates both measuring both attitudes and an organization’s climate. By measuring the amount of training, audits and safety initiatives, an organization is able modify its management systems and plan courses of further action. Correspondingly, measuring undesired events is a backward looking evaluation associated with aberrations and dangerous situations. Due to this, Henttonen [2] indeed emphasizes that while fostering organizational safety, it is inappropriate to just react to aberrations. He notes that to improve management systems it is more rewarding to foresee aberrations and risks.

4.0 Results

The purpose of the current study was as two-fold: Firstly, to accentuate the driving forces and competences behind a safety culture that management must observe in order to create a strong safety culture. Secondly, to create a novel kind of support system in order to facilitate management’s tasks in their decision-making processes. In current study the researcher has given rise to results of creating, elaborating and piloting a safety-based evaluation system, the Bicorn Co-Evolute System, such that an organization’s management has an effective and proactive tool in order to improve learning and knowledge creation processes. This decision methodological research aims at modeling system called Bicorn. This application prototype focuses on creating, exploring and developing a knowledge-intensive safety culture for the nuclear power sector. Additionally, the existing computer applications have been adapted to be applicable to safety concepts in general in industry.

Bicorn is intended to operate as an indicator, a supportive tool to give weak signals for managers to their decision-making processes. The researcher tried to gather specific information relating to literary reviews of safety cultures. This database, containing approximately 119 statements is used to evaluate an organization's state of the environment including both learning and the knowledge creation of safety culture. The Bicorn-application has three different levels: *a practical level, a system level* and *a meta-level*. Features, which are presented in table 6 cover the organization's internal and external targets for development and charts of improvements. According to Vanharanta [14], this kind of methodology allows an individual's own evaluation to focus on safety-related issues. The researcher notes that by involving the whole organization in a collective effort to be aware of a comprehensive safety culture, it gives a throughout perception of the organization's goals. Thereby, by focusing on safety-related development throughout the organization, it can enhance its core competences and turn safety activities into a competitive advantage, i.e. added value process.

Following the evaluation of 119 statements, the Bicorn-application's goal is to convert a practical bottom-up view of different classification to the meta-level. The following table (Table 1) illustrates the content of a viable safety culture, which enable the responsive environment for both learning and knowledge creation processes of safety culture. Furthermore, Table 2 illustrates the system level ontology, which embodies those systems, which are considered to be vital in the pursuit of developing an organization's environment toward a more responsive safety culture.

Table 1: The Created Safety Culture Ontology

Features	Categories	Constructs
Industrial safety level, Sense of responsibility, Demands for safety circumstances	Combination of safety issues	Culture based safety dimension
Demand level for industrial safety, Efficiency related to safety functions	Awareness of big picture of safety culture	
Prowess, Consciousness	Consciousness and development of individual	Behaviour based safety dimension
Openness to new ideas and education, education	Support to new ideas and education based on safety issues	
Co-operation, Working environment, Leadership	Improving safety with the help of socialization	
Creation of new knowledge and experience, Learning and understanding by doing	Internalization referring to new knowledge and experience of safety issues	Management & leadership based safety dimension
Flow of information, Safety codes	Externalization of the safety regulations	

Table 2: System Level Ontology

Maintaining Systems	Maintaining System's Feature
Control Systems (Command – Control, cf. Samuelson)	Leadership, Human Resource Management, Management of Technical Issues, Business Management, Conversation Management, Knowledge Management, Fluctuation and Creative Chaos, Commitment, Measuring and Evaluation
Working Systems (Operation – Production, cf. Samuelson)	Autonomy, Team Work, Rotation of Personnel, Mentoring, Continuous Improvement (Kaizen)
Information Systems (Information–Communication, cf. Samuelson)	Redundancy, Requisite Variety, Human Capital, Intellectual Assets, Dissemination of Local Knowledge, Knowledge Channels, Knowledge Activists
Support Systems (Maintenance – Support, cf. Samuelson)	Organizational Culture, Dimensions of Care, Systems of Incentives, Human Resources Development Policy, Tools Supporting Learning

This kind of analysis has been made through the use of fuzzy sets. Fuzzy logic is a subset of conventional (Boolean) logic that has been extended to handle the concept of partial truth - truth values between completely true" and "completely false" [6]. Generally speaking, the principles guiding of fuzzy logic as follows: a set of input data from an array of sensors are fed into the control system, after which the values undergo a process termed as "fuzzification", which converts the discrete values into a range of more specific values. Fuzzified inputs are evaluated against a set of production rules. Whichever production rules are selected will generate a set of outputs. Output data is "defuzzified" as distinctive control commands. [1]

With the help of Figure 2, we will show how the individuals saw the system's features from system report.

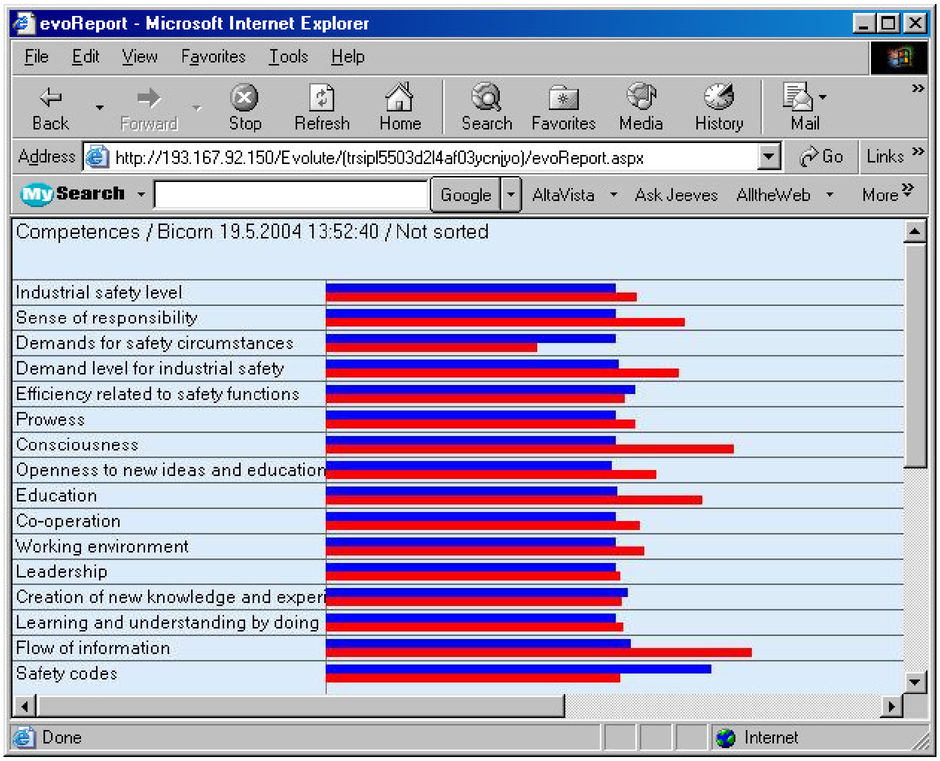

Fig. 2. Competences Indicated by Bicorn-Application.

As Figure 2 illustrates, the system exhibits two different results. The first one, the darker element, represents current state, and the second, the lighter one, represents the desired level. The difference between these two is considered to represent the development potential (cf. creative tension). By means of these 119 statements and four maintaining systems we have been able to describe an organization's state as a responsive environment for learning and knowledge creation. Also this meta-classification facilitates the decision-making processes of organization's management to cope with a turbulent environment, while at the same time getting specific information from a systematic and value-added viewpoint. There is evidence that suggest that by systematically and continuously testing individuals within an organization, it enables a process of change and an awareness of possible problem areas.

Bicorn has so far only been tested in one organization. The first test was conducted by students as a laboratory case at Tampere University of Technology's Pori Unit in Finland. This laboratory test was organized with students analyzing an organization's safety culture. The second test, which will hopefully give the true indicators, will be carried out in near future. The researcher's purpose is to gather some real-world cases. The first test results have been positive, in that they have shown that Bicorn has the potential of giving organizations several indicated competences concerning the development of a responsive environment for learning and knowledge-creating safety culture.

This application was first tested in cooperation with our data base administrator concerned with verifying the technical functionality and validity of Bicorn. The results were effective and showed themselves to be reliable in accordance with Cronbach's alfa value. According to Jussi Kantola [4] alpha's coefficient values vary from zero to one. He remarks that a value closer to zero indicates a greater diversity of values. The diversity indicates a more random range of statements, whereas the closer the value is to one the more consistent are the statements. According to recent studies, values between 0.6 and 0.80 represent values, which indicate a high degree of convergence toward statements. The alphas have been calculated within every application of the Evolute-platform, and they all fall between the recommended guidelines.

However, the researcher questions whether an alpha value is a sufficient measure in validating the statements of a larger perspective. Furthermore, is it enough to assess an organization's safety culture only through the alpha value, or do we need a more meaningful tools to analyze the validity of statements? However, in the absence of other tools for validation and for the purposes of this thesis, we have to rely on the alpha value theory. After verifying functionality and validity, we formed a test group of 8 individuals. The results were extremely clear and showed no need to remold the Bicorn-application. However, with the test group's size being so small, the results can only give a directional sense and therefore cannot be interpreted too literally**.**

Based on the first test results, we are extremely pleased to discover that this application can be used as a common tool for management to evaluate an organization's capability to learn and create safety knowledge. These results give us the possibility to identify the important characteristics, properties and creative tensions, which can lead to the successful planning and improvement of safety culture in high-risk industries. Furthermore, this evaluation system is considered to be a consultative application, by which an organization is able to develop a more responsive environment for learning and creating information related to a viable safety culture. However, this kind of experiment or research requires a larger scale, scope and diversity of organizations to be examined. Therefore, our inclination is toward developing this application in co-ordination with case-companies. We also hope that someday we will have the possibility to incorporate neural nets (Self-Organizing Maps/SOM) into analysis in order to facilitate management's resources for allocating targets for development. The early results based on SOM have indicated that by using these methods, we are able to structure, analyze and visualize large amounts of multidimensional data, regarding the responsive environment from a safety culture viewpoint.

5.0 Discussion and Conclusion

In recent years organizations have witnessed a growing concern over the issue of a safety culture within the nuclear power industry and other complexes, and high-risk industries. Many reports claim that a safety culture must be static, pervasive, understood and practiced throughout an organization by its members. Furthermore, we are able to confirm that it should be considered to be a continuous process. Both organizational learning and systems thinking have recently been linked with an ordered safety culture to enable to model, analyze and engineer just like physically complex systems. Through these models, organizations are able to utilize improvements in both risk management and evaluation processes, which can lead to important competitive advantages. Additionally, there has also been in recent years a tendency towards an effective management process in order to control and prevent risks associated with health and safety in an organization's environment. However, many organizations have also noticed that there are some limits to what can be achieved simply through hardware and technology. Therefore, from an organization's point of view, there is a proactive vision to create a supportive and responsive organizational culture through information technology for people working for the benefit of organizational success.

According to this discipline, the advantages brought by the technology have not been implemented properly. Therefore, novel kinds of theoretical frameworks, methods and empirical testing are required to clarify the influences of the development of information technology and the exploitable possibilities to capture tacit knowledge (users). The researcher has highlighted a new methodology to utilize existing theories in order to better understand the interaction between humans, technology and culture. The ultimate goal is to reconcile that everything must both be in harmony and in active development such that security is optimized and security-related concerns are minimized. Thereby, we can create a safer future.

The study is in most part considered to be theoretical and therefore a new safety culture framework has been created. The reason for opting for a literature based approach, was the researcher's ambition to get a clear picture regarding dimensions of a safety culture, as well as to see from the literature the new possibilities to create a framework where the new technology can play an important role.

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APPLICATION OF THE DELAY-TIME CONCEPT IN A MANUFACTURING INDUSTRY

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Abstract

This paper has been written to give a methodology of applying delay-time analysis (DTA) to a maintenance and inspection department. The aim of this paper is to give a brief overview of DTA together with its uses as a tool to achieve cost effective inspection maintenance. This is achieved by reducing downtime of plant items or reducing maintenance and inspection costs by removing unnecessary inspections. A case study of a company producing carbon black has been included to demonstrate the proposed methodology.

Keywords: Maintenance, Inspection maintenance, Delay-time analysis.

1.0 Introduction to Delay-time Analysis Concept

Delay-Time Analysis (DTA) is a concept whereby the time h between an initial telltale sign of failure u and the time to actual failure can be modelled in order to establish a maintenance strategy. Delay-time is the period of time when inspection or maintenance could be carried out in order to avoid total failure. Figure 1 illustrates the delay-time concept (Christer and Waller (1984)).

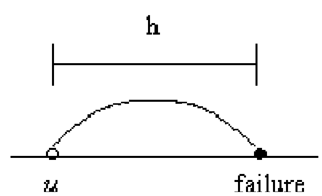

Fig. 1. The delay-time concept

2.0 Methodology

In order to develop a maintenance model using delay-time analysis a methodology needs to be developed in order to give the process a framework. Delay-time analysis can be used as a tool for reducing the downtime, $D(T)$ (Christer et al. (1995)) of a machine or a piece of equipment based on an inspection period T, given the probability of a defect arising within this time frame $b(T)$. For a particular plant item, component or series of machines, delay-time analysis is useful because the equipment in question is generally high volume and high capital expense, therefore any reduction in downtime due to breakdown or over inspection can be beneficial. As with the modelling of downtime per unit time, it is also possible to establish a cost model, *C(T)* (Leung and Kit-leung (1996)), again based on an inspection period *T* and probability *b(T)*, this model estimates the expected cost per unit time of maintenance. This modelling has also been used for safety criticality (Pillay and Wang (2003)) on a fishing vessel giving safety criticality of a failure and operational safety criticality.

A methodology for applying delay-time analysis is proposed as follows:

- Understand the process.
- Identify the problems.
- Establish data required.
- Gather data.
- Establish parameters.
- Validation of the delay-times and the distribution.
- Establish assumptions.
- Establish a downtime model D(T) and cost model C(T).

When the probability distribution function of a delay-time *f(h)* follows an exponential distribution, i.e. when the failure rate λ or 1/MTBF is constant over a specified time period, the distribution function, as shown in equation (1), is used to calculate the probability of a defect arising *b(T)*:

$$f(h) = \lambda e^{-\lambda h} \tag{1}$$

The probability of a defect leading to a breakdown failure *b*(*T*) can be expressed as follows in equation (2).

$$b(T) = \int_0^T \left(\frac{T-h}{T} \right) f(h) dh \tag{2}$$

Combining the distribution function *f(h)* into the breakdown failure probability *b(T)* this gives:

$$b(T) = \int_0^T \left(\frac{T-h}{T} \right) \lambda e^{-\lambda h} dh \tag{3}$$

This term can be further simplified as:

$$b(T) = \frac{1}{T} \int_0^T (T-h) \lambda e^{-\lambda h} dh \tag{4}$$

It is important to note that *b(T)* is independent of the arrival rate of a defect per unit time (k_f) but it is dependant on the delay-time *h*.

2.1 Downtime Model D(T)

It has been demonstrated (Leung and Kit-leung (1996)), (Pillay et al. (2001)) that with establishing a probability for breakdown failure *b(T)* it is also possible to establish an expected downtime per unit time function *D(T)* as shown in equation (5).

$$D(T) = \left\{ \frac{d + k_f T b(T) d_b}{T + d} \right\} \tag{5}$$

where;

d	= Downtime due to inspection.
k_f	= Arrival rate of defects per unit time.
$b(T)$	= Probability of a defect arising.
d_b	= Average downtime for a breakdown repair.
T	= Inspection period.

Substituting *b(T)* from equation (4) into equation (5) gives:

$$D(T) = \left\{ \frac{d + k_f T \left[\frac{1}{T} \int_0^T (T-h)\lambda e^{-\lambda h} dh \right] d_b}{T + d} \right\} \tag{6}$$

2.2 Cost Model C(T)

Similarly, given the cost of inspection $Cost_i$, the cost of a breakdown C_B and the cost of inspection repair C_{IR}, the expected cost per unit time of maintenance of the equipment with an inspection of period *T* is *C(T)*, giving the equation:

$$C(T) = \frac{\lfloor k_f T \{ Cost_B b(T) + Cost_{IR} [1 - b(T)] \} + Cost_i \rfloor}{(T + d)} \tag{7}$$

where;

$C(T)$ = The expected cost per unit time of maintaining the equipment on an inspection schedule of period of time *T*.
$Cost_B$ = Breakdown repair cost.
$Cost_{IR}$ = Inspection repair cost.
$Cost_i$ = Inspection cost.

The cost of an inspection is shown in equation (8).

$$Cost_i = (Cost_{ip} + Cost_d)\ T_{insp} \tag{8}$$

where;

$Cost_{ip}$ = Cost of inspection personnel per hour.
$Cost_d$ = Cost of downtime per hour.
T_{insp} = Time taken to inspect.

The cost of a breakdown is calculated as the cost of the failure plus the costs of corrective action to bring the equipment back to a working condition. The details of a breakdown repair are shown in equation (9).

$$Cost_B = (M_{staff} + Cost_d)\ (T_{insp} + T_{repair}) + S_p + S_e \tag{9}$$

where;

M_{staff} = Maintenance staff cost per hour.
T_{repair} = Time taken to repair.
S_p = Spares and replacement parts cost.
S_e = Special equipment / personnel / hire costs.

The cost of an inspection repair is somewhat identical to the breakdown repair cost apart from the following:

- Inspection repair will not generally have equipment hire costs (S_e).
- The time to repair will be of shorter duration for inspection repair.

The time for an inspection repair having a shorter duration is mainly due to a breakdown having a greater knock-on effect. The equation for inspection repair is shown in equation (10).

$$Cost_{IR} = (M_{staff} + Cost_d)\ (T_{insp} + T_{repair}) + S_p \tag{10}$$

A point to note regarding the cost model C(T) (equation 7) is that it describes a worst case scenario. This worst case scenario is a fault leading to failure before an inspection takes place or a fault being detected at inspection. Conversely, a best case scenario would be no failure taking place before inspection and no fault being present at inspection.

3.0 Case Study

In order to demonstrate the above models for downtime D(T) and cost C(T) a case study of a factory producing carbon black in the UK is given.

This particular process of creating carbon black is made up of three units A, C & D. The three units cover the whole process stream from the reactor, MUF (Main Unit Filter) which collects & separates the product from the gasses produced and conveying of the carbon black into storage containers. A low pressure air and natural gas produce a flame of high temperature (1500 degrees centigrade) in the combustion zone of the reactor.

Heavy oil, which is known as feedstock, is sprayed into the flame and the carbon black reaction occurs. After the feedstock is exposed to the high temperature it is quenched with water in order to stop the carbon black formation reaction. At this point the basic form of carbon black is formed, carbon black powder. The filter is a bag type filter measuring approximately 10cm in diameter and 2.5m in length. The cost of a filter is around £28 each with a life expectancy of three to four years. There is a second manufacturer of the filter that has a cost of around £7.50 but it has a life expectancy of between 12 to 14 months with a lower tolerance to acid than the more expensive filter.

3.1 Costs of a Failure

When a filter bag is to be changed the compartment has to be closed down. This requires 8 hours of cool down followed by a period of 6 and 24 hours downtime for repair and replacement then a further 2 hours to warm the unit back up, if a total re-bag is required downtime is generally around 7 days. When a unit is brought off-line it continues to burn gasses in order to keep the temperature in the reactor constant thus wasting energy. Also the system allows any energy created can be used by the facility and any surplus energy is sold back to the national grid, therefore any downtime can be costly in respect of not just wasting energy but also potential income from surplus energy. Sometimes specialist maintenance crews need to be brought in to deal with the problem. A typical example of a breakdown which took 7 days to repair and replace all bags is demonstrated below.

- Loss of production per hour: £1,500
- Burn of gasses per hour: £238
- Loss of export of energy per hour: £26
- Cost of maintenance personnel per hour: £28
- Cost of supervisor per hour: £36
- Cost of replacement filters (205): £40,180
- Jetting crew: £710
- Jetter hire: £300
- Cherry picker hire: £2,500

This gives a total cost for a breakdown resulting in 1,435 filters being replaced effecting 1 MUF for a period of 7 days to be £350,794.

3.2 Establishing a Delay-time Analysis

In order to establish a delay-time analysis for this example several parameters need to be known. The parameters used in this example are as follows:

- The arrival rate of a defect, k_f - 0.28 per day.
- Mean time between failure (MTBF) - 3 years.
- Downtime for an inspection, d - 0.1 days.
- Downtime for breakdown repair, d_b - 7 days.

- Breakdown repair cost, $Cost_B$ - £350,974.
- Inspection repair cost, $Cost_{IR}$ - £5,000.
- Inspection cost, $Cost_i$ - £67.

Applying the parameters to equation (6) it is possible to establish an inspection interval where a minimum downtime is of primary concern as illustrated in figure 2.

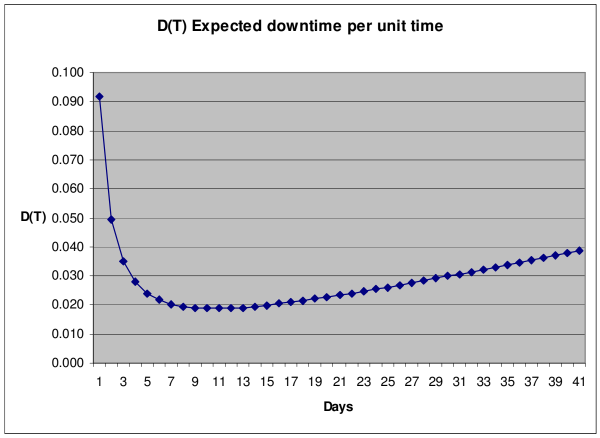

Fig. 2. Optimal inspection period based on minimum downtime D(T).

As illustrated in figure 2 the minimum inspection interval based on minimum downtime D(T) is 14 days. When the cost C(T) is of primary concern the optimum inspection interval is 11 days with a cost of £940 as shown in figure 3. If the inspection interval was moved to 14 days in line with minimum downtime the cost would rise to £977 which is a nominal increase of £37.

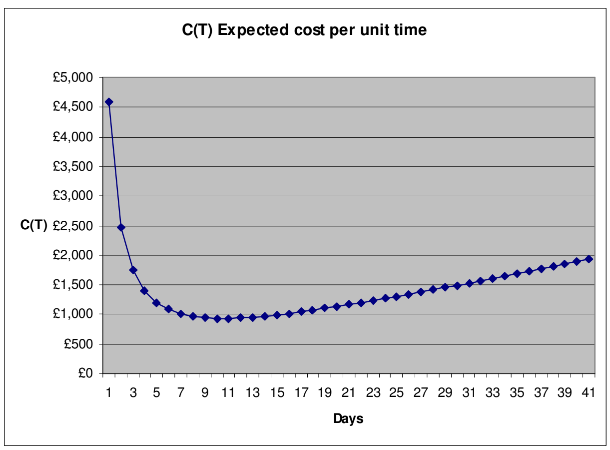

Fig. 3. Optimal inspection period based on minimum cost C(T).

4.0 Validation

In order to analyse the effect of change to the results of D(T) and C(T) a sensitivity analysis was carried out on each model. The analysis varied certain input data by 5% and 10% resulting in the following.

4.1 Validation of D(T)

The optimal inspection interval remains very close to the original interval given an increase and decrease of 5% and 10%. The sensitivity analysis for D(T) is shown graphically in figure 4.

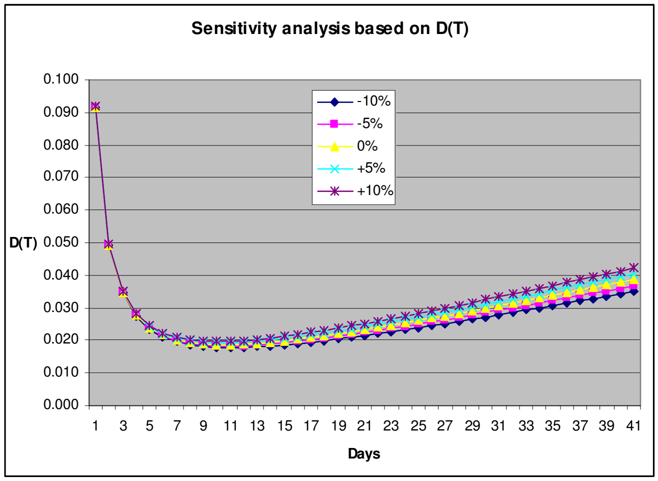

Fig. 4. A graphical representation of the sensitivity analysis.

4.2 Validation of C(T)

A sensitivity analysis was carried out on the cost of an inspection repair and the cost of an inspection in order to analyse the effect of a change in the costs. The cost of an inspection repair and an inspection has been increased and decreased by 5% and 10%. The sensitivity analysis is shown graphically in figure 5. The optimal inspection interval remains very close to the original interval given an increase and decrease of 5% and 10%.

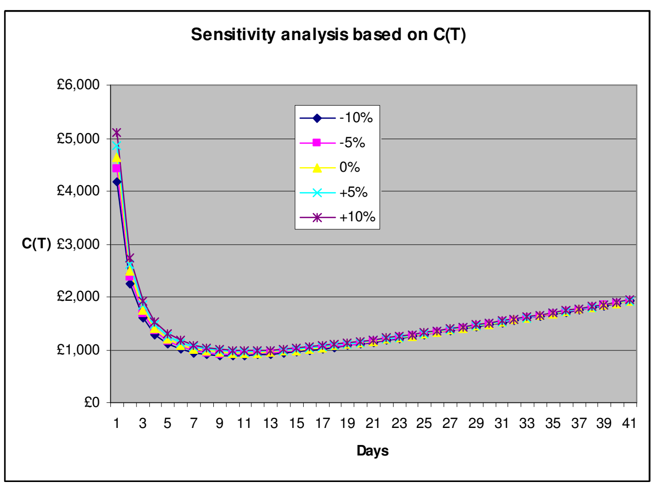

Fig. 5. A graphical representation of the sensitivity analysis.

5.0 Discussion

It has been demonstrated in this case study that an optimal inspection interval taking into account a minimum downtime D(T) of 14 days has been established using the delay-time analysis technique. Using minimum cost C(T) as the criteria an inspection interval of 11 days with a cost of £940 was calculated.

Current practice at the company is that of a weekly inspection interval involving a flame check and a cloth check. It can be argued that this inspection interval could move to an interval of weeks but given the nature of the two inspection checks and the fact that it does not stop production, a weekly inspection interval appears reasonable.

6.0 Conclusion

This case study looked at a company in the UK producing carbon black. This paper demonstrates the delay-time concept for the use of minimising downtime and costs, setting inspection intervals to achieve this. Information was gathered from historical data as well as expert judgement, with parameters established from this information in order to develop the delay-time models.

Acknowledgements

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MODEL BASED DESIGN OF ECONOMY OF SCOPE AND SCALE PRODUCTION SYSTEMS

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Abstract

Increasingly often enterprises are required to realise economies of scope production, i.e. be capable of efficient re-programming & reconfiguration to realise multiple value streams with a common set of resources. Key business models used in the furniture industry are explicitly documented using an ISO Enterprise Modelling (EM) technique. This has enabled an analysis of impacts of product dynamics to be observed in the furniture industry and has informed the development of a specific case EM which documents the business processes of a particular company making 'fixed furniture'. Also explained is how the specific case EM was used to helped stucture the design of number of 'context dependent Simulation Models (SMs)'. These SMs can be reused on an ongoing basis to inform 'process', 'resource' and 'product' aspects of production systems design. In this way business benefits arising from alternative configurations of production systems can be predicted. This developed modelling approach has enabled the relative performance (in terms of value generation, process costs & lead times) of economy of scope and scale production systems to be compared with counterpart systems capable only of economy of scale production. The modelling methods and concepts described promise model driven means of coping with possible future impacts of product variance and product volume variation, leading to production system designs capable of efficient mass customisation of products.

Keywords: Product dynamics, Economy of scope, Economy of scale, Enterprise modeling, Simulation modeling and Production systems design

1.0 Introduction and Product Dynamic

Manufacturing Enterprises (MEs) are complex and change continuously [1, 2]. Therefore responding rapidly and cost effectively are key features to survival and remaining successful in any business environment. Four types of Product Dynamics have been classified by Cui & Weston [3], namely: ***product (class, type and feature) variances***; ***production volume variations***; ***product mix variances*** and ***new product introduction***. This paper describes a new approach to using integrated modelling techniques to create re-usable models of production systems and to subject these systems in a virtual environment to impacts arising from product dynamics. Thereby candidate production system designs can be computer executed and design decisions made rapidly and effective to reduce lead-time and minimize investment risks.

2.0 State-of-the-Art manufacturing Philosophy and Research Assumptions Made

According to Ben Wang, there are two aspects of responsiveness: 1) reducing the manufacturing cycle to meet the market demands; 2) shortening the product development cycle to meet the market opportunities [1]. GT is a manufacturing philosophy which advocates simplification and standardization of similar entities which include (parts, assemblies, process plans, tools and instructions). The underlying idea of GT is to take advantage of similarities that exist among items to increase effectiveness during production [5]. Grouping allows similar, recurring activities to be conducted more efficiently, like part family scheduling. Here a *part family* is all parts in a family that require similar treatment and handling methods. Efficiencies are achieved by processing the parts together, so that productivity can be increased by reducing set-up times, realising benefits of part family scheduling, achieving improved process control and by using standardized process plans [6, 7]. RMS is a manufacturing philosophy centred on being cost-effective and responsive [2]. This is because the machines in RMS are designed with an adjustable structure to enable the system to be scalable in response to market demands. RMS principles seek to combine the high throughput of Dedicate Manufacturing Lines with the flexibility of Flexible Manufacturing Systems. There are some outstanding advantages which can benefit industry: 1) the adjustability of RMS machines allows flexibility not only in producing the variance of parts, but also the reconfiguration of the system itself. 2) The customized flexibility of RMS can lead to faster throughput and higher production rate [2, 8]. Figure 1 was constructed by the authors to characterize ***economy of scope production systems***. This shows three cases of production system configuration. Case 1 is not considered to realise economies of scope, because it can only deal with one product 'type' within a 'class'. The terms 'type and 'class' are defined by Figure 2. It follows that if significant production volume variation occurs in a single product Case 1 system then the economy of that system may come into question. However if the volumes are sufficiently high then economies of scale can be realised by Case 1 systems.

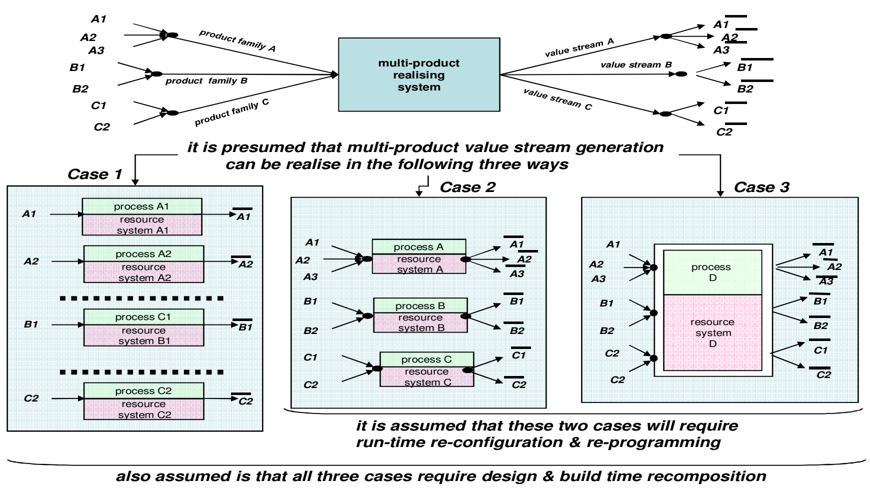

Fig. 1. Possible alternative configurations of multi-product realization systems and related 'flexibility' assumptions to be tested

Case 2 systems can realise both economies of scope and scale because they can realise more than one value stream associated with a number of product types within a class (or product family). The notion of economy of scope comes from the fact that if production volumes fall for one product type within its scope it may be possible to compensate by an increased volume requirement for another within the systems' scope . Naturally for this reason Case 3 production systems have the greatest scope and therefore have the greatest potential (in theory) to realise economies of scope. Figure 2 illustrated possible impacts on production systems design arising from product dynamics.

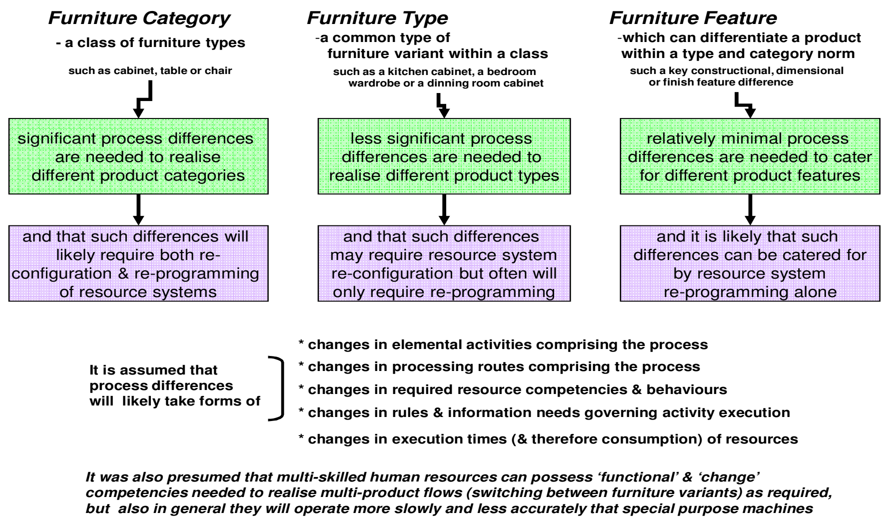

Fig. 2. Assumptions about causal links between product and process change to be tested

3.0 Choice of Case Studies Company and Enterprise Modeling

The furniture industry was chosen as a subject of study, for which three prime business models are in use namely 'Fixed furniture' production; 'Flat Pack furniture' assembly and 'Custom furniture' fitting. Figure 3 was constructed to illustrate some of the purposes, common features and a common products produced by this industry and indicates the predominant business models use to realise them.

Figure 4 shows examples of two of a total of seven graphical modelling templates that were populated with generic furniture industry information so as to create a part of a 'Generic EM' covering all three furniture industry BMs. Subsequently this model informed aspects of 'product variance' in that industry and established an explicit link to 'production systems design'. The EM was modeled using standard CIMOSA modelling constructs [9].The generic 'context diagram' shown in Figure 4 illustrates how six generic actors work collaboratively to realize furniture; while the 'interaction diagram' in Figure 4 shows how material, products and information and money are transferred between domain processes (DPs) and domains (DMs When modelling it was observed that distinctive 'structure diagrams' needed to be constructed for each BM type. The project report details how for each BM the various DPs were decomposed into CIMOSA conformant Business Processes (BPs) and Enterprise Activities (EAs). By studying these structure diagrams it was possible to gain explicit understandings of the business context of working and to derive context depended information about the general sequential ordering of BPs and EAs belonging to each DP.

Area of Home	Common Features	Common Products	Applicable Business Models
kitchen	* standard 'spaces' (can standardise most furniture dimensions) * standard 'people ergonomics' (can standardise many furniture features) * functionality then aesthetics (in most kitchen furniture) * reliability & safety key	* cabinets * tables * chairs * work tops	* flat pack (main) * fixed (main) * custom (minor)
bedroom	* non-standard 'spaces' (exceptionally can standardise dimensions) * standard 'people ergonomics' * BOTH aesthetics & functionality	* wardrobes * dressing tables * beds * chairs	* flat pack (minor) * fixed (main) * custom (main)
dining room	* non-standard 'spaces' (exceptionally can standardise dimensions) * standard 'people ergonomics' * mainly aesthetics then functionality	* cabinets * tables * chairs	* flat pack (minor) * fixed (main) * custom (minor)
lounge	* non-standard 'spaces' (exceptionally can standardise dimensions) * standard 'people ergonomics' * mainly aesthetics then functionality	* occasional tables * sofas * chairs * book cases	* flat pack minor) * fixed (main) * custom (minor)
office (at home)	* non-standard 'spaces' (exceptionally can standardise dimensions) * standard 'people ergonomics' * functionality & ergonomics important	* computer desks * tables * chairs * shelving	* flat pack (fairly minor) * fixed (main) * custom (minor)

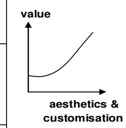

Fig. 3. 'Drivers' for product dynamics

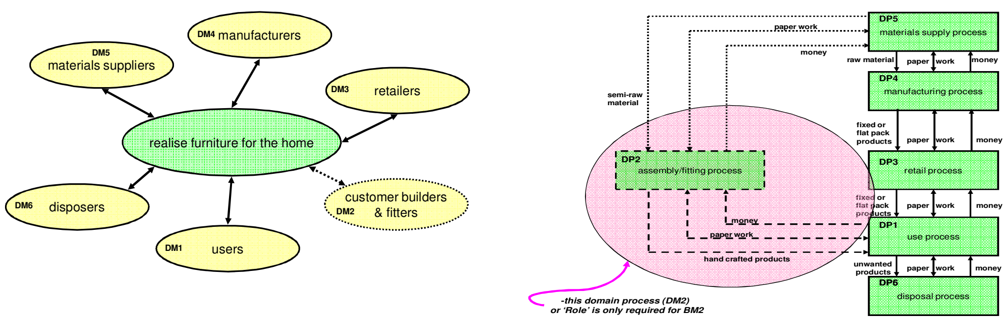

Fig. 4. Generic Enterprise Models (CIMOSA-context and interaction diagram) for the Furniture Industry

4.0 Integrated Enterprise and Simulation Modelling in Fix Furniture Assembly Section

A detailed study was made of the sequence of operations used to assemble Farm House and Drop Leaf table products. Those sequence part of BP71-2 Assemble Carcasses & Fit Component', which is realized by the assembly section of a 'fixed furniture' Case Study Company. These types of table product are two of a total of 18 product types produced by the Case Company. BP71-2 was decomposed into 4 EAs, which are illustrated in Figure 5. Each of these EAs was studied in detail to develop groundwork knowledge needed to create SM1 which related to Farm House table assembly. Here detailed studied centred on processing activities and routes, and on needed human and other resources to realise each EA, and on possible activity grouping into 'roles' that can be assigned to Work Centers (WCs) incorporated into SM1. In the case of SM1, enterprise activity EA 7.1.2.1 is executed by WC1 Collect component; EA 7.1.2.2 is executed by WC2; EA 7.1.2.3 is executed by WC3; and finally EA7.1.2.4 is executed by WC4. Following the same method, the assembly process of Drop Leaf tables was modeled based on the capture of specific company information; the aim here was to use the same modeling approach to create SM2, which is illustrated by figure 6. Both SM1 and SM2 are economy of scale systems.

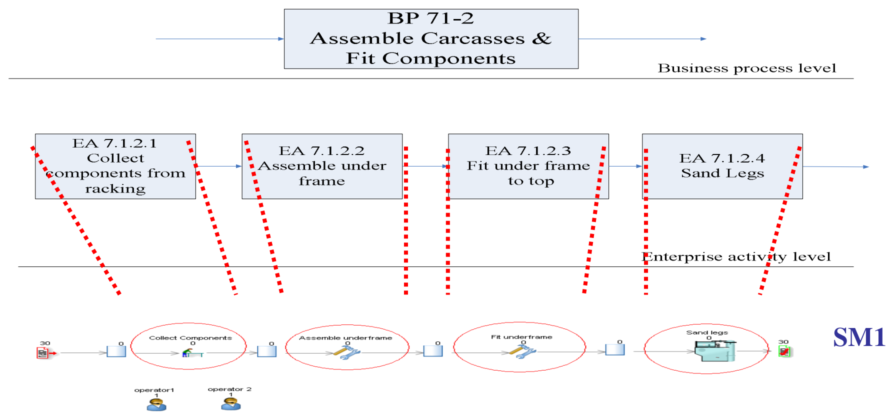

Fig. 5. Farm House table assembly processes simulation model

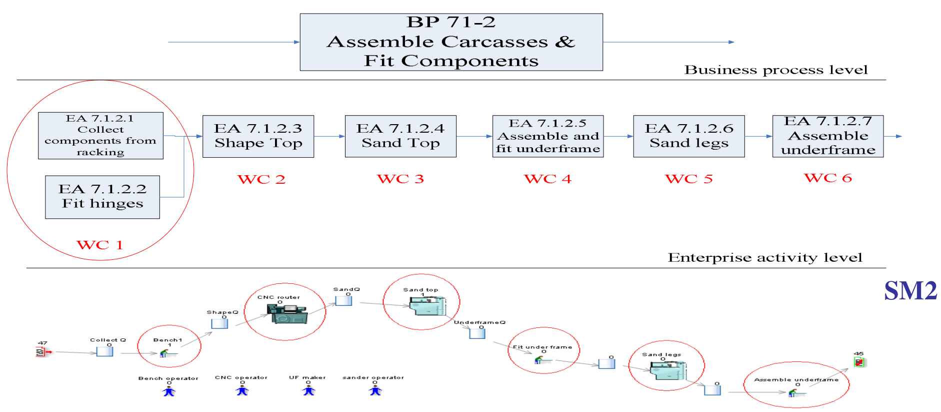

Fig. 6. Drop Leaf table assembly processes simulation model

The next production system studied was a possible future configuration able to realize dual economies of scope and scale. Farm House and Drop Leaf tables are fed into the same simulated production system, modeled by SM3; such that they share one assembly process with the same set of work centers that are resourced by common underlying human and technical systems. The screen shot of SM3 is shown in Figure 7.

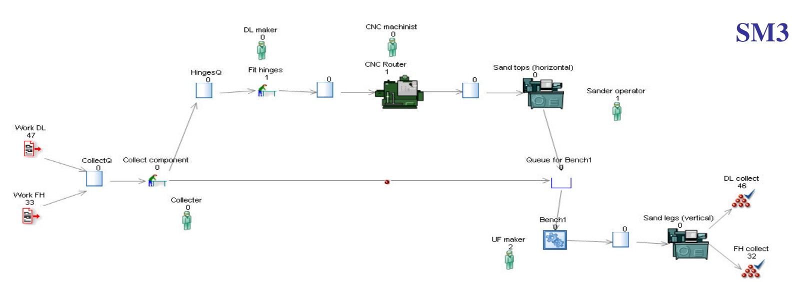

Fig. 7. Economy of Scope configuration of multi-product model

When comparing the simulation results of the single and multi-product assembly systems, it was decided that there are three main performance measures that should be taken into account. Choice here was made bearing in mind the general aims and objectives of the authors, namely to assess: 1) Lead time spending in each model; 2) Utilization of machines and human resources; 3) Revenue and Cost comparisons. These factors were calculated for different simulation runs and example results are compared graphically in Figures 8, 9 and 10.

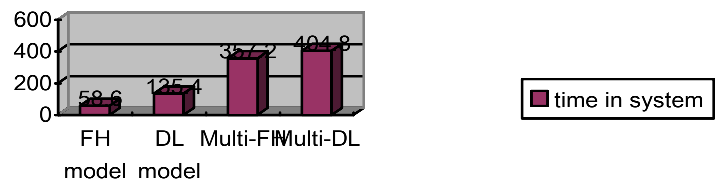

Fig. 8. Comparison of Lead-time between economy of scale and scope models

In SM3, FH and DL table work items have to share the available time of machines and human resources used to realise processing operations. For example in WC5 Bench1, they share the vertical sander to get both types of leg sanded. Because resources are shared during FH and DL table production the utilization of shared resources is increased. The operation times for FH and DL are distinct hence in SM3 it was necessary to distinguish the processes of the different product flows by using numeric labels. Figure 9 compares the utilization of Bench1 (one of the WCs) which has competencies assigned to carry out the operations needed to assemble under frames and fit under frame to tops. This illustration shows that in the multi-product model SM3, the utilization of both bench and human resources (associated to WC Bench1) will be higher than that in either SM1 or SM2. Revenue generation and Cost consumption comparison between multi and single product models is illustrated in figure 10. These two figures show that economy of scope systems can perform more cost effectively. With more product types the effectiveness will increase.

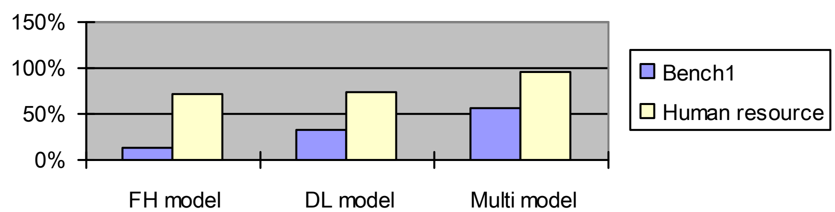

Fig. 9. Comparison of unitization between economy of scale and scope models

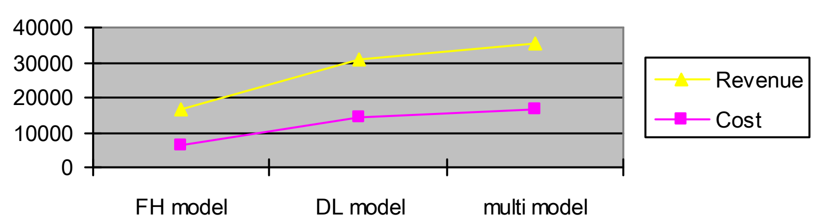

Fig. 10. Comparison of profit between economy of scale and scope models

5.0 RMS Embed in Economy of Scope-Component Based Model

SM3 was therefore designed so that it demonstrated economy of scope phenomenon, i.e. by generating multi-products values with a common set of resources. SM3 model experimentation led to the design of further SMs with an inherent capability to realize increased economies of scope. This includes a study of Case 3 production system. Literature review states that the manufacturing approach of RMS can in principle address the industrial need for rapid & effective change. Hence when designing and building further SMs, RMS principles were combined with those of GT principles to inform the design of a 'component based' simulation model SM4. SM4 is illustrated by Figure 11. Experiments performed with SM4 showed significant increased in economy of scope production. In SM4, furniture (table) products are grouped into parts, with respect to similarities of their attributes and operations times. SM4 design was centred on the use of 3 different processing groups (or work centers) to which alternative resource configurations can be assigned. Also the routes taken between processing groups by different products was made flexible by the use of label and visual logic programming facilities. In this way, SM4 design was structured to enable computer execution and quantitative illustration of benefits and dis-benefits of alternative RMS and GT principles. Therefore it proved possible for different versions of SM4 to be subjected to similar product dynamic patterns of change, so that multi product systems can be visualized and optimally designed over a specific period of operation

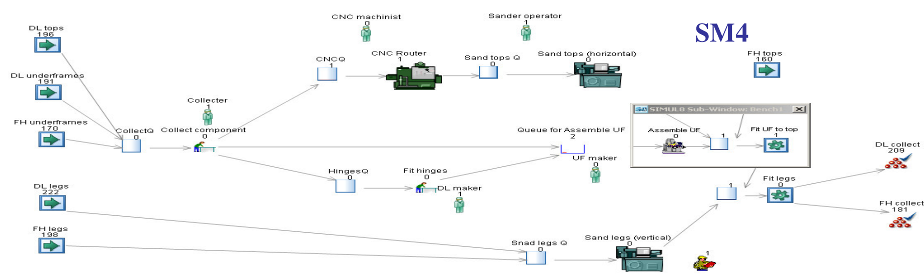

Fig. 11. component based simulation model

6.0 Reflections and Conclusions

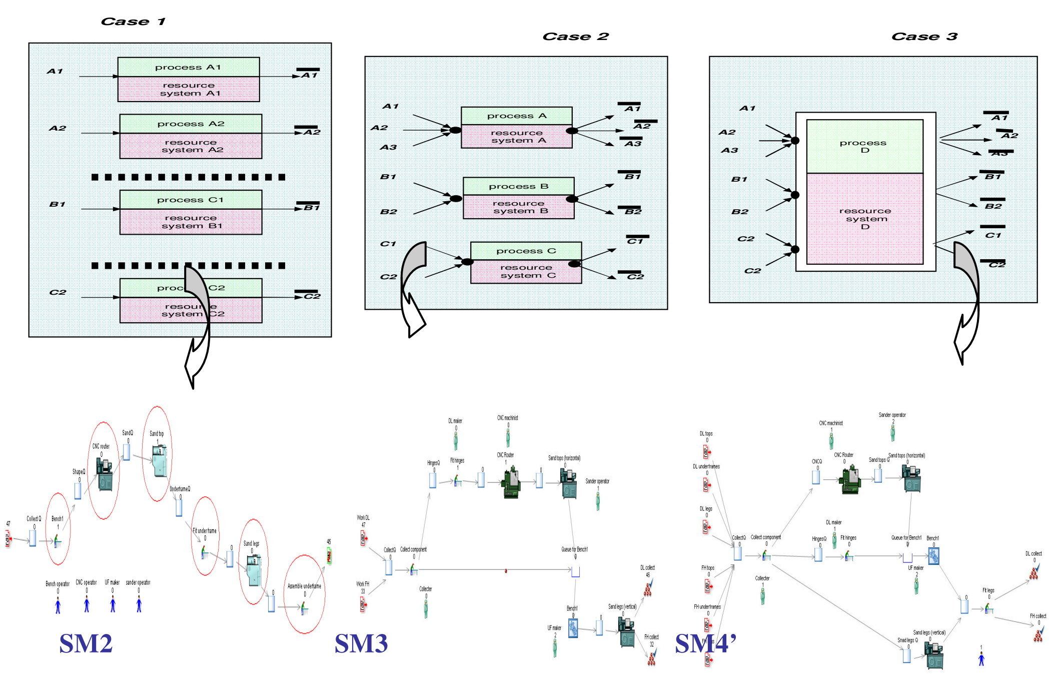

Fig 12 Testing approaches of assumptions.

Figure 12 summarizes how the integrated EM and SM approach was used to systematically and quantitatively model single and multi-product systems. SM2 experiments were conducted to provide a benchmark against which a multi-product SM experiments could be compared. This is because SM2 modeled a single value flow (economy of scale Case 1) production system configuration. Then SM3 was built to model a production system that can assemble both Farm House and Drop Leaf tables. Hence SM3 model is a (Case 2) dual economy of scope and scale production system. SM4' is a development of the SM4 component based model and is currently being developed, so that a full Case 3 production system can be modeled. In this Case3 production system, product components that are common to both 'table' and 'cabinet' types are processed with common resources to realise additional economies of scope and scale relative to SM4. Therefore the project has case study tested a novel way of systematically designing and quantitatively predicting performances of economy of scope systems. When so doing it had contributed new understandings about:

(A) How different types of 'model' can usefully characterize the 'business context' of economy of scope systems. Characterization is made in respect to: 'product variance' in that industry; creating text descriptions of different business models used by that industry; and by using an ISO EM technique to explicitly model the network of business processes used by the industry concerned.

(B) How a specific case of EM can be used to structure and inform the creation of 'context dependent simulation models'. The subsequent computer execution of these SMs has generated alternative behaviors of both single product and multiple product realizing assembly systems. This has allowed performance criterion of alternatively configured economy of scope and scale production systems to be compared

(C) How generic reference models of economy of scope and scale production systems, can help guide the design and testing of 'economy of scope production systems' and can inform and quantify benefits gained from applying GT and RMS principles.

The use of new understandings generated by this project might ultimately guide industry in regard to: investment planning in existing and new production systems; planning of new product introductions, e.g. into existing or new production systems; and planning and scheduling of existing production systems subjected to on-going product dynamics.

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MOVING UP THE VALUE CHAIN OF COCOA: THE ROLE OF FAIR TRADE

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Abstract

Fair Trade has emerged as an alternative form of international trade supporting equitable and sustainable models of trade that benefits producers, consumers, industry and the environment. Smallholder producers of cocoa in West Africa combine to give the region a 69 % share in the world cocoa production and have began taking advantage of the benefits associated with forming cooperatives and being Fairtrade certified.

Ensuring fair prices for Fairtrade certified cocoa producers is morally just but is it the best that can be obtained for the producers? Would moving up the value chain of cocoa in developing countries yield better proceeds? What is the role of Fairtrade in such an initiative? This paper reviews the different facets of Fair Trade and attempts to answer the questions raised above.

Keywords: Value chain, Fairtrade, sustainable, ethical consumption

1.0 Background

The continent of Africa sits on a trove of natural resources. Economic commodities like Cocoa, Cotton, Coffee and Gold abound in Countries like Ghana, Cote d'Ivoire, Nigeria, and Cameroon. While most of these resources are grown and extracted in Africa, it is predominantly processed and consumed in the Western world [1]. From *fig. 1*, it can be deduced that 69% of the world production of cocoa comes from West Africa. *Fig. 2* reveals a meagre percent share of West African countries in the world cocoa consumption.

The economies of most producer countries of cocoa such as Cote d'Ivoire and Ghana are heavily dependent on this commodity for sustenance [2]. The Government of Ghana for instance, has set up a development plan known as 'Vision 2015' towards achieving middle-income status by the year 2015. The Success of this economic development plan depends on the expected earnings from exports [3] like cocoa, Gold and fresh fruits. However, Ghana Export Promotion Council (GEPC) suggests that targets set in this vision are unachievable as long as Ghana continues to depend on traditional (unprocessed commodities) exports.

West Africa has experienced significant improvement over the years in the cocoa bean value chain however, the quantities of intermediaries and final products from cocoa exported from the region is still low.

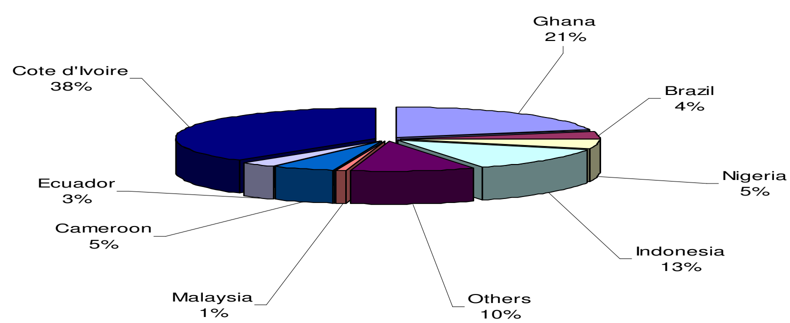

Fig. 1. The share of countries in total cocoa beans production (2005/2006) [4]

The Food and Agricultural Organization (FAO) has forecasted that the benefits of cocoa processing in adding value will continue to be enjoyed mainly by the importing countries that are also consumers if producer countries do not take up the challenge of value addition to the commodity. Benefits gained moving up the value chain are economic growth through higher returns on the commodities, reduction in unemployment, as well as future export earnings.

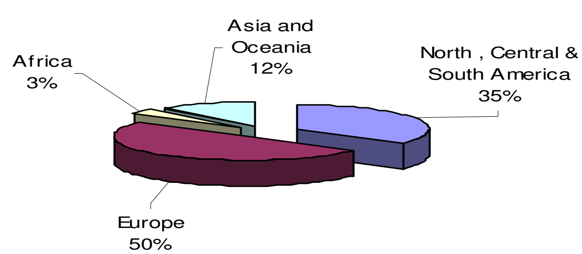

Fig. 2. The share of regions in total cocoa consumption in 2004/2005 [5]

Reviewing years from 2001 to 2005 shows a consistent trend of cocoa processing in West Africa. Analysing table I reveals the quantities of intermediaries [liquor, cocoa butter, cake, cocoa powder] exported by West African countries whiles table II reveals the quantities of raw cocoa exported by Ghana.

Table 1: Intermediaries of cocoa exported from West Africa 2001-2005[5]

Year / Country	2001 Qty in ton.	2002 Qty in ton.	2003 Qty in ton.	2004 Qty in ton.	2005 Qty in ton.
Cote d'Ivoire	176172	188685	201264	227219	247989
Ghana	51778	45807	30361	43443	46312
Nigeria	8690	9494	10653	10718	12362
Cameroon	25514	22098	17874	16426	16978
Total	262154	266084	260152	297806	323641

Table 2: Raw cocoa exported from Ghana 2001- 2005 [6]

Crop Year	Metric Tonnes
2000/2001	389,772
2001/2002	340,562
2002/2003	496,846
2003/2004	736,911
2004/2005	600,000

Table 3: Percentages of processed cocoa exported from Ghana

Crop Year	% of Processed Cocoa Exported
2000/2001	13.3
2001/2002	13.5
2002/2003	6.1
2003/2004	5.9
2004/2005	7.7

Table 3 reveals a progressive decrease in processed cocoa exported in Ghana between the years 2001 and 2004 even though the crop year 2001/2002 experienced a slight increase over the previous crop year. The crop year 2004/2005 saw an increase in the export of processed cocoa by a margin of 1.8% over the previous year. In the same year (2005), the government through the Cocoa Processing Company (CPC) embarked on a project to increase the quantity of processed cocoa within Ghana. Presently, the initial capacity of 25000 tonnes has increased to 65000 tonnes.

The Ghanaian government through partnerships with the private sector targets processing 300000 tonnes of the current production quantity of 700000 tonnes of cocoa beginning 2008. However, the ultimate government target is 80% [7].This increase in processing capacity would yield benefits for the private sector other than the primary producers.

From table1, similar processing patterns to Ghana are derived for Cameroon but the quantity of cocoa processed in West African between the years 2001 and 2005 increased by 24% as a result of significant increase in processing quantities for Cote d'Ivoire and Nigeria, yet gave West Africa a substantially small share of 14% [8] globally.

2.0 The Cocoa Value Chain

The global cocoa value chain has experienced significant growth over the past decades and this has generated competitiveness among players in the cocoa sub-sector. However, in some countries, the competitiveness in the value chain is threatened by inconsistencies in quantity and quality in production of the raw cocoa [9], while others lack infrastructure, logistics and good policies [10].

This is true for the major players in the cocoa market - Cote d'Ivoire, Ghana, Indonesia, Cameroon and Nigeria even though the level of dependency of their economies on cocoa vary as a result of high diversification [2].

The cocoa value chain in most of the West African countries is comparable. The similarities arise from the extent to which they process while the differences are as a result of the level of involvement of government and private sector along the chain. Fig. 3 shows all the players along the value chain of cocoa in Ghana. The government is involved from the farmer's level to the end of the value chain. Apart from the involvement of smallholder producers, private sector involvement is only allowed after quality assurance.

Moving up the value chain basically involves the physical transformation of raw materials into manufactured goods as well as improvements in the quality of raw and manufactured goods. Other researchers like Porter [11], have the value chain spanning the transformation processes to the final product as well as the interactions that exist among those processes and any other external entity [12].

Contrary to happenings in Ghana, the trading in cocoa in other countries is not monopolised by government thereby introducing fierce competition among collectors and traders with few barriers for entry into the market. The cocoa market environment differentiates little for quality [9] and hence the cocoa producers have little incentives to upgrade to more costly production and post-harvest practices which improve the quality of the cocoa bean produced.However, processors and manufacturers have clear incentives to establish closer supplier relationships in order to improve the quality and consistency of their raw materials [9]. The suppliers have the responsibility to ensure that the strict standards of quality needed for processing and manufacturing are adhered to.

Some of the determinants of the price of cocoa include the forces of demand and supply but at the point where competitiveness plays a role in who gets access to the market, other factors come into play [9] such as availability of supply, fat content and flavor.

A study conducted by USAID on some cocoa producing countries to determine their strength in terms of value delivery to the customer, revealed Indonesia produces cocoa which is inferior in quality and fat content yet there is demand for the commodity (especially from China).

2.1 Challenges to Moving Up the Value Chain

A solid financial base, access to appropriate technologies, legal and policy frameworks (certification, standards, taxation, and tariffs), knowledge and skills, Education, research and training are invariably pre-requisite to moving up the value chain.

Lack of a sizeable domestic market for products made from cocoa is another challenge to moving up the value chain. Policies to curb the over dependence of domestic markets on imports of cocoa products could promote moving up the value chain in West Africa.

The unavailability of other raw materials required to manufacture cocoa products impedes moving up the value chain.

Cocoa processors and smallholder producers in Nigeria are incurring higher costs (in tariffs) in order to access the market in the European Union (EU) following the nations' refusal to sign the Economic Partnership Agreement (EPA) [14]. These high tariffs imposed on raw cocoa and even higher tariffs imposed on intermediary exports into the EU have the tendency to impede moving up the value chain.

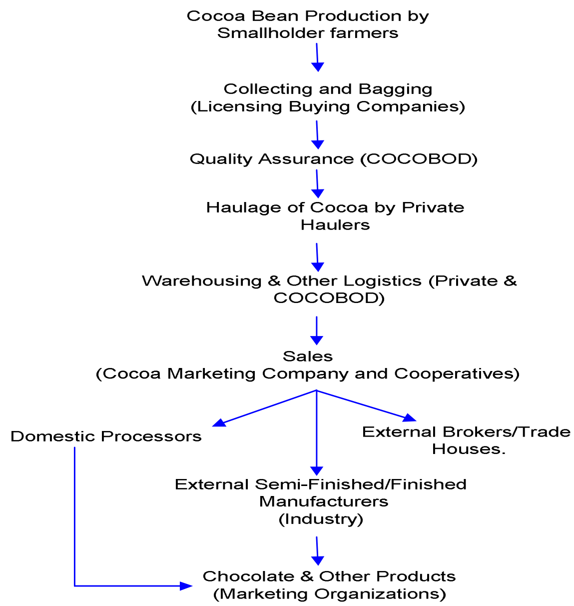

Fig. 3. Cocoa value chain in Ghana [13]

In Ghana, only a small quantity of cocoa is manufactured into chocolate due to the lack of logistics and infrastructural support for transporting the finished product abroad. In view of this challenge, attempts are being made to channel efforts into the processing of intermediaries (liquor, cake, cocoa butter and cocoa powder) which are relatively easy to transport.

Foreign multinational companies are vertically integrated and so prefer to source raw cocoa as opposed to processed cocoa. This is because of the high investment made in technology acquisition and research and development. This is a challenge to moving up the value chain in West Africa as these multinational companies have the buying as well as the negotiating power to influence what they purchase as well as the power of choice to source from other countries.

3.0 The Fair Trade Initiatives

Fair Trade has emerged as an alternative form of international trade to promote payment of fair prices as well as labour and environmental standards in areas related to the production of a wide variety of commodities.

Fair Trade ensures eligibility to buy, process, and sell fair trade products through:

- Standards
- Certification of institutions
- Labeling of products (Max Havelaar , Fairtrade, UTZ certified and MADE BY)
- Strict monitoring
- Smallholder producer participation in a democratic organization
- Harmonization of the Fair Trade message
- Attempts at harmonising the Fair Trade certification mark.

The certification authorizes producers and manufacturers to use the designated Fair Trade label on their products and guarantees consumers of commodities meeting labour and environmental standards [15, 16].

The Fairtrade Labeling Organization International (FLO) collaborates with other organizations known as Alternative Trade Organizations (ATOs) to develop trade systems that promote sustainable production and trade with the disadvantaged workers and producers around the world.

3.1 Products and Markets

The quest to make Fairtrade part of mainstream trade has led to the expansion of the range of products. Currently, over 3000 products have been licensed to carry the Fairtrade mark [17]. Amongst these are flowers, rice and those manufactured from the primary range of commodities such as chocolate, clothing, football, jewellery and other ethical gifts.

Fig.2 is a typical representation of the market available for cocoa producers in the developed world. Processors and consumers would want to buy cocoa at the cheapest price possible but with education and awareness of ethical issues, the market for Fair Trade is growing significantly. Europe and United States of America (USA) hold the largest share. In spite of the fast growing nature of the market, there are still lingering doubts among critics of Fair Trade as to whether the Fair Trade market could reach a size large enough to have substantial impact on the standards in developing nations [18].

3.2 Price Determination for Fairtrade Products

The minimum Fairtrade price is set at the average producers' costs of sustainable production ('COSP') per product [17]. A global or regional minimum price is normally set; however when this is not possible because of the large variation in the costs of production of cocoa in the different regions, a national minimum price is set.

Fairtrade is said to create distortions in the market as it attempts to help producers elude the full weight of the demand supply forces [19] leading to the over production of Fair Trade goods [20]. It is worth noting that the market for Fairtrade products is limited hence not all Fairtrade products get marketed under the Fairtrade scheme. Fair Trade is also said to discriminate between suppliers with identical quality [21] and in different countries. However, Mann [20] argues that the attributes of Fairtrade products are incomparable to attributes of products in the conventional line of trade. Mann [20] further argues that even though the price models used in determining price for products may generate price differences among producing countries, the Fairtrade price is set above equilibrium [17] and hence Fair Trade rests on market forces as much as the conventional trading does.

3.3 Awareness Programmes

Commencing almost half a century ago, Fair Trade did not receive as much attention and patronage as it is receiving presently. Public interest in the products certified by the Fairtrade Foundation has improved through awareness creation and campaign for changes in the conventional model of international trade championed by the UK and USA.In UK alone, over 300 'fair trade towns' have been created with over 300 companies licensed to sell Fairtrade products [17]. 2006 saw a rise in sales by 49% [17]. Awareness of the Fairtrade mark amongst UK adult population grew to 57% in 2007[16]. This percentage signifies more avenues for growth and expansion. A Fairtrade fortnight has been set aside to boost awareness of Fairtrade and the sale of Fairtrade products in the UK.

3.3.1 Role of Institutions in the Growth of the Fair Trade Initiative

Many institutions are buying into the concept of ethical consumption. The willingness and cooperation of both smaller and larger companies to participate in the Fair Trade initiative is one of the reasons underpinning the success of Fair Trade.

The K-2 Unit of TransFair USA for instance has created a Fair Trade Curriculum to educate students on "The Journey of the Cocoa Bean from Farm to Fair Trade Chocolate" [22] teaching the concept of global interdependence in order to make students take responsibility for the impacts of their actions on human communities and the environment.

3.3.2 Involvement of Major Super Markets

Major supermarkets in the UK like Sainsbury, Waitrose, Tesco and Marks & Spencer (M&S) have joined the chains of supermarkets to promote the Fairtrade initiative. M&S for instance has refused to sell any tea that does not bear the Fairtrade mark and all tea sold by Sainsbury now bear the Fairtrade certification mark. Asked whether the supermarkets would relent in their efforts to support the new model of trade, representatives for the supermarkets, pledged their unflinching support to marketing Fairtrade products. These examples cannot be discounted as merely the practices of an obscure and irrelevant group of progressive producers and elite consumers [15].

3.4 The Fair Trade Debate

In the past decade, there were concerns among consumers and civil society groups whether the Fair Trade model could be extended to factory manufacturing and clothing. Presently, the range of products covered is wider through the efforts of Fair Trade activists. There are still lingering doubts about the possibility of extending the Fair Trade model to cover all manufactured goods and the availability of enough ethical consumers to sustain the initiative.

The possibility of retailers of Fair Trade products charging above the mandated prices of the products raises concerns. Following this, the questions are whether governments should get involved to devise alternative ways of fixing the prices of Fair Trade products [20] through regulations. In response, Lamb [23] argues that the involvement of governments would dilute the standards: a voluntary scheme owned by producers and driven by the public with integrity and credibility is appropriate. She added that maintaining neutrality and rigour is the strength of Fair Trade.

While others also argue that only a quarter of the earnings reach the farmers due to corruption along the supply network, Ronchi [24] reports of producers having acknowledged receipt of all proceeds in addition to having the prerogative to decide on the community project to invest premiums in Ghana.

The debate is not without questioning the credibility of producers and manufacturers. Critiques assert that products passing for Fair Trade prices may not have necessarily complied with the standards [25] of Fair Trade consequently defeating the aims of Fair Trade proponents.

Proponents of Free Trade are challenging Fair Trade activists to produce hard evidence of what Fair Trade claims to achieve instead of relying on anecdotes [26].The evidence of the impact of Fair Trade is evident in the attestations of producers and the increase in the number of applicants wanting to be Fairtrade certified. One of the greatest challenges of Fair Trade is the attribution of impacts to factors like government policy among other [24]. This is further complicated because critics are often looking for the translation of the impacts into money in the pocket of producers. However, Fairtrade supports the producer organization as well as the producer, giving the prerogative to producers through voting rights to determine areas of investment [23, 24].

4.0 Role of Fair Trade in Moving Up the Value Chain

FLO International, together with other members of the Fair Trade Movement, aims for the highest impact possible on disadvantaged producers and workers in developing countries [17].

Global analysis on the cocoa market prospects to 2010 suggests a continual expansion of cocoa production, processing and consumption [27].The anticipated increase in consumption is as a result of efforts to boost domestic consumption in the producing countries and the scientifically backed nutritive and cancer fighting capabilities of cocoa-rich chocolates [27] and cocoa products.

Moving up the value chain requires a steady supply of cocoa without which the anticipated rise in demand of cocoa may not materialize. Challenges to a steady supply of cocoa are cocoa diseases and pest infestation. This is a typical instance where Fairtrade may make a difference as the Fair Trade organization arranges for the education and training of smallholder producers on how to handle the pest and diseases associated with lower yields.

Under the conventional model of trade, the forces of supply and demand determine the price of the commodity however, Fairtrade guarantees a stable minimum price to producers enabling them to plan long term, invest and develop technical support for the future [15]. The minimum price goes to the smallholder producer while the premiums are used for community projects to enhance the livelihoods of smallholder farmers and their dependants. The prerogative of what premiums should be used for is decided by members of the producer organization and so premiums go to address the dominant needs of the smallholder farmers.

The producer organizations under the Fairtrade scheme may be able to attract loans to establish grinding and manufacturing plants which would empower producers to develop the capacity to compete in the global market place as well as the moving up of the value chain. This possibility is not farfetched as the Ghanaian producer organization (Kuapa Kooko) has been able to secure a part ownership of the Devine Chocolate Company in the UK and USA which has recorded a first dividend share this year [28].

If the concept of Fairtrade is supported and promoted, the future could see producers having a share in supermarkets, manufacturing plants, shipping lines, and eventually, the whole supply chain would be underpinned by the Fair Trade concept.

The involvement of private sector in moving up the value chain is appreciated however; efforts could be invested into making the value chain processes equitable so as to reinforce the Fair Trade effort of improving the livelihoods of disadvantaged producers in the south.

5.0 Conclusions

In conclusion, moving up the value chain requires a host of resources, changes in policies and attitudes linked to access to finance. Fair Trade is not the only answer to moving up the value chain however, it provides a means through which marginalised producers who may not even be able to afford products manufactured from commodities grown by them, the opportunity of partaking in the returns from their hard work. The Fair Trade concept also empowers consumers in the West who may previously have not been able to interfere in trade negotiations, the opportunity to better the livelihoods of disadvantaged smallholder producers in developing nations.

Even though there may be a lot of debate about the claims of Fair Trade, the concept has the capacity to initiate value addition to commodities.

The journey for economic liberation and poverty alleviation in developing nations would have to begin from somewhere and it is definitely not in the continual giving of aid, and grants. A better model of trade is preferable.

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PEOPLE DEVELOPMENT SYSTEM TO ENHANCE PROBLEM SOLVING CAPABILITIES IN IMPLEMENTING LEAN PROCESS MANAGEMENT: A CASE STUDY IN AEROSPACE COMPANY

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Abstract

Globalization and customers' expectations for higher quality services and products with competitive cost requires OEM's (Original Equipment Manufactures) in Aerospace, Automotive and Electronics Industries face various challenges such as fast deliveries when needed. Higher cost of operations is putting heavy demands on supplies to provide solutions with higher quality and reliability in order for them to be competitive and profitable. Supplies and solutions providers are challenged to improve their own operating cost and performance more effective and efficiently through strategic initiatives such as Lean Process Management (LPM) to driven wastages and losses in their manufacturing, administration and entire supply chain processes. It can be successfully implemented in any organization if be there is good commitment from top to bottom management. Human factor plays an important role in ensuring lean process management to be successful and provides good proposition for the success of the organization in the long run. One of the main elements of people is their problem solving capability (PSC) in identifying and eliminating wastages. So, this paper presents the conceptual framework and focuses on how this people development system can help organizations to enhance employees' capability in identifying and eliminating wastages continuously and effectively. By means of a case study that discusses the people development system (PDS) framework, the strategy used by the aerospace company for implementing lean process management, and the significant benefits that were accrued in manufacturing operations and meeting

company goals by identifying and eliminating wastages. The data for this study were obtained through actual monitoring of a pilot study in aerospace manufacturing company. The pilot study was conducted to validate the people development system framework; and the results of the assessment were satisfying and many improvements have been done to achieve company goals by identifying and eliminating wastages. The obstacles, benefits, future work and improvement on implementing the people development system are also discussed.

Keywords: Lean Process Management, Problem Solving Capabilities, People Development System.

1.0 Introduction

In today's competitive world, no company can afford to waste all form of resources. The most underutilized resource of most manufacturing company is their people. The number one asset of any organization is also its people. In fact, people are one of the few appreciating assets an organization has second to products or services. The real advantages of employee's involvement are to focus a group of employees with different perspective on a single objective that support the organization's strategic focus. The companies that develop and leverage the capabilities of all their employees will achieve continuously better performance than those that do not. The companies that fail to unlock the potential of their workforce will be forced to carry more overhead, have more layers of management, and will be slower to react to changing business, social and political needs. Lean process management definitely becomes their arms to fight to achieve this goal with the employees' problem solving capability in eliminating wastages.

2.0 Background of Study

Many industries ranging from aerospace to service and health businesses have successfully adopted lean manufacturing practices and principles and made their operations more efficient. Most of these companies are still not what can be considered fully lean organizations [1]. In order to become fully lean, a company must understand lean as a long-term philosophy where the right processes will produce the right results and value can be added to the organization by continuously developing people and partners, while continuously solving problems to drive organizational learning [1]. While there is no exact definition for a fully lean organization, it is important that an organization must understand and apply all of the practices and principles. It is also important to understand that lean thinking, which affects the whole business model, is the key and not solely leaner production, where only parts of the whole lean philosophy are applied.

The goal of becoming a fully lean organization can only be reached if the employees are well aligned with the new philosophy. Gagnon's [2] work suggests, "production employees who are not well aligned with a philosophy will exhibit lower levels of desired attitudes and behaviors". Since lean thinking requires a great level of employee's involvement and change in attitude and behaviors [2], strategic employees alignment plays an important role in the quest to become lean. To ensure employees alignment, it is particularly crucial to have open, honest communication, and delegation of authority. Spear [3] argues that these are necessary for a successful lean implementation.

Emiliani [4] defines repeated mistakes as another primary type of waste and argues that a business that is unable to learn and change its behavior will, “no doubt, risk the future existence of their entire enterprise as currently governed”. In a lean company, learning continues, since “lean is a continuum and not a steady state” [5]. Although lean thinking is a buzzword, the lean philosophy, practices and principles offer industry a potential mechanism for improving performance.

2.1 Objective of the Study

A scientific approach is needed in order to engage people from Top to shop floor personnel to solve and improve the problem solving its source. Every problem is an opportunity to improve the process and to develop people. In this research it was shown that people is only key or primary factor to make decision to make changes to drive the strategic initiatives of the organizations to be world class or be the best. As such it is important to consider the best way to overcome the interruptions and hiccups in the processes. There is a need for a common approach to problem solving capabilities across the organization and a common language for communicating the diagnosis and the results. This includes for a policy deployment framework for aligning and prioritizing problem solving activities in line with the business goals of the organization. The managers’ (e.g. CEO, GM, MD, Directors, Dept. Heads, Section Managers, and Supervisors of various departments) role to lead by developing the abilities of their staff with problem solving capabilities, at every level in the organization and throughout their career is very crucial in lean process management and a key feature of Toyota Production System (Lean Process Management) is not to lay-off its employees.

Therefore, the research conducted in this thesis aims to identify the following research problem on why lean process management is focusing on people as a key driver to obtain the optimum participation of employees in eliminating wastages and how can we enhance problem solving capability across the organization. Consequently, two research questions are derived and will be answered in this thesis. What are the characteristics of lean process management which are focusing on people as a key driver to obtain the participant of employees in eliminating wastages and how to enhance problem solving capability across the organization.

3.0 The Need of Developing a New System to Enhance Problem Solving Capability

Each of the three systems in framework has an own objective. The objective of the lean process management system is to identify and eliminate wastages by removing non value added activities. People management systems need to provide the capability for rapid improvement and adoption to change. Here, again, we must accept the fact that change is inevitable and that the speed with which the necessary modification are made is the deciding factor in our survival. The objective of the business management system is to apply carefully the organization’s limited resources, including capital and hard assets as well as time and human assets.

Three integration elements with total employee involvement from top to bottom play an important role for sustaining problem solving among employees in practicing lean concept. It is important to create people development system (PDS) which consists of all these three elements with total involvement of people to increase problem solving capability. People management system, Business management system and Lean process management system are integrated by principles that, in a sense, hold them together. These principles are meant to provide a framework (Fig. 1) to focus the direction in enhancing problem solving capability among employees by forming as people development system (PDS) in lean process management. They are:

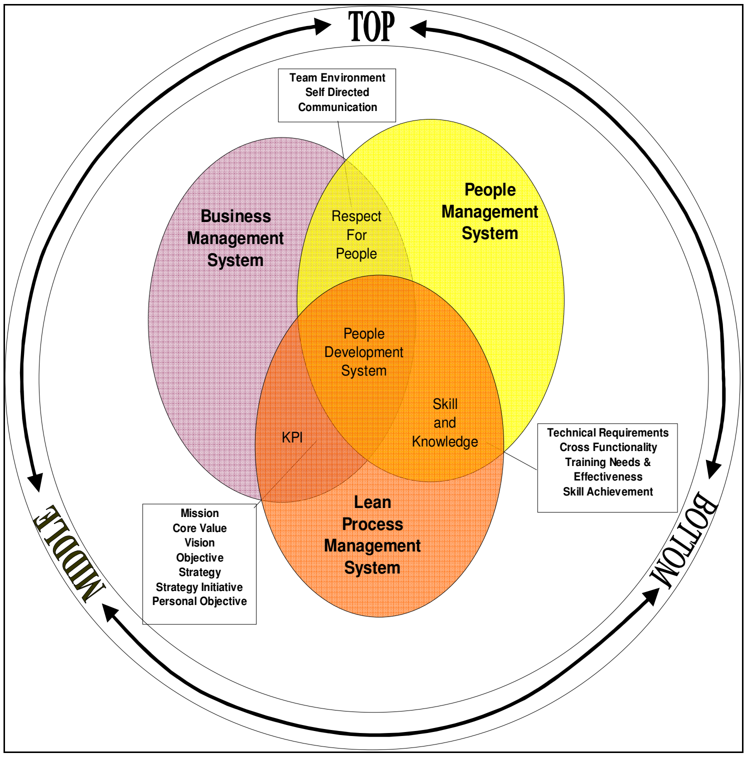

Fig. 1. PDS Framework for Enhance Problem Solving Capabilities among Employees [6]

- Key performance indicator - KPI for every level such as company, department, section and individual levels which is link towards organization goal.
- Respect for people – Respect for people which mainly focuses on the lean behaviors that each employee in organization should build in their mind.
- Skill and Knowledge – Skill and Knowledge for employees will support them in practicing lean concept effectively and efficiently by utilizing the lean tool and techniques.

Another important element incorporated with this people development system framework is teamwork of top, middle and bottom management. The total commitment of all these three levels will enhance of problem solving capability in lean process management among employees.

3.1 Key Characteristic, Critical Success Factors (CSF) and Related Performance Matrix

The following key characteristics, CSFs and related performance metrics are identified as crucial in people development system of lean process management as in Table 1 below.

Table 1: An analytical framework for measuring problem solving capability in lean process management [6]

Key characteristics of integration elements	Critical success factors (CSF) of People Development System	Performance Matrix
KPI Mission Core Value Vision Objective Strategy Strategy Initiative Personal Objective	Customer Satisfaction On Time Delivery Zero Defect Cost reduction Effective Operation Cost	Achievements of KPI for each level versus goal/target. • Productivity • Customer complain • Scrap/Number of reject • Attendance/ Absenteeism • Tardiness (Schedule time) • Using QCDAC principles
Respect for people Team Environment Self Directed Communication	Top Management Commitment Team effectiveness/formation Ideas cost or value Continuous improvements Lean Behaviors Rewarding system	• Number of ideas generated • Level of people involvement • Usage of lean tools • Total cost saving projects Measured by Likert-type scale on the following items: • Top Management Commitment • Lean behaviors • Achievement of Leanness level
Skill and Knowledge Technical Requirements Cross Functionality Training Needs & Effectiveness Skill Achievement	Produce skilled, knowledgeable and innovative employees	• Lean tools and techniques assessment • Employee skill metric • Audit by 3rd party or customers on lean practice

- KPI in lean process management determination through Mission, Core Value, Vision, Objective, Strategy, Strategy Initiative and Personal Objective for people development system is crucial. This will align overall workforce of the company to follow for one common goal. Each level has its own portion of contribution towards the target. The results are compared with the target or goal used to measure the success of KPI. The accumulation of success from each portion will reflect the overall achievement of the company goal.

- Respect for people in lean process management is another crucial factor in developing the lean culture throughout organization. In order to measure the lean behaviors, top management commitment, leanness level of the company and perception of team member's capability, Likert-type scale is used to get the responses from respondent. For example, one can ask managers to rate the degree of support by top management on five-point scale from no support (1) to total support (5). Beside this, the problem solving capability also can be measured by counting the number of ideas generated, Level of people involved and the total cost of the project.

- Skill and Knowledge in lean process management is the fundamental requirement for employees to equip themselves. Without this they can't perform well in solving problem to identify and eliminate wastages. Lean tools and assessment techniques by using assessment criteria to determine the level of implementation using spider web chart with rating of 1 (beginning to introduce) to 5 (practice with excellent). Another measurement on employee skill metric will emphasize on employees skill and their cross functionality.

4.0 Methodology

The method of data collection was by participatory action research at kitting department as Case Study Company. The researcher attached with pilot team throughout the study conducted to implement the people development system developed [6]. The performance measurement model (Fig. 2) was developed to measure the effectiveness of People Development System framework developed. The performance measurement is divided into three phases, which are:

- ***Phase I (Input)***

  Phase I begin by generating the Value Stream Mapping (VSM) of current state by value stream manager with the help of functional manager. The VSM will be create by using a simulation software which is PROMODEL, information such as run ratios, scrap rates, manpower, work hours & schedules, changeover times, tool change times, and inventory level will be key into PDS database, here value added and non-value added activities will be identified by propose the future value stream mapping. Wastage identified will be categorized under the QCDAC principles.

- ***Phase II (People Involvement)***

  Phase 2 will incorporate 'People Involvement' which refers to the employee participation of the respective department. The identification of the 11 wastages in the previous phase 1, will lead to problem solving. Phase 2 will incorporates the involvement of the employee in the problem solving activities. PDS will measure the people involvement through few types of measurement mechanism that will cover each of the QCDAC principles which are Quality, Cost, Delivery, Accountability, and Continuous Improvement.

- ***Phase III (Output)***

  In Phase III lean metrics is link towards the company KPI. Phase III lean metric is adopted from one of the case study company's customer to show the leanness level of the company in practicing lean concept. By eliminating wastages activities take place in Phase II through involvement of people Phase III lean metrics is generated. Beside this, the results also will be use to benchmark with the company KPI achievements.

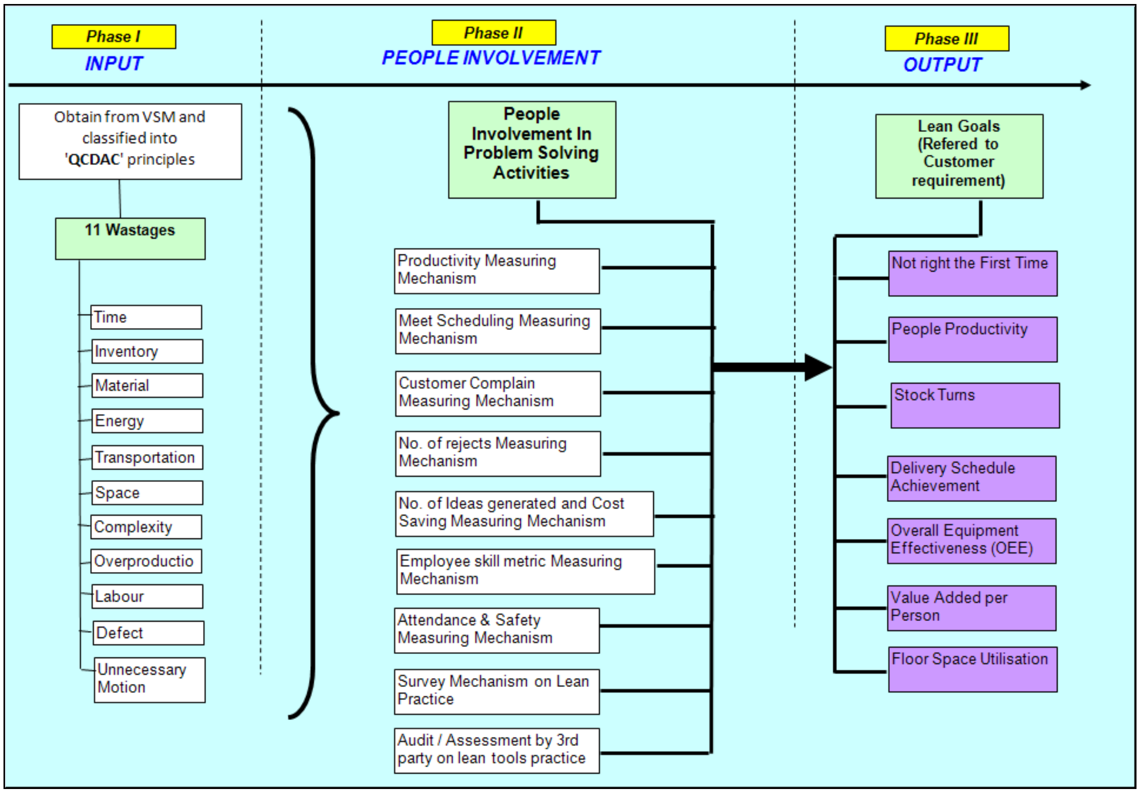

Fig. 2. PDS Performance Measurement Model

5.0 Results and Analysis

The PDS implementation results achievement during pilot study at kiting department for the duration of one year are presented here. They are only a summary according to the main objectives achieved through the deployment of the PDS framework which has been enhancing the people involvement in eliminating wastages. The PDS performance methodology (Fig. 2) are use to monitor the activities of employees in eliminating wastages. Furthermore, PDS Database was developed using Microsoft excel and Microsoft assess was used to developed interface for employees to easily key in and generate visual indicator for their use.

5.1 Total Employee Involvement in Lean Process Management

The employees' involvements are categorized into three main levels which are top, middle and bottom management. The pie chart on Figure 3 below shows the level of involvement of employees by generating ideas in eliminating wastages for the year 2007. The highest contribution comes from the **b**ottom level which is 27% and followed by middle level with 9%, while top level is 1%. This indicates that the bottom and middle level involvement which can highly contribute to eliminating wastages activities. Beside this, there are also combination level involvements in waste elimination. Bottom-middle level with 37%, middle-top with 25% and bottom-top 1%, which shows the important role of middle management in lean process management implementation to become the mediator to create communication from top to bottom and from bottom to top level management. Furthermore Figure 3 also consists of pie charts on distribution of type waste eliminated and type of lean tools used in eliminating wastages.

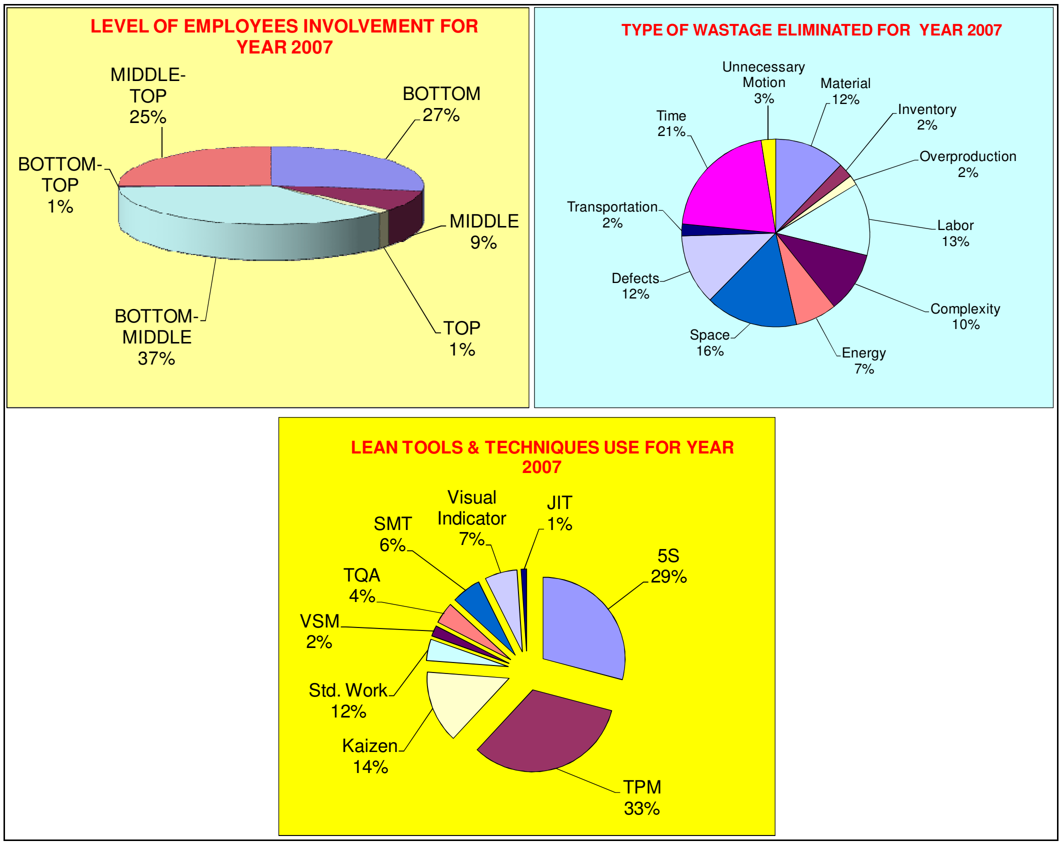

Fig. 3. Pie charts Illustrate on people commitment on LPM implementation

5.2 Top Management Commitment, Leanness Level and Lean Behavior through Questionnaire Surveys

Degree of leanness (DOL) was measured as the average of the actual changes taking place as measured by the nine principles of lean manufacturing [7]. Degree of management commitment (DOC) was measured by the level of investment in supporting manufacturing infrastructures, as measured by WEMP, TRAIN, GROUP and QLEAD [7]. The degree of lean behavior (DOLB) is measured using the 30 lean practices [8]. The table 2 indicates the mean and index value of DOL, DOC and DOLB.

The initial results of January 2007 indicate the degree of leanness of the company is low with mean value is 2.90±0.20. However, at the end of the year which is on December 2007, the mean value increased to 3.87±0.47, increments is 33.4%, and become moderate to high level. Meanwhile, there is a significant increment in the index value of lean behavior, as it raised from 0.691 to 0.7164, though there is a minimal gap to meet the lean standard (0.800). Furthermore the degree of management commitment is moderate at January 2007 with mean value is 3.32±0.10.but, for December 2007 it also increased to 3.85±0.7, an increment of 16%, which is almost close to the high level.

In conclusion, we can say that when the degree of management commitment is increased, the degree of leanness and lean behavior also increased. So, the level of management supporting manufacturing infrastructures have made the company to be more lean and increase level of lean behavior among employees.

5.3 KPI Achievement

KPI is an important element that enables the achievement of vision, mission, core value, strategy, and personnel objective for people development is crucial. Achievement of KPI shows the evidence of people involvement to drive high performance so that stakeholders and customer will be satisfied. Monitoring on each performance measurement and countermeasure taken to solve any problem occur have contributed to the achievement of KPI. Without classification of any wastage into performance measurement, no monitoring can be made and no problem solving can be done to reduce the wastes, which have directly caused the failure of KPI achievement. Kitting department of the Company have gain benefits from many element that are not been monitored before and have been monitored after PDS is been implemented. Wastages have been reduced dramatically.

Table 2: Kitting Department KPI Achievement for the year 2007

Principles	Matrix	Unit	Goal/Limit	2007 Achievement
Quality	Scrap	MQ%	**2.60%**	**1.97%**
	NCR	%	**7.80%**	**0**
	Snag Sheet	Control Limit%	**20%**	**0**
	Audit	# of CAR	**Zero**	**1**
Cost	Overtime	Total Monthly man hours%	**12%**	**10.50%**
	Downtime	%	**10%**	
	DCS 1	%	**10%**	**9.14%**
	DCS 2	%	**10%**	**8.80%**
	DCS 3	%	**10%**	**7.65%**
	S91	%	**10%**	**10.34%**
Delivery	Output	%	**97%**	**100%**
Accountability	Attendance	%	**92%**	**90.7%**
	Training	Hours	**188hrs**	**2314hrs**
	Staff/trg hours	%	**47 staff**	**100%**
	Major Accidents	Qty accidents	**Zero**	**0**
	Accident Free Days	# of days	**90days**	**365**
Continuous Improvement	Kaizen	RM	**150K**	**156K**
	SMT	Level	**Level 4**	**L4**
	5S	Level	**Level 4**	**L4**

Table 2 shows the main QCDAC principles with the Performance Measurement metric. Each one has its own targets and limits. The impacts of PDS implementation have pushed scrap percentage below the limit value which has the value of 1.97, that can be considered as achievement of leanness. The reason why the value is achieved is because PDS have solved many scrap issues, such as material dry and ply damage for the whole year. Beside these, complains on product produced from internal and external customer shows null. But still there is one finding from quality audit by external auditor on the freezer temperature issue which was due to problem on the temperature sensor was faulty.

As for Cost, there are two elements that are comparable, which are Overtime and Downtime. As for Overtime, kitting department has set the limit to below 12% for the year 07, during PDS is being implemented, overtime are controllable all the time, not even a month exceed the limit of overtime, which eventually give a value of 11.5% for the whole year. The value of down time for each machine that DCS 1, DCS 2, DCS 3, and S91 are identified and then been converted into percentage value. As a result, all three (3) machines, DCS 1, DCS 2, DCS 3; downtime value are 9.14, 8.80 and 7.65 whereby is below the KPI value of 10%. Machine S91 shows a slight overshoot of KPI value with a value of 10.34%. It can be said that downtime of machines available in kitting department are controllable to below 10% which are considered as an achievement of leanness.

Under Accountability, attendance KPI for kitting department has been set to above 92% for the whole year. Problems such as emergency leave, annual leave and unpaid leave have cause PDS attendance failed to achieve its target. It only managed to achieve 90.7% below the minimum requirement of 92%. A solution to overcome this problem has been proposed by kitting department and some of the action items have been executed, for example implementing in-house clinic for employees for those required treatment due to sickness. Beside this the top management has decided to give rewards for those giving the best commitment. Focus on the training and development of employees at kitting department shows achievement of KPI in term of training hours and total training program conducted. Employees' involvement in any accidents throughout the year is zero.

In term of continuous improvement, the Kitting department manage to save cost around RM147,000 for the year 2007 with projects such as JIT production system implementation, There is a reduce in set up time for S91 machine, implementing tools trolley usage, Split and batch paperwork implementation, eliminate dry and resin rich issue. The ideas for the kaizen projects are inspired from the observation on visual indicators (Phase 2) that was created through the PDS implementation. Each activity also shows the involvement of employees from various levels to make the project success. Finally, Kitting department also successfully achieved level 4 for the practice of lean tools on 5S and SMT (Self Management Team) which was audited by third parties on lean practices.

6.0 Conclusion

Based on a method point of view, the lean practices at kitting department able to classify and monitor the performance measurement of PSC of employees in eliminating wastages. By analyzing the Phase 2 portion, which will become the Visual Indicators for employees to notice any abnormalities, PDS also enables the improvement on capabilities of employees in eliminating wastages to achieve company KPI. From a lean process point of view, PDS can be implemented in the Manufacturing Environment to eliminate wastages. Among the benefits of PDS are:

- To enhance problem solving capability among employees at all levels.
- To get total commitment of employees from top to bottom.

- To create lean behaviors among employees and become change agent with the lean culture.
- To produce workers with skills and knowledge in using lean tools and techniques.
- To increase CI (Kaizen) Activities.
- To work towards Vision and Mission of company and Integrate LPM in company strategy to work towards achieving business goals and be cost competitive.

The development of PDS takes a different attitude towards total commitment of employees in lean. It promotes the proactive employees in solving problems to eliminate wastages. By using PDS, Problem solving capabilities among employees increase. PDS was successfully implemented and it helps employees under pilot study to enhance problem solving capability in eliminating wastages. It also helps the pilot study to achieve its KPI. For future work the author would like to proliferate the implementation to other sections which are different in nature of business such as, area which is not involving machinery and service department to get generalization for the PDS framework to adopt and benefit from it. Furthermore, the author also intend to develop the PDS software which can help the practitioner to be more efficient and user friendly with the system.

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MODEL DRIVEN AND CHANGE CAPABLE PRODUCTION SYSTEMS

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Abstract

The next generation of production systems will need to be sufficiently programmable and re-configurable to realise multiple value streams with a common and finite set of human and machine resources. It follows that new forms of engineering environment are required, capable of enabling the full life cycle of component based production systems. Such systems will likely need to cater for a growing product dynamic. This paper reports on a new integrated approach to production systems engineering, which is based on the use of new modelling formalisms, virtual engineering tools, infrastructure services and reusable production system components. The approach deploys reusable models of people, product, process and plant (ip4) such that large scale production systems design and on-going change can be achieved with reduced engineering effort and/or within reduced timescales. The presentation will illustrate a use of the integrated approach in an automotive industry case study.

Keywords: Production Systems Engineering, Complex Systems Modeling, Virtual Engineering, Virtual Engineering, Component Based Systems.

1.0 Introduction

The business environment world-wide has become more dynamic and uncertain. Product related aspects of that dynamic can typically take the following forms: (i) increased product variance during normal operation of production systems, (ii) more varied production volumes, again during normal operation, (iii) more varied production mix, during normal operation, (iv) more frequent significant change requirements, when new products are engineered and introduced into production.

A consequent outcome is that the average economic life of production systems will reduce unless they are 'change capable'; i.e. can be readily and effectively engineered to cope with impacts arising from 1) to 4).

Various manufacturing philosophies have emerged that can guide industry toward increased responsiveness such as Group Technology [1], Cellular Manufacturing [2], Reconfigurable Manufacturing Systems [3], Agile Manufacture [4], Mass Customization and Postponement [5], Economy of Scope Production [6] and Holonic Manufacture [7]. But there is significant overlap in their underlying concepts and related emergent methods and tools. However the process of choosing a suitable guiding manufacturing philosophy is not a trivial one. What is more, if a bad philosophy is chosen, such that production systems developed and deployed do not well match their engineering and business environment, the likelihood is that the Manufacturing Enterprise (ME) will fail sooner or later. Further, as their environments change over time the best choice of philosophy will change; as might that best choice with respect to different product groups made by a ME

It follows that design of any given ME must recognize key characteristics of its business environment as well as understand impacts arising from associated engineering and operational constraints. This requirement is illustrated conceptually by Figure 1. If these characters and their impacts are well known, in principle the said ME can select a manufacturing philosophy which suits its specific circumstance; so that significant competitive advantage can be achieved relative to other MEs. But the reality is very complex; especially if a given ME needs to diversify its product range. In such cases typically MEs must use a finite human, IT and machine resource to achieve so called economies of scope, as well as economies of scale.

Hence, a new opportunity exists for ME's to realize a step change in production systems delivery and change, leading to world class high value, small to medium volume production. This paper reports on developments that promise such a step change, initially in auto, aero and construction equipment industries with roll out to other sectors. It describes how integrated models of people, product, process and plant (ip4) can be deployed, using virtual engineering software tools, along with innovative forms of reusable assembly system components, to full life cycle engineer large scale assembly systems.

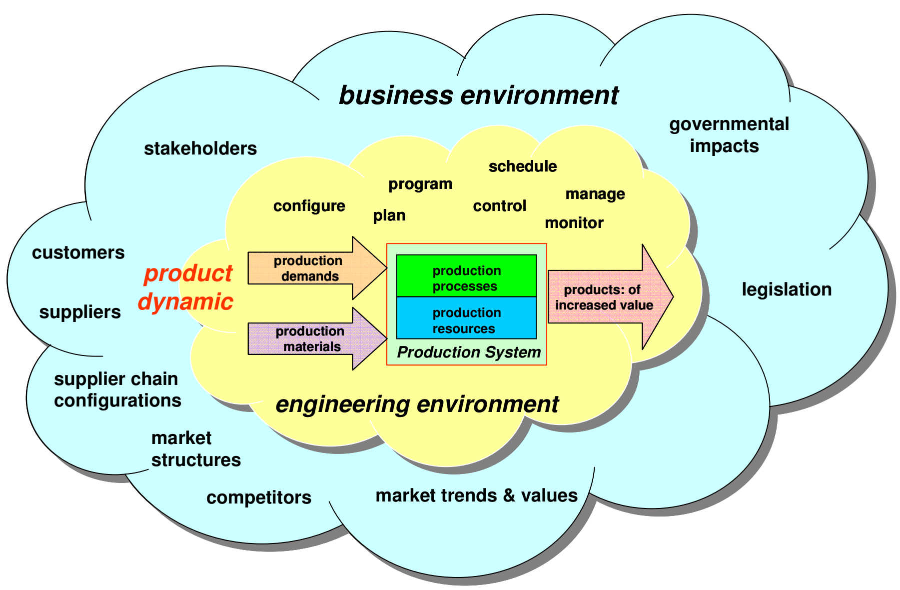

Fig. 1. Next generation production systems must continue to fit their changing environments

2.0 Full Life Cycle Engineering Requirements Defined

Here automotive industry best practice is outlined when engineering a large scale assembly system[9] which is required to make car engines in significant volumes. The purpose of so doing is to illustrate how virtual environments have potential to realize a step change in best practice industry wide; such that 'full life cycle engineering' of next generation manufacturing systems can lead to business benefits. Figure 2 illustrates elements of a typical automotive engine assembly line.

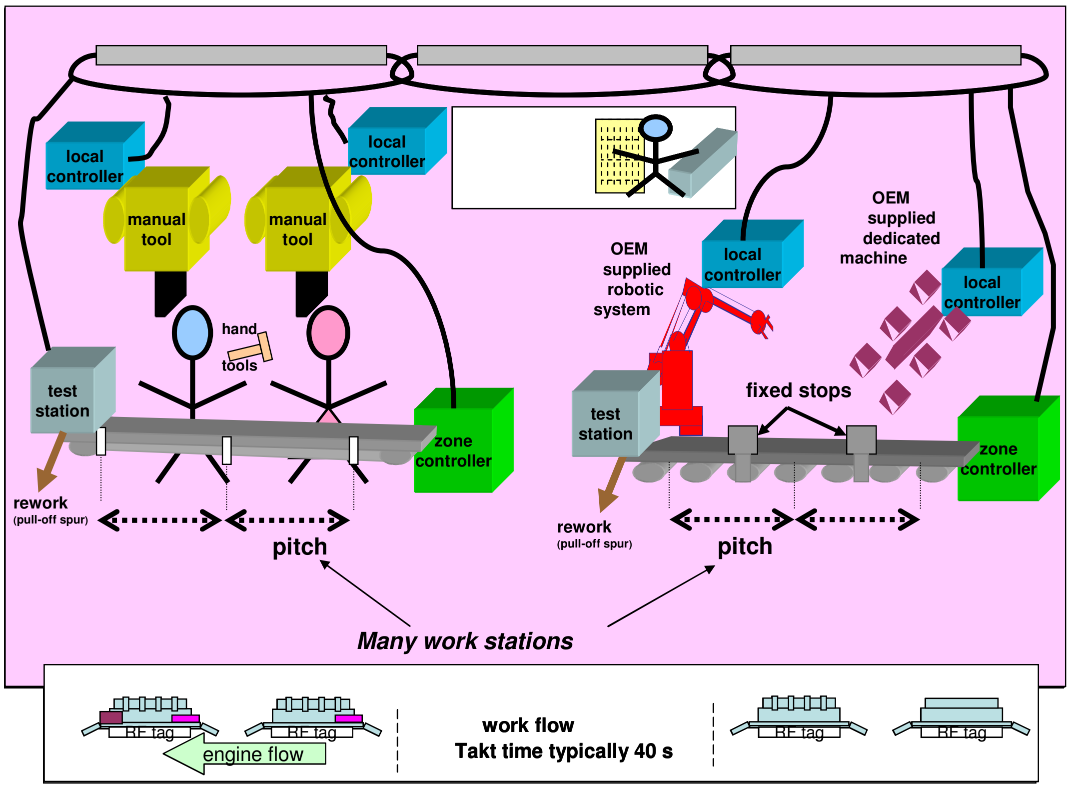

Fig. 2. Illustration of current best practice automotive engine assembly system

Often such a line comprises some 40 to 70 workstations that range from being largely automated to primarily manual; dependent on specific assembly operations required at each stage of value generation. Common practice is to 'pull' engines through work stations at a specific Takt time; which determines the production-rate at which engine products are output from the line. This requires complex component feeding operations and effective synchronization of operations and work flows. Also distributed controls are used to achieve information support and process synchronization.

Current auto industry assembly systems engineering practice is world class and is conceptualized by Figure 3. But significant constraints remain with respect to making custom products. Inherent complexity levels necessitate formation of multidisciplinary teams, some affiliated to end user manufacturers, others to original equipment manufacturers and technology vendors. Those teams can be distributed globally and typically comprise 10 to 100 persons. The perspectives of team members on 'what is required', 'possible conceptual and detailed solutions' and on 'runtime operations' and 'support services' are different but complementary.

But they are all concerned with people, product, process and plant (p4) issues, which themselves have complex interdependencies. What team members do and when, is structured by proven methods and enabled by many kinds of computer tool and information support system. Methods used are generally Manufacturing Enterprise specific but build upon widely known approaches to systems engineering, software and database engineering, control systems engineering, waste reduction, process synchronization, etc.

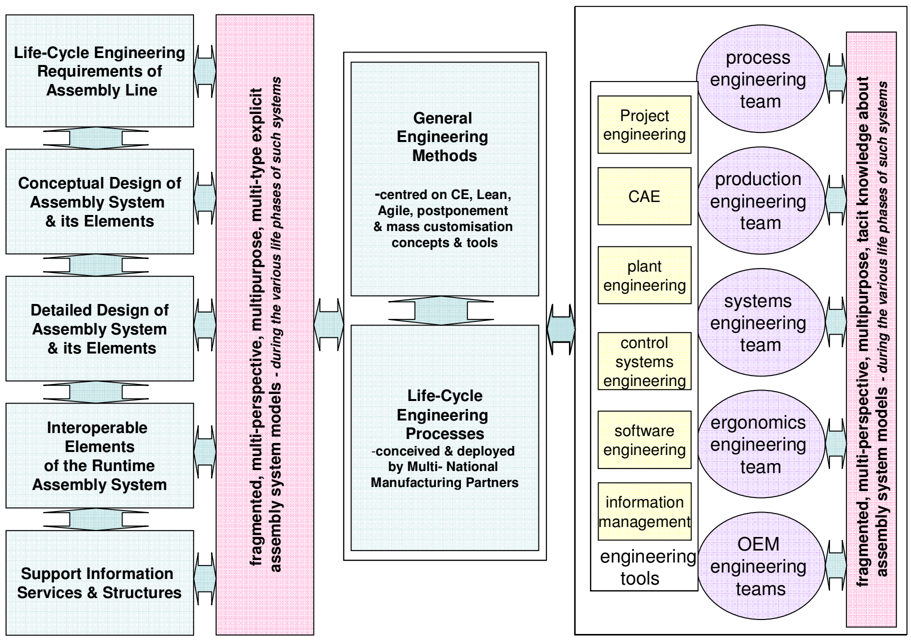

Fig. 3. Conceptualization of Current Best Practice Assembly Systems Engineering

One major constraint of current best practice is that necessary requirements to reprogram and reconfigure (collective and individual) operations of workstations (that typically comprise a large scale auto assembly system or 'line') need largely to be determined during first off systems engineering. This requires significant foresight about needed processing routes and operations, for all product variants, that must be realized by the assembly system during its intended lifetime. To some extent remaining uncertainties can be mitigated by embedding redundant capabilities into assembly systems, but generally such an approach cannot lead to economic and timely assembly of multiple product types (with their different ramp up and down profiles) through extended time periods. It follows that current best practice first off engineering is very costly. Also as current practice only facilitates limited externalization and integrated reuse of p4 knowledge and data then subsequent projects (e.g. to create a new large scale assembly system or to make a major change to an existing one) may be equally costly. Even relatively minor unforeseen changes may not be catered for without very significant re-engineering implications.

Consequently, the useful lifetime of conventionally engineered large scale assembly systems will in general decrease as product lifetimes decrease.

Other major constraints arising from current best practice include: lack of multi-perspective project quantification and decision support; lack of well designed and explicitly specified 'interfaces' between system elements (e.g. modules or 'assembly system components'); ad hoc use of systems integration technologies and services; and locking into specific technology or OEM that constrains later change.

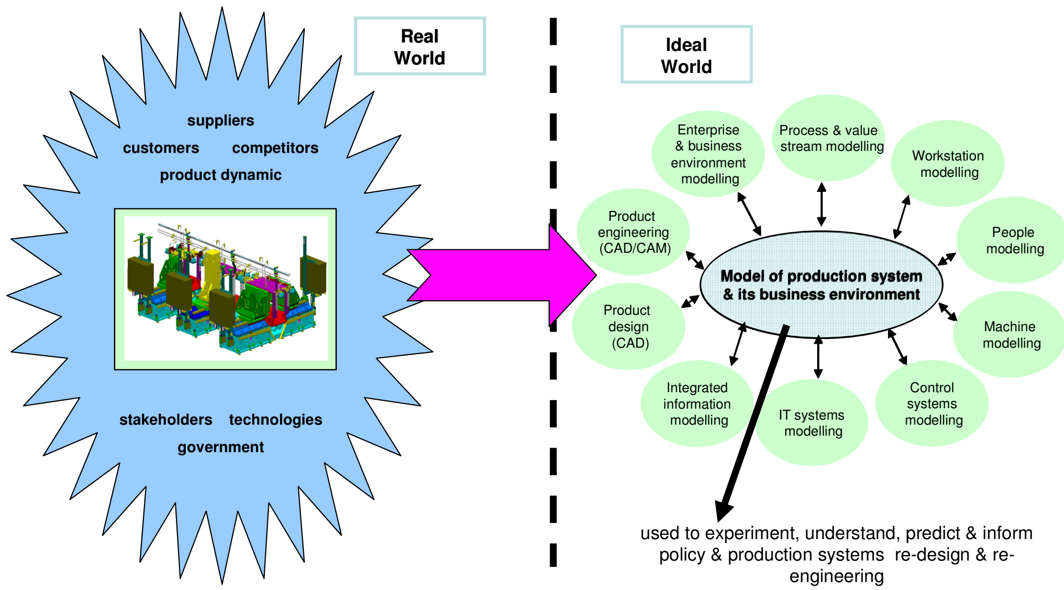

Fig. 4. Virtual engineering of responsive production systems

Current work of authors and their research colleagues in the MSI Research Institute and Centre of Excellence for Customized Assembly at Loughborough University seeks to deliver a step change in current best practice leading to 'full life-cycle engineering' of large scale assembly systems; this paper and conference presentation explains in outline how new forms of 'virtual engineering environment' and 'reusable assembly system components' are being developed that are suitable for cross industry sector deployment. Figure 4 shows in concept how CECA project engineers are deploying a set of virtual engineering tools to create an integrated set of multi-perspective models of assembly systems and their dynamic behaviors. This toolset brings together models of products, processes, people and machines (plant) related to the design, implementation and ongoing programming and reconfiguration of production systems capable of coping with predictable and unpredictable product dynamics of types 1) to 4). As illustrated conceptually by Figure 4, three prime keys to the use of this virtual engineering toolset are:

1) Use of enterprise modeling to provide modeling formalisms that are needed to cope with the high levels of complexity involved when capturing enduring characteristics of the business and engineering environments in which a given reconfigurable production system will be used; thereby providing a well defined context for production systems modeling

2) Use of a Product Lifecycle Management (PLM) software platform to manage coherent access to actual product, process, people and machine data and models pertaining to a given ME and its production systems, and

3) Use of various simulation tools including discrete event and continuous simulators that computer execute and animate models of workloaded production lines and production workstations and their related machine and people systems; thereby enabling the selection and matching of suitable manufacturing philosophies.

The set of modeling viewpoints shown conceptually in Figure 4 is being used to create an integrated set of graphical and computer executable models that represent the example engine assembly production line shown in Figure 2. The approach taken is illustrated in Figure 5.

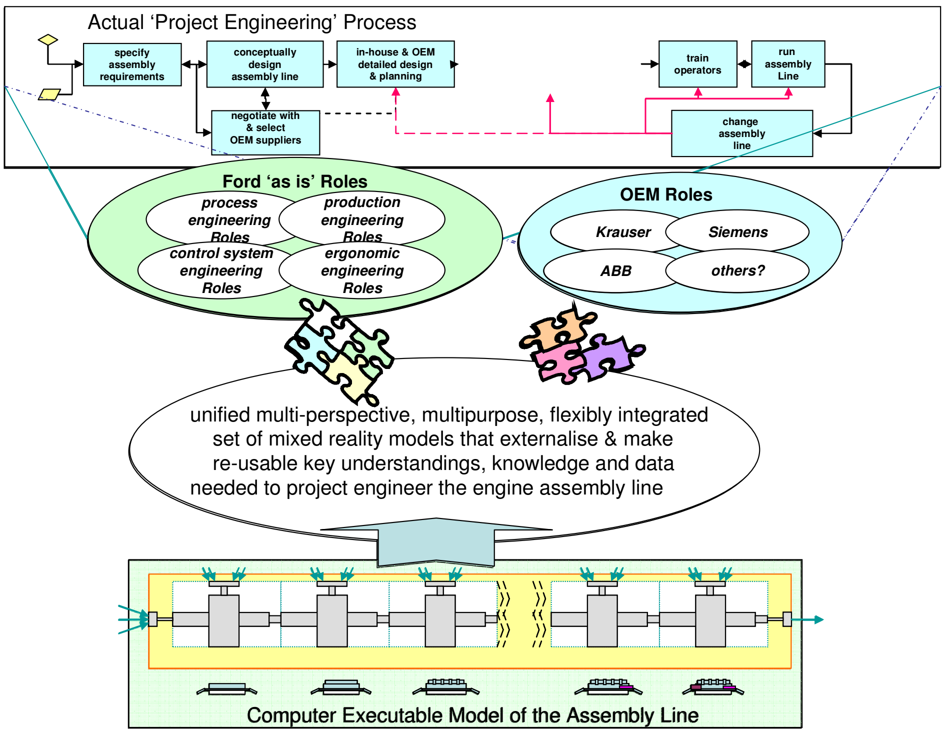

Fig. 5. Illustrative Use of Multi-Perspective Assembly System Models by Engineering Teams

3.0 Dynamic Producer Unit (DPU) Concepts; enablers of iP4 model Integration

It was observed that new modeling concepts are required to facilitate (I) the required integration of modeling viewpoints illustrated by Figures 4 and 5 and (II) realize effective modeling of production system components. This led the authors and their colleagues in the MSI Research Institute to conceive and develop so called Dynamic Producer Unit (DPU) modeling concepts. The prime purposes of DPUs is to enable human, machine and IT resource systems to be described coherently and explicitly as 'reusable', 'change capable' 'components' of manufacturing enterprises. DPU characterization is designed to facilitate: (1) **graphical representation** of resource systems (2) **explicit specification** of resource systems and (3) **implementation descriptions** of resource systems that can be computer executed within simulation modeling environments. Also developed has been a methodological use of the DPU modeling constructs, in which their use complements that of ISO Enterprise Modeling and proprietary (discrete event and continuous) simulation software. By so doing the modeling of responsive production systems is enabled; where such systems comprise user defined configurations of process networks, resource systems and time dependent flows of units of work. This modeling method enables decomposition and semantically rich representation of complex systems composed from interoperating DPUs that can be computer exercised within specific organizational contexts.

It follows that a DPU is defined as being 'an organizational unit comprising people, machines and/or computer systems that form a configurable, re-usable and interoperable component of a more complex production system'. Figure 6 illustrates key properties of DPUs that are modeled. DPUs need to function (a) individually, as a holder of one or more assigned roles and (b) collectively, by interoperating with other DPUs to realize higher level roles (i.e. some configuration of roles to which the interoperating DPUs are assigned).

Dynamic character sets are used to describe and quantify inherited and acquired behavior traits of DPUs. The generic attributes defined for this purpose belong to three classes: (1) productivity characters, (2) change capability characters and (3) self characters. In general it assumed that all DPUs behave in ways related to these traits, but when a given configuration of DPUs is assigned to a specific role set it is understood that not all character sets are of equal importance to different users of manufacturing system models (e.g. to product, process, automation, IT systems and ergonomic engineers or to business and manufacturing managers). The conference presentation will illustrate a case study use of DPU concepts to: (i) conceptually model alternative manufacturing system configurations, (ii) to match these alternative DPU configurations to work loaded roles and (iii) to predict individual and collective DPU behaviors when subject to different forms of product dynamic.

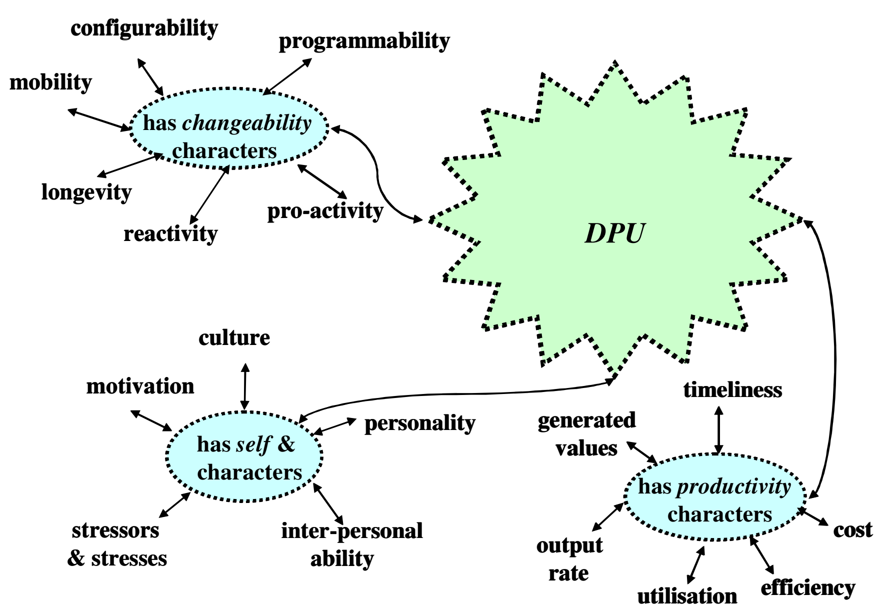

Fig. 6. Dynamic Producer Unit Concept

4.0 Conclusion

This paper has described in outline how virtual engineering tools can be used in a unified fashion to model people, process, product and plant (machine) aspects of responsive production systems. The multi-perspective models developed can be captured, managed and updated and used by various members of large-scale production systems engineering teams to design and support ongoing engineering of actual production lines. They achieve this by computer executing and experimenting with the various modeling viewpoints afforded to them. The approach described is particularly novel in the way that it uses a combination of (i) enterprise modeling concepts, to structure the design of the multi-perspective models, (ii) extended product lifecycle management software, to provide an integrated platform of reusable p4 information, and (iii) DPU component based modeling concepts, that bridge a current gap in proprietary virtual engineering technology provision by providing a generalized abstraction of any form of component building block used in production systems.

The overall approach is being case tested in automotive, aerospace and furniture industries. The conference presentation will illustrate in outline how significant benefit is promised to industrial collaborators in terms of: extended production system lifetime, and better, faster, more responsive and leaner production.

Acknowledgement

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AN INTEGRATED METHODOLOGY FOR STRATEGIC SELECTION PROBLEMS

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Abstract

The strategic selection problem is a multi criteria problem which includes conflicting tangible and intangible criteria. In order to select the most appropriate strategic alternative, it is necessary to make tradeoffs between these criteria, as well as taking into account the resource limitations which may exist. Available methods neglect the distance concept which exists between the alternatives' weights with regard to a single criterion and its target value. In this paper in addition to applying the Analytical Hierarchy Process (AHP) as a stand-alone methodology, an integration of the AHP and Zero-One Goal Programming (ZOGP) is proposed. In this integration, each single criterion is viewed as a constraint in a ZOGP model which enable the model to take into account not only the distances but also to consider the real resource limitation for tangible criteria. In order to justify the methodology, it is applied to selection of Advanced Manufacturing System (AMS).

Keywords: Strategic, Selection, AHP, ZOGP, AMS

1.0 Introduction

The strategic selection problem is an important task for companies. Choosing the best manufacturing process, choosing between different advanced manufacturing technologies and choosing between different suppliers are some examples of this situation. In these situations, those alternatives should be selected which best consistent with the company's strategic objectives. The selection process is the process of narrowing the set of alternatives under consideration [1,4]. A large set of alternatives should be initially screened down to a smaller set because some are clearly not feasible for obvious reasons, such as infeasibility for manufacturing or the cost of producing [7]. Using rational decision making techniques which compare the remaining alternatives, a dominant alternative can be chosen [11].

The strategic selection process is a complex task because of the conflicting tangible (such as cost) and intangible criteria (such as flexibility), sub-criteria, different stakeholders and real constraints. An alternative which is best from the point of view of, for example, the manufacturing department, may not be the best from another department, for instance, marketing, because each individual department has its own perception, viewpoint and criteria. In general, this sort of problem should be investigated at the Multiple Criteria Decision Making (MCDM) environment [5]. In this situation, the decision maker(s) is unable to decide between a numbers of alternatives not only because of the presence of different objectives but also because there are often multiple conflicting criteria. To make a decision, decision maker(s) should make tradeoffs between the conflicting criteria in order to prioritise the goals and criteria for selecting one alternative. In this situation, decision makers should decide which criteria have most effect in the decision [3].

This paper suggests a methodology based on integration of AHP and Zero-One Goal Programming (ZOGP) for selecting the most appropriate alternative among available conventional and strategic alternatives, considering the distance concept.

2.0 Methodology

The basic idea in the methodology is to use problem decomposition and explicit value or preference tradeoffs from the point of view of each criterion or sub-criterion. When there are multiple criteria for evaluating alternatives, the best alternative from point of view of each criterion is different [5]. Therefore, there are distances between the final selected alternative and the best alternative from point of view of each single criterion.

Goal Programming (GP) is a procedure for handling multiple-objective situations within the general framework of linear programming. Each objective is viewed as a goal. Then, given the usual resource limitations or constraints, the decision-maker attempts to develop decisions that provide the “best” solution in terms of coming as close as possible to reaching all goals. The analytic hierarchy process (AHP) has been proposed as a means of reconciling initial decision-maker’s expression of preference, as well as means of identifying the consistency of that expression. It provides an estimate of additive utility weight that best matches the initial information provided by the decision-maker. Moreover, when the AHP is used to obtain an initial estimate of the priorities, the initial points are selected on the bases of pairwise comparison of alternatives. The AHP addresses how to determine the relative importance of a set of activities in a multi-criteria decision problem. The process makes it possible to incorporate judgements on intangible qualitative criteria alongside tangible quantitative criteria. The method utilises pairwise comparisons of alternatives as well as pairwise comparisons of the multiple criteria. The use of such pairwise comparisons to collect data from the decision-maker offers significant advantages. It allows the decision-maker to focus on the comparison of just two objects, which makes the observation as free as possible from extraneous influences. Additionally, pairwise comparisons generate meaningful information about the decision problem, improving consistency in the decision-making process. AHP-ZOGP objective function seeks to minimise deviation from desired targets for limited resources. The goal constraints represent the availability of limited resources. The right-hand side of each equation reflects the targeted or desired level of the resources utilisation. In the combine model, the objective function seeks to minimise deviations from desired levels. The most obvious advantage of using the AHP model for deriving weights for the problem is that it provides for consistent decision-making. The combined AHP-GP method offers a systematic, easy-to-use approach to the service quality control instruments selection decision problem.

The methodology tries to select that alternative which has minimum total distances using the ZOGP model. The distances are minimised with their associated weights, which are the relative importance of each single criterion, obtained by global weights of the AHP.

In the methodology, each individual criterion or sub-criterion has a constraint in the ZOGP model. The global weights of criteria become the objective function coefficients of the ZOGP model. These coefficients associated with the distance from the left hand side (coefficients of each individual alternative) can be obtained by AHP (if they are related to intangible criteria), and a normalization process (if they are related to tangible criteria). When alternatives are compared with regard to a single criterion, they will have weights that show the relative importance of the alternatives regard to that criterion. These weights become the coefficients of the zero–one variable (non-selection and selection) of an alternative, respectively. The right hand side (the target value) of each constraint is in fact, the best coefficients of left hand sides' coefficients for intangible criteria and normalized target values for tangible criteria. There is also a distance between the left hand side and target value of a constraint. The distances are the slack (surplus) variables of each constraint. If the best alternative from point of view of a criterion is identical with the final selected alternative, then the distance is zero. Otherwise, there is a distance which impacts on the value of objective function. The model minimisation iterative process tries to eliminate those alternatives where the related criterion coefficients in the objective function are more than others. The nature of zero–one variables will select one alternative which has the smallest distance.

3.0 Case Study

To implement the methodology, the problem of AMS selection is considered which has been previously solved by AHP method [2]. The AMS selection is a strategic decision because of its long term intangible benefits (such as improving flexibility and the standards), non-repetitively, having many conflicting criteria, and non-existience of the status quo alternative [8,9,10]. These factors necessitate applying the MCDM approach because traditional financial methods are not able to include intangible benefits associated with AMS. A comparison is then made between using AHP and the proposed methodology. This problem is selected because all the elements of the methodology such as hierarchy construction, determining criteria, pairwise comparisons, AHP solution, have been identified. The problem involves the selection of one alternative among Flexible Manufacturing System (FMS), Transfer Line (TL), Flexible Manufacturing Cell (FMC), Flexible Manufacturing Module (FMM), and Job Shop (JS) for developing a company.

3.1 Solving the Problem using AHP alone

This problem has been solved using AHP [2]. All the criteria and pairwise comparisons have satisfied their associated rules. The hierarchy, criteria, alternatives, relative importance of criteria, and final weights of alternatives have been depicted in Figure 1. Applying AHP indicates that the ranking of alternatives are FMS, TL, FMC, FMM, and JS, respectively. Interested readers are referred to the reference for a full description of the criteria and alternatives.

3.2 Integration of AHP and ZOGP

To solve the problem using an integration of AHP and ZOGP, it is necessary to construct the constraints and objective function of the ZOGP model. The alternatives should be evaluated by pairwise comparison against a criterion in order to obtain the partial weights which will form the parameters of constraints in the ZOGP model. In other words, the winner alternative can be determined from the point of view of each criterion by the relative importance of available alternatives. These partial weights can be found in the original paper [2].

3.2.1 ZOGP Model

The ZOGP model of this problem based on minimisation sum of individual relative importance of criteria or sub-criteria and using partial weights for parameters of constraints is as follow:

$$Min\, 0.202d_{01}^{-} + 0.214d_{02}^{-} + 0.026d_{03}^{-} + 0.042d_{04}^{-} + 0.038d_{05}^{-} + 0.068d_{06}^{+} + 0.129d_{07}^{+} + 0.110d_{08}^{-} + 0.014d_{09}^{-} + 0.123d_{10}^{-} + 0.017d_{11}^{-} + 0.017d_{12}^{-} \tag{1}$$

Subject to

$$0.036TL + 0.499FMS + 0.239FMC + 0.149FMM + 0.077JS + d_{01}^{-} - d_{01}^{+} = 0.499 \tag{2}$$

$$0.141TL + 0.491FMS + 0.243FMC + 0.086FMM + 0.039JS + d_{02}^{-} - d_{02}^{+} = 0.491 \tag{3}$$

$$0.149TL + 0.483FMS + 0.218FMC + 0.107FMM + 0.044JS + d_{03}^{-} - d_{03}^{+} = 0.483 \tag{4}$$

$$0.146TL + 0.537FMS + 0.193FMC + 0.081FMM + 0.043JS + d_{04}^{-} - d_{04}^{+} = 0.537 \tag{5}$$

$$0.150TL + 0.506FMS + 0.210FMC + 0.091FMM + 0.042JS + d_{05}^{-} - d_{05}^{+} = 0.506 \tag{6}$$

$$0.130TL + 0.493FMS + 0.242FMC + 0.098FMM + 0.036JS + d_{06}^{-} - d_{06}^{+} = 0.036 \tag{7}$$

$$0.445TL + 0.284FMS + 0.151FMC + 0.079FMM + 0.041JS + d_{07}^{-} - d_{07}^{+} = 0.041 \tag{8}$$

$$0.462TL + 0.297FMS + 0.126FMC + 0.079FMM + 0.037JS + d_{08}^{-} - d_{08}^{+} = 0.462 \tag{9}$$

$$0.118TL + 0.503FMS + 0.252FMC + 0.087FMM + 0.039JS + d_{09}^{-} - d_{00}^{+} = 0.503 \tag{10}$$

$$0.505TL + 0.261FMS + 0.132FMC + 0.067FMM + 0.035JS + d_{10}^{-} - d_{10}^{+} = 0.505 \tag{11}$$

$$0.027TL + 0.069FMS + 0.136FMC + 0.266FMM + 0.502JS + d_{11}^{-} - d_{11}^{+} = 0.502 \tag{12}$$

$$0.115TL + 0.482FMS + 0.261FMC + 0.100FMM + 0.042JS + d_{12}^{-} - d_{12}^{+} = 0.482 \tag{13}$$

$$TL + FMS + FMC + FMM + JS = 1 \tag{14}$$

$$TL, FMS, FMC, FMM, JS = 0 \text{ or } 1 \tag{15}$$

$$All\ d_{j}^{+/-} \geq 0 \tag{16}$$

For example, 0.036 in first constraint (2) is the relative importance of TL alternative when all the alternatives are compared against flexibility criterion. Objective function coefficients are the relative importance of each criterion which has been shown in Figure 1 (level 2). The target values of constraints are the best parameters of relative constraints, so that when choosing the best alternative from a special criterion, there is no distance or difference between the target value and the chosen alternative. However, when a non-optimal alternative is chosen in respect of that criterion, there is a distance which is considered with its global weight that is now the coefficient of objective function. It is worth noting that the nature of objective function minimises the undesirable distances. The result of the AHP and AHP-ZOGP approach are shown in Table 1. As the table shows, when more than one alternative should be selected (for instance two of them), then the solution of new methodology is differed from AHP alone. The AHP alone selects the FMS and TL, while the new methodology chooses FMS and FMC.

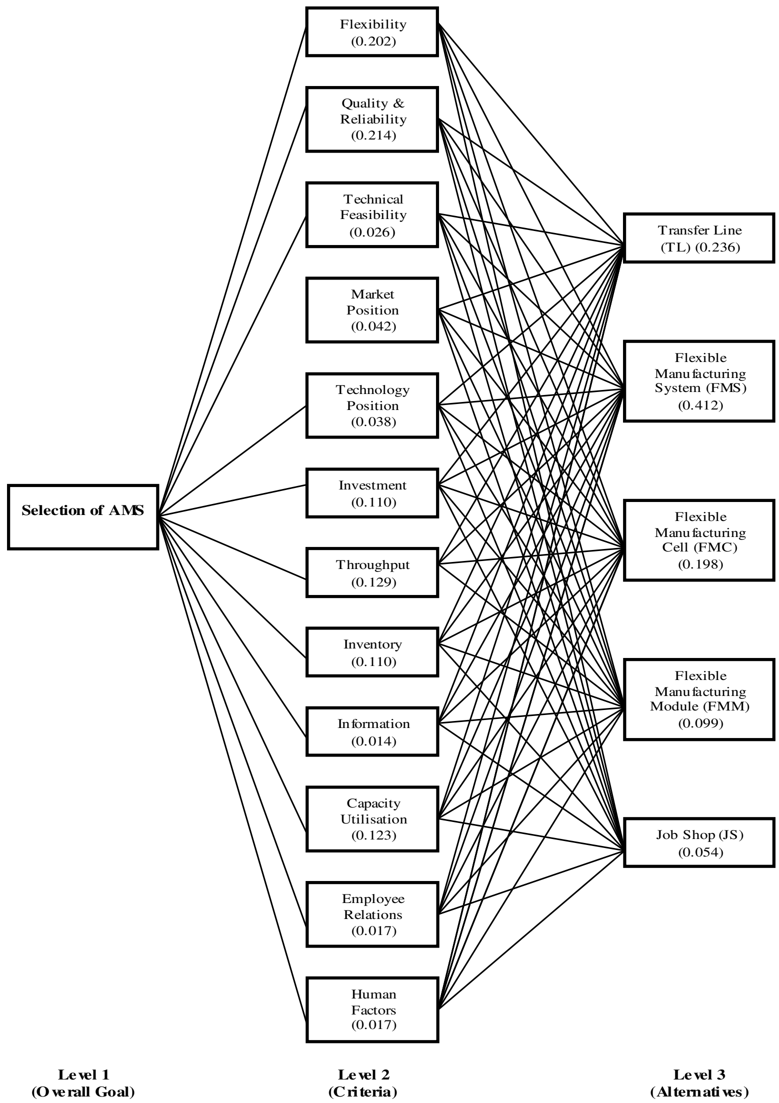

Fig. 1. Hierarchy, criteria, and alternatives of AMS problem

Table 1: Result of AHP and AHP-ZOGP

Alternatives	Orders using AHP	Orders Using AHP-ZOGP
TL	Second	Third
FMS	First	First
FMC	Third	Second
FMM	Fourth	Fourth
JS	Fifth	Fifth

4.0 Conclusion

This paper indicated that when making a strategic selection decision involving diverse range of conflicting criteria, integration of AHP and ZOGP could help the decision maker(s) to make a sound decision. AMT selection was applied to justify the methodology because of its strategic nature. The case study demonstrated that the proposed approach can give the decision maker(s) some useful aids in order to make a final decision. These aids include the deviations from each target value which means with selecting a specified alternative, what criteria are satisfied exactly and how much attainability has been occurred for other ones. This methodology introduced resource limitations for tangible criteria (such as budget limitation) and criteria constraints in order to remove the drawbacks of AHP when it is used alone. The methodology can be applied for identical selection decisions such as selection of design alternatives in the early stages of design process, selection of the contractors for manufacturing the special parts for production, selection of suppliers, and so on. It is obvious that for these applications, the problems will have the special criteria and limitations which will be included in the selection process.

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AN IT PERSPECTIVE OF LEAN

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Abstract

It is generally accepted that Lean improves manufacturing processes with recognised tools and techniques, and equally assumed that present day IT systems, particularly enterprise-wide systems, are essential for companies seeking efficiencies through organisational integration. Addressing the question "can Lean and IT co-exist or even should they?", it may be observed that both Lean and IT are tools with respective uses and strengths. Hence, a potential exists to maximise impact for a business if they are used concurrently. The authors of this paper bring a collective insight into this debate based on practical experiences in delivering Enterprise Integration and Lean respectively, and the development of a methodology that is constantly evolving.

The central theme of this paper it to evaluate how a Lean programme should be supported and enhanced by a complementary IT infastructure and tools. The proposition is that a well configured IT system acts as the "information spinal cord" and "nervous system" reaching out and connecting departments as well as the processes taking place. Two case studies are used to illustrate the coupling between Lean and IT being investigated in these long term studies conducted jointly by two teams in the North East region of England.

Keywords: Lean, IT, Enterprise Integration, ERP, Continuous Improvements.

1.0 Introduction

Lean Manufacturing has become an established and proven mechanism to improve competitiveness within a manufacturing organisation given the success of Toyota Corporation [14]. With regard to IT based systems intended to provide business-wide integration and efficiency, these have been evolving since the early 1950s through MRP and MRPII to the current ERP (Enterprise Resource Planning) and ERPII. Nevertheless, change programmes and implementations of ERP systems have been adopted with varying degrees of success and failure [6] and various strategies and approaches exist for implementation of these systems in an organisation [10]. The research of Bhasin and Burcher [5] who, quoting Mora [17]; Sohal and Eggerston [22]; Baker [3] and O'Corrbui and Corboy [19], report failure rates at 90%. A fundamental question is which technology should a business implement first or should there be a parallel approach. The authors of this paper have encountered this quandary many times in their consultancy and training activities over recent years. Hence, this paper aims to addresses the question of compatibility between computer based manufacturing support systems and what is recognised as the Japanese approach to productivity improvement and enters the chicken-and-egg discussion as to which should be commenced first: an integrated IT driven enterprise or a Lean programme. Two case studies illustrate a developed methodology, where two support programmes are working together to achieve overall business improvement within a company.

2.0 Holistic Approaches in Organisational and Systems Change

The origins and analysis of communication networks go back to 1940-50s in the work by Leavitt et al [13]. In their findings, "all-channel" networks were found the most suitable for organisations for corrective feedback possibilities, which are important for an organisation to take rapid decisions and deploy actions. Nevertheless, as more and more parties are involved in a communication network, the complexity increases. For example if 16 individuals or departments are represented, 120 bi-directional channels are required (combination rule in Math) for effective cross-functional collaboration in carrying out a task. Therefore, a more holistic and integrating tool is proposed in current environment to cope with the increasing complexity, manage information flow and ultimately increase the levels of integration. An appropriate and fit-for-purpose tool will assist people to manage information, have a greater perception about targets, responsibilities, problems, actions required to tackle constraints primarily in their own areas and then in the organisation as a whole.

If we represent an organisation as a pyramid with three distinct layers, conceptualised as Strategic, Tactical and Operational, we could be looking to implement an IT system such that it would help integrate these management tiers in an effective manner, managing both the information and material flow between departments or functions so that gaps between the functions do not occur. Fig. 1 depicts how the vertical tiers and horizontal silos combine to form islands in an archipelago.

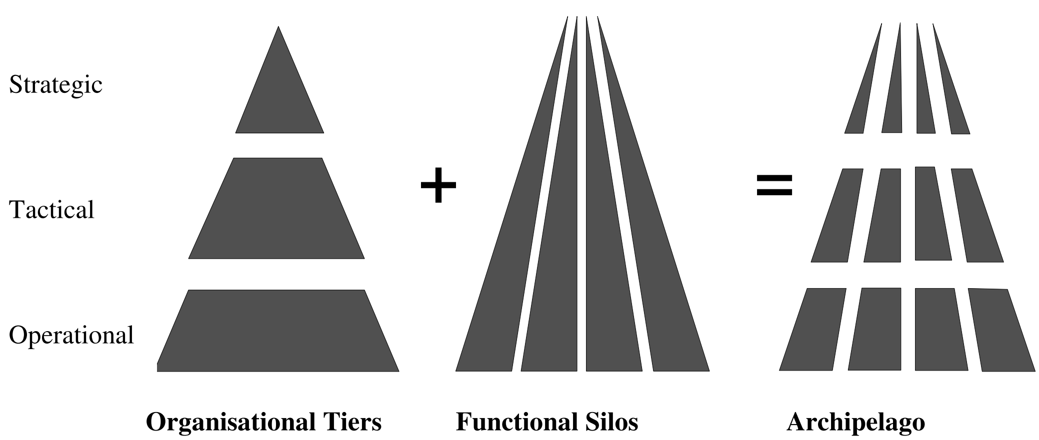

Fig. 1. Evolution of an archipelago

The use of integrated systems and ERP systems in particular, attempts to bridge these islands within the archipelago. Only if the organisation and its processes are harmonised with the systems capabilities will the islands move from the archipelago to a truly integrated "continent" as proposed by Bessant and Haywood [4]. From research [1]-[2] and direct experience of the authors, this integration also benefits company mission and strategy, which can be divided into Critical Success Factors (CSFs) or sub-goals; Key Business Processes (KBPs) to achieve the CSFs and Key Performance Indicators (KPIs) to monitor the performance and the effectiveness of KBPs. Furthermore, every department or function benefits as it has its own unique processes. Some examples of these are given below:

Table I: Examples of departmental processes

– People Training, Development and Teamwork	– Production Planning and Scheduling
– Financial Performance	– Data Collection
– Customer Relationship Management	– Financial Reporting
– Marketing & Business Development	– Time and Attendance
– Product and/or Process Quality	– Business Communication
– Organisation Structure and Culture	– Recruitment, Reward and Retention
– Supply Chain Management	– Lessons learnt & Continuous Improvement
– Sales Analysis & Forecasting	– KPI Measurement

3.0 Lean Manufacturing vs. IT

The demands on a company that sets out to implement a Toyota production System (TPS) type methodology are far reaching, and may require a total revision of the organisation. There is an acknowledgement from some researchers of the difficulty of introducing a paradigm shift such as Lean Manufacturing. The work of Papadopoulou and Özbayrack [20] confirms this by reporting: "The transformation process to a Lean Manufacturing production system requires a lot of effort, participation of all levels in the hierarchy, introduction of new principles not only in the shop-floor level but also in the company culture and organisational structure." Motwani [18] also highlighted the commitment required. A vision of a Lean company by James-Moore and Gibbons [11] should have the following five characteristics, which lend themselves to measurement: flexibility, process control, optimisation, waste elimination, and people utilisation. These parameters clearly highlight the need for a feedback and control mechanism in order to implement and monitor them. Moreover, the subject of what is a Lean company is important. Jayaram et al [12] and James-Moore and Gibbons [11] suggest that a Lean company is much more than a Lean manufacturer. They also emphasised the fact that a whole organisation is involved across all tiers and layers; e.g. not just the production department. This is why the authors have laid considerable emphasis on enterprise tools, notably ERP. To introduce a paradigm shift such as Enterprise Integration and Lean Manufacturing specifically, there must be consensus within all the management as to how a company would like to set out a strategy and operate to fulfil that strategy [15]. Perez [21] suggests: "When the full constellation of a new techno-economic paradigm tends to take over the bulk of production within a society, it will not yield its full growth until the socio-economic framework is transformed to adapt to its requirements". There is no reason why the organisational structure of a manufacturing company cannot be considered as the same as a socio-economic framework in miniature. TMC's CHI methodology [2] is based firmly on this premise, such that without the consensus and commitment from the top management team, no further step or work is initiated.

3.1 North East Productivity Alliance (NEPA) Approach for Lean Manufacturing

NEPA is a public/private advisory programme, which was created to improve the competitiveness of North East England regional manufacturing [8]. The programme has two elements: The Digital Factory Programme, which was created both to introduce engineers to digital manufacturing technology and up-skill engineers in the latest software and Best Practice Dissemination Team (BPDT), which has the role of disseminating "world's best" manufacturing practice into regional manufacturing [9].

3.2 Enterprise Integration through TIE Approach

TMC (Teesside Manufacturing Centre) is based at the University of Teesside, specialising in consultancy and tailored training services in order to assist manufacturing and engineering companies to become better integrated from an organisational, cultural and systems perspective, by using its own developed methodology [1]. The aim is to utilise carefully selected integrated electronic-based management systems to benefit a whole organisation through changes in associated processes and procedures, and also people skills and attitudes. As Enterprise Integration can be a problematical and lengthy task and it involves large and diverse numbers of staff, associated processes and suitable systems, a three-phase methodology known as CHI [2] has been developed by TMC in order to "embed" its TIE (Totally Integrated Enterprise) concept. The three steps consist of: **Phase 1: C**onsensus to be achieved by the top management team on the strategic and operational needs for enterprise-wide integration and improvement; **Phase 2: H**oming-in to the requirements by assessing the processes and procedures at present to identify potential solutions; **Phase 3: I**mplementation of systems and new procedures across the company.

3.3 Harmonising Systems and Operational Processes

All processes operate better if outputs or outcomes of a process are predictable within defined limits; indeed, this is the prime objective of the tools and techniques of Lean. Integrated systems also operate better with an element of predictability. It is the concept of sustainability/predictability which may have an influence on the chicken or egg question (Lean or IT first). An out of control process requires constant and accurate updates. Therefore, it is suggested that parallel activities are commenced within a company to introduce stability, which will introduce predictability with regard to outputs and introduce a system, which will report on and drive the process. The strength of an integrated approach (such as the CHI process) forces the management to think about what their requirements are. The Lean process gets on with the removal of waste to introduce the stability. Figure 2 depicts an illustrative situation in a company, where the two types of interventions, from NEPA and TMC, are occurring more or less concurrently.

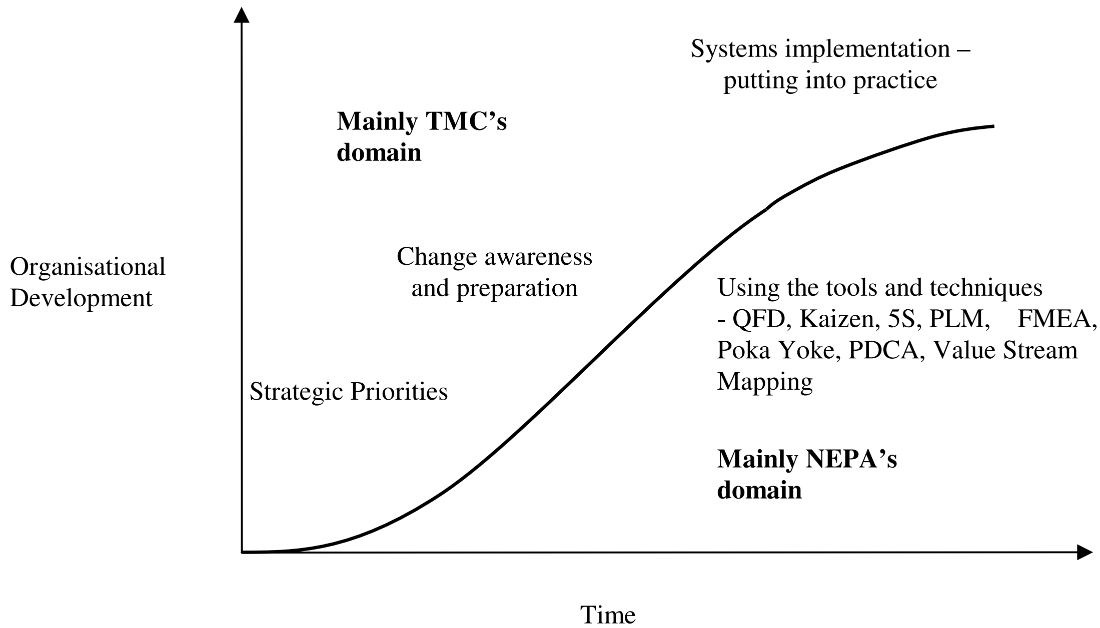

Fig. 2. Joint NEPA and TMC roles in organisational development

A common characteristic (in both TMC and NEPA approaches) is the involvement of people from the outset, then addressing the processes involved and finally setting the scene for systems. Any improvement initiative has to involve people and has to tackle processes that are people familiar with. This enables the sign-on being achieved and builds the foundations for good communication between all parties concerned. This people focused methodology then instigates analysis of the processes and encourages an enterprise-wide thinking acknowledging that processes ripple through the whole organisation. Capturing the "as is" state and appreciation of how processes interact with departments and individuals within the organisation or the whole picture is crucial to engineer the "to be" state, facilitating introduction of appropriate integrated systems and, most importantly, for successful Enterprise Integration.

4.0 Case Studies

The first case study organisation is a small company; a family owned business employing around 70 people. It is a manufacturer of accurate machined products, mainly consisting of steel rods and tubular components. The bulk of its customers are in the automotive industry. Through interchanges with TMC, the company realised that the most effective way to improve the company's overall manufacturing performance was through systems. Senior management realised that in order to achieve this goal the company would have to undertake a comprehensive programme of change. In the joint experience of both TMC and NEPA, these situations are particularly fundamental and prevalent in traditional family run businesses. Some problems did arise in this company, with conflicts within the family hierarchy as to the need for change and the nature of the mechanisms being implemented. Since this was happening during the period that TMC and NEPA were engaging with the company, the consequences for the day to day to operations had to be dealt with by the two teams, alongside the implementation of systems and working practices.

Phase 1 – Consensus - was carried out by running strategic management workshops with the management team to review the company's position compared to the vision and strategic priorities. The team participating in this phase included some people, who also had operational roles, and this had the great merit of opening up the wider picture. The process facilitated the management team to develop Critical Success Factors and Key Business Processes, and set the scene for an Enterprise Resource Planning (ERP) system. Towards the end of Phase 2 – Homing-in, a KTP - "Knowledge Transfer Partnership" (partly funded by the UK Department of Trade and Industry), was initiated in order to deploy a postgraduate "KTP Associate", who then became the dedicated project coordinator and leader. An ERP system was specified, selected and acquired. Additional departmental interviews and exercises were carried out to identify improvement areas and identify operational requirements, training, etc. Soon, it was realised that shop floor efficiency and associated practices were proving problematic. Hence, the NEPA team was called in to address the issues, and subsequently both Enterprise Integration and Lean initiatives ran in a parallel and collaborative manner.

The second case study organisation is a medium sized company in the Oil & Gas Sector that employs around 650 people, operating in a niche market segment with technically complex and sophisticated products. The company has been acquired and sold several times over the past decade, which prevented the organisation from properly addressing and streamlining its business processes. This resulted in outdated systems, manual interventions, duplications and most importantly the archipelagos as depicted previously in Figure 1.

The first contact was made by NEPA. Following a diagnostic assignment [8], commenced a programme of disseminating selected Lean tools and techniques over an initial 12 month period to improve quality, cost and delivery performance. Soon it became clear that the principal problem was the ability of the company to order and deliver the correct components to the point of fit when required. As a result TMC was asked to also engage with the company. The company's senior management quickly acknowledged that Enterprise Integration was a strategic undertaking, and the CHI methodology was put into action. Phase 1, the strategic management workshops, examined the company's current position compared to the vision and strategic priorities Critical Success Factors (CSFs) and Key Business Processes (KBPs) prompted senior management to order an internal review of its top-level thinking, which were later used as the basis of an organisational re-structuring exercise. Hence, Phase 1 activity is described as a "top down" approach. Phase 2 – Homing-in - was carried out immediately following the organisational restructuring and consisted of departmental interviews to capture the "as is" state of existing processes, systems in use, gaps between the departments, linkages required in order to communicate with other departments and cultural issues inherent within the organisation. Hence, this phase can be described as a "bottom up" approach. The findings of this phase were then communicated back to the senior management team. Now that the inefficiencies and problems at the tactical and operational levels could be identified, these problems were prioritised and the decision was made to tackle them before introducing any systems. This resulted in the re-engaging of the NEPA team to address the manufacturing processes and quality issues. As a result the future strategy is now one of twin track as more and more people in the company began to understand that an enterprise is the whole organisation in its totality, and that a holistic approach was going to be necessary to implement change.

TMC then used the information gathered through the Phase 1 and Phase 2 activities to specify and select a comprehensive ERP system to operate across the enterprise as a major facilitator for change and improvement. During this process of selection the team continued a parallel activity of enterprise-wide awareness of the anticipated systems and process reappraisals. Once again, a Knowledge Transfer Partnership (KTP) has been awarded by UK Government to facilitate the major changes being implemented in systems, processes, working practices and organisational culture. In this instance there are two KTP Associates, one focusing on the front end activities (supply chain, customer interfaces, etc) and the other focusing on back end activities (manufacturing, planning, scheduling etc). In addition TMC has provided a project manager and extra people resources for the implementation in the company over a one to two year period, to sustain the new systems and the associated working practices in the organization so that the changes are not just implemented but embedded for the long term. The company is now growing rapidly, with manufacturing operations overseas, and has been floated on the UK Stock Exchange. The joint work of NEPA and TMC will continue to be an important factor as it strives to handle this expansion with integrated systems and processes.

5.0 Conclusion

Our observation so far in the industry is that improvement schemes around Lean and integrated IT Systems, usually in the form of ERP, to address company requirements, have so far been running in a disjointed manner and the literature has been unfairly dismissing any collaboration initiative. There is also the problem of the consultants working in a separate manner in the areas concerned, mainly because they lack the expertise across both the disciplines. As our partnerships in both case studies have shown, organisations will reap the benefits through the combination of Enterprise Integration and Lean if the activity is undertaken in a cohesive manner. The depiction in Figure 3 represents the TMC and NEPA partnership and working model. It attempts to illustrate how both short term operational and long term strategic aspects are brought into play in this joint approach. The overall objective is organisational development. The place of Phase 3 of TMC's methodology is not indicated explicitly but is embedded within the "operations" box, which is influenced both by the Computer Integrated System and by the NEPA Lean approach.

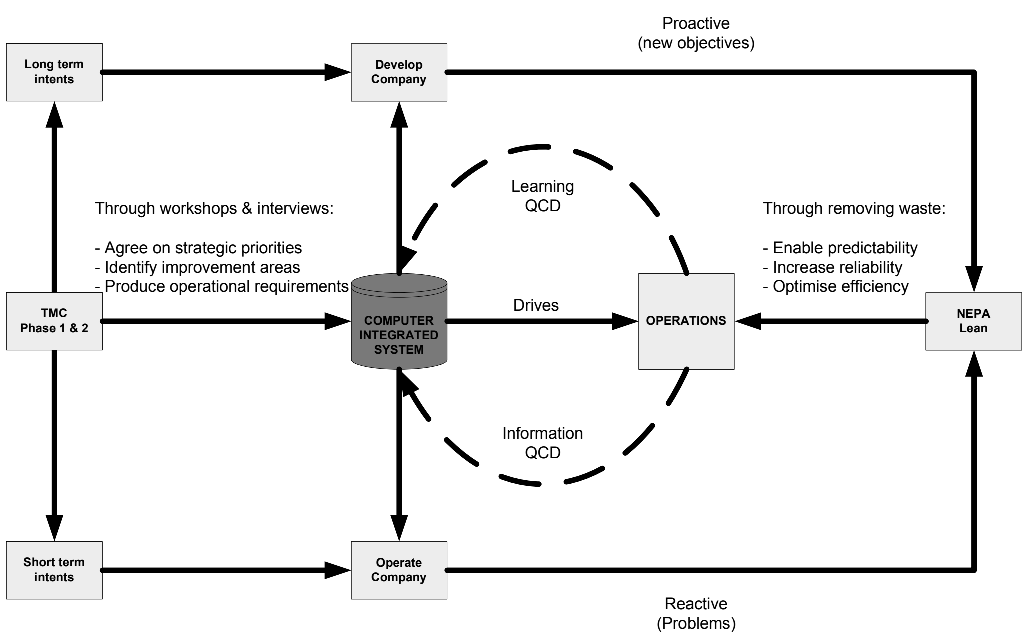

Fig. 3. TMC/NEPA Collaborative Working Model

Our experiences have shown us that such a collaborative model ties the improvement initiatives across the whole organisation covering strategic, tactical and operational intents rather than offering a point solution in a specific area. TMC's approach enables the company to see the bigger picture, covering the long term and short term intents in the existing operations. The NEPA approach removes waste within processes so that operations fulfill the remits of quality, cost and delivery expectations through "quick wins" or "low hanging fruits" after initial reactive responses. As the company knows the strategic direction and intents from the TMC's approach, any improvements made could be injected back into the learning loop and decisions could be made proactively to develop the company forward on the foundations. An additional point is that IT or an integrated system cannot change a company on its own. It needs activities on the ground to respond to data and take action. Those who take the action have to be skilled enough to open the tool kit of Lean tools and techniques and apply them. The application must be directed by the system and generate its own data for the system. The cycle of continuous improvement should be driven by data, as there is a clear cause and effect flow, which will direct the next lean activity.

In this ever-changing and ever-competitive business environment, it is our view that Integrated Systems thinking, i.e. ERP, is increasingly dependent on one of the most effective continuous improvement initiative - Lean. On the other hand, Lean should also be operating in a subservient manner in the TIE up of the two ends. Both TMC and NEPA approaches should be adopted and monitored in a longitudinal manner to see the long-term impact and quantifiable benefits, and plans are being put in place for this. The next stage of our work is to follow up the results of our interventions with selected companies over a long timescale, monitoring the progress, measuring the improvements, and analyzing the problems encountered. This will be reported in future papers.

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APPLYING MODULARITY-IN-PRODUCTION AND LEAN PRODUCTION IN A TERRY WEAVING MACHINE ASSEMBLY ENVIRONMENT

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Abstract

Lean manufacturing techniques can be found today in many industrial environments. There is a growing trend for higher product complexity at lower cost, modularity-in-production and shorter delivery times. Textile machines that produce high quality woven terry fabric are niche products and are assembled in cellular configuration, without a well-defined internal logistical flow, with a lack of standardised work procedures and with poorly defined quality standards.

The problems encountered in the implementation of lean manufacturing techniques to the assembly of a niche market textile machine are discussed in this paper. Design criteria for factory design and assembly process are defined. The basic design of cellular work cells producing modular pre-assemblies and delivering to a short assembly line are described and critically analysed.

Contribution of this paper is the research on modularity-in-production in combination with lean production in a terry weaving machine assembly environment. This manufacturing approach is unique in the market of terry weaving machines.

Opportunities and threats are stated clearly. An improved assembly methodology was developed and implemented to mount pre-assemblies on to a basic machine platform. The findings raise new questions about future trends in the assembly of niche market textile machines.

Keywords: modular assembly, lean production, niche market, terry cloth

1.0 Adoption of Lean Manufacturing

1.1 Fordism and TPS

At Highland Park, Michigan, USA, 1913, Henry Ford married consistently interchangeable parts with standard work and moving conveyance to create what he called flow production. [3]. As Kiichiro Toyoda, Taiichi Ohno and others at Toyota looked at the Ford system just after World War II, it occurred to them that a series of simple innovations might make it more possible to provide both continuity in process flow and a wide variety in product offerings. They revisited Ford's original thinking, and invented the Toyota Production System. [3] The Toyota Production System (TPS) [9] was developed in Japan by Ohno and Shingo and forms the basis of lean manufacturing. John Krafcik labelled the Toyota System as 'Lean Production'. He said that Lean Production was 'a system that uses less human effort and less capital to design products faster and with fewer defects.' [8] Toyota could not afford the capital-intensive mass production systems used in the USA so instead focused upon minimising waste in all aspects of its operations. [1]

1.2 Lean Used in Non-Japanese, Non-automotive, Situations

The superior performance of (automotive) lean manufacturing systems has encouraged the idea of transferring lean manufacturing to non-Japanese and non-automotive situations. [1] This is based upon the premise that manufacturing problems and solutions are universal. However, in practice, Western (non-automotive) manufacturers are often able to emulate the structural parts of lean, but have found it difficult to adopt the required organisational culture and mindset. The impact is often localised and falls short of the desired improvements in the overall system. [2]

1.3 Lean Thinking

As lean thinking continues to spread to every country in the world, companies are also adapting the tools and principles beyond manufacturing, to logistics and distribution, services, retail, healthcare, construction, maintenance, and even government agencies and non profit organizations. [3] Automotive leaning manufacturing techniques can be found today in many industrial environments. With the growing demand for producing product with higher complexity but at lower costs and shorter delivery times, lean techniques have found their way to the niche market of design and manufacturing of terry cloth weaving machines. (figure 1)

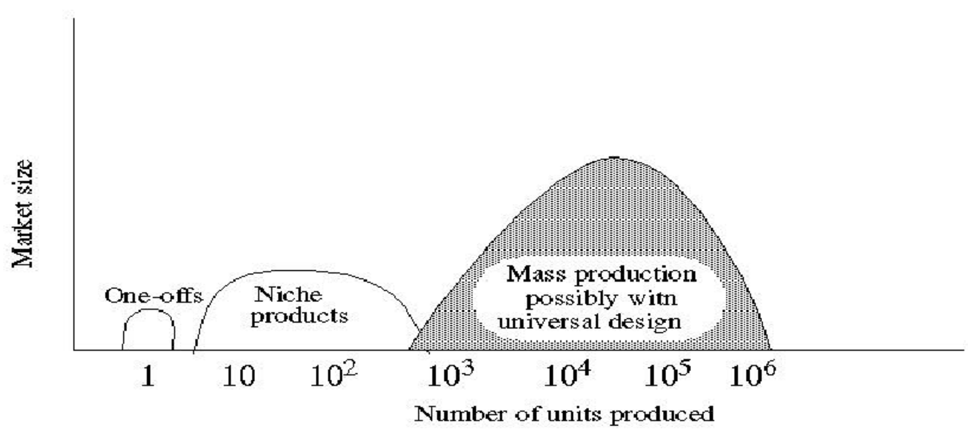

Fig. 1. Visualization of market size of niche products versus one-offs and mass production.

2.0 Problems Definition

2.1 Overview of Terry Weaving Machine Assembly Area before Application of Lean.

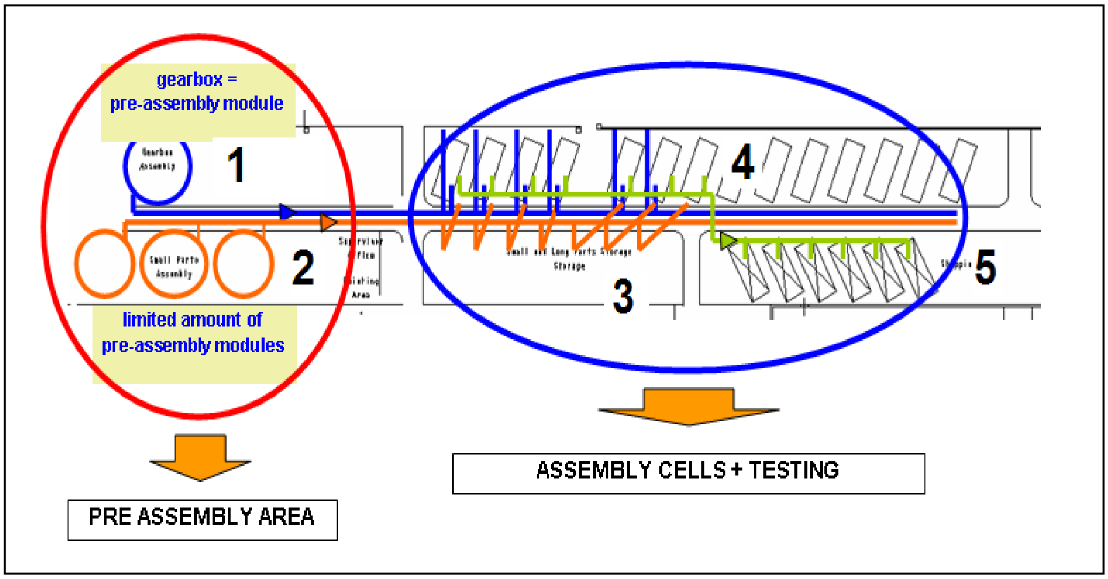

Fig. 2.

Basic layout of non-lean assembly area of niche market, low volume, weaving machines.

2.2 Manufacturing Systems in 2004, before Application of Lean.

The low volume assembly facility for production of terry weaving machines, before application of lean, was set up in 2004 and measured 1080m². The facility was planned to produce 130 weaving machines on a yearly basis. Total assembly time of a terry weaving machine was 103 hours.

Assembly was divided into five sub-areas: 1. pre-assembly of gearboxes (or direct machine drives), 2. assembly of small parts, 3. storage of small and long parts, 4. machine assembly, 5. shipping area. (see figure 2)

The 2004 design process was a concept-driven process. Terry weaving machines were completely assembled in assembly cells from frame building up to final testing (area 3, figure 2). Direct machine drives, mounted on both sides of the machine, were modularly assembled from dedicated small pre-assemblies (area 1, figure 2)

Modules were manually delivered to the assembly cell with a dedicated cart. Other small and long parts, which required no pre-assembly, were stored at area 3 (fig. 2). When the assembly and testing was completed, the completed machine was moved to area 5, shipping area.

Introduction of modularity in the Terry assembly in 2004 was a cost-efficient solution. ‘It supports step-by-step investment, where later upgrades and modifications to the system are easier’, says Heilala and Montonen. [10]

A kitting system was designed to present material to storage area 3 (small and long parts). Basis for this decision were component part obsolescence, reduced inventory cost and increased process control.

2.3 Problems Areas in the 2004 Layout, before Application of Lean.

In the assembly area, terry weaving machines were launched in batches of 6 machines; spread over 21 metres of working area. With a maximum capacity of 18 cells, machines were spread over a length of 63 metres. Initially, operators spent 25% of their working time searching for parts in the small and long parts storage (area 3, fig. 2).

Due to the use of lift trucks to move long and heavy parts from storage area 3 to assembly cell area 5, waiting times were incurred and added to the delay in deliveries.

For all working areas there was a lack of standardised work, visualisation, quality standards and internal logistical flow. These items were not well developed due to the lack of assembly knowledge of the operations manager and engineering team. In assembly area 5, there was no focus on total cycle time, touch time and dwell time. Quality level, time and cost objectives were not within control given adequate importance.

The integration of modular assembly in the gearbox (or direct machine drive) area 1 required additional attention. Single-piece flow, kanban, flow racks and JIT-driven flow were not introduced.

2.4 Defining the Targets of Introduction of Lean in 2005.

The management team agreed upon some overrearching principles that would guide the design process towards implementation of lean principles and modularity-in-production.

Cross-functional teams were formed and worked on design concepts that covered layout and design of shop floor area. The result was the production of the following working objectives:

- elimination of waste, focus on over-production
- standardised work
- visualisation of quality issues and assembly sequence
- one-piece-flow
- Jit-driven flows and queues
- minimal touch time
- modularity as design and operations strategy: modularity-in-design and modularity-in-production [13]
- kanban delivery of small fixation parts: bolts, nuts, clips and others
- flexible workforce and simple adaptable equipment
- straight and short assembly line

2.5 Authors' Contributions Solving the Problems.

According to Starr [4], Feitzinger and Lee [5], Van Hoek and Weken [12], research on modularity-in-production focuses mainly on the efficiency and flexibility gains stemming from the decoupling of the main and module flows. A few studies have analysed the issues that firms must manage well in order to actually achieve these operational performance benefits. (Fredriksson) [11]

Contribution of this paper is the research on modularity-in-production in combination with lean production in a terry weaving machine assembly environment. This manufacturing approach is unique in the market of terry weaving machines. The authors and management of the company defined the concepts for the factory design launched in 2005 and 2007. Engineering and logistical study of the projects 1 and 2 were performed by the authors and the operations management team. Modularity design principles were discussed with machine designers and management team.

3.0 Project 1: Applying Lean Principles to Gearbox Pre-assembly Area 1 in 2005

Project 1 was launched in 2005 in order to start applying lean principles on the shop floor, train operations managers and operators in lean thinking and to introduce the principles of modular assembly.

3.1 Design Concepts

- main focus of developing a lean system was the elimination of waste, mainly over-production and waiting times, whereby waste was defined as 'anything that adds cost without adding value'
- a pull logistic system (kanban) supports elimination of waste
- an attempt to balance the flow of material to match the rate at which it is needed while making the most efficient use of labour
- adopt the modular assembly approach with a flexible workforce and simple adaptable equipment. [7]

3.2 Performance Improvements

The following improvements were recorded resulting from the re-design and implementation of the new operations system:

- Waste was efficiently tackled by linking the outgoing flow of the gearbox pre-assembly to the incoming flow of the machine assembly. The operator who pre-assembled the gearbox was also responsible for mounting the gearbox on the machine. Over-production and waiting times disappeared quickly because the operator started to work at same tact as assembly line. Assembly time of the gearbox decreased from 17 hours to 14, 4 hours.
- The modular assembly approach resulted in better quality, delivery and cost performance. The explanation is that people could better see the relation between their activities and the outcome, were better motivated and focused.
- Other design concepts integrated in this small gear box line were made visible below in 'actual configuration' (fig. 3) such as one-piece-flow, straight assembly line, same centre of gravity between assembly and pre-assembly, improved logistics, development of an assembly fixture on wheels and optimized locations for incoming logistics (fig.4)
- Reduced number of assembly activities made it more difficult to define a well-balanced work flow.

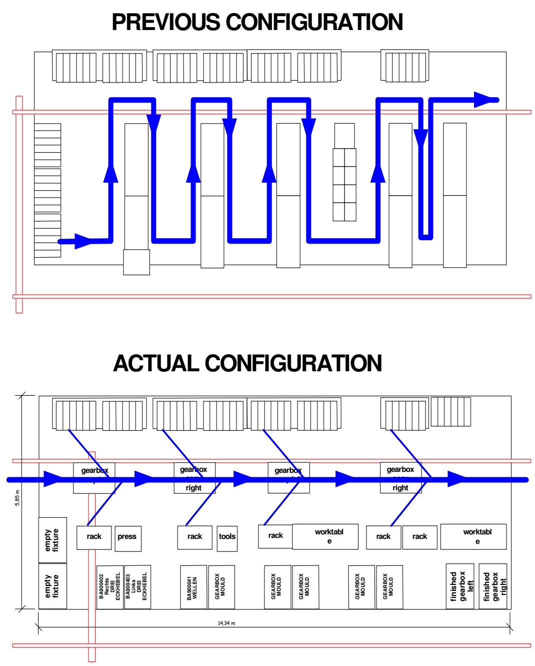

Fig. 3. Evolution of a gearbox pre-assembly area using lean principles

Fig. 4. Photo of storage racks location relative to production line

4.0 Project 2: Design Criteria of the New and Lean Terry Assembly Area in 2007.

4.1 Design Concepts

The layout of the original, non-lean, machine assembly area of 2004 was completely revisited in 2007. Lessons learned from project 1 were implemented in the new line layout.

Additional design concepts were added to this production line design (fig. 5) and these were as follows:

- modularity-in-production (components on modules in pre-assy areas) and final assembly (components and modules into end-products on the assembly line) [11]
- reduction of total assembly time and work-in-process
- optimised ergonomics

- dynamic line assembly instead of assembly cells
- introduction of air-cushion technology to move the 3000kg heavy machine on the line.
- reduction of walking distances by re-locating pre-assembly areas next to the assembly line
- assembly fixtures to improve repeatability and to assure quality of assembly operations
- optimised incoming logistics with barcode scanning linked to the MRP software.
- use existing weaving machine platform and develop the terry application on top it.

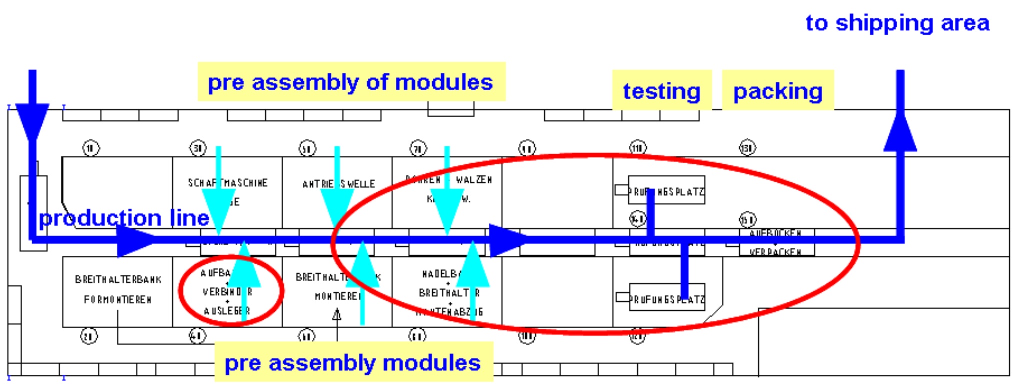

Fig. 5. Optimized line layout with modular assembly areas and air-cushion technology

4.2 Performance Improvements with Justification.

Important reduction in development cost and time-to-market was achieved by using an existing weaving machine platform and developing a niche application on top of this platform. Quantification of the improvement data was not made available by company. The project was delivered on time and within budget in January 2007. Start-up level of 1,5 machines per day was achieved immediately at re-start of the assembly line, compared with a maximum daily output of 0, 8 machines on the previous 2004 assembly line.

In the assembly process, modules were build instead of parts being transported loosely around the line. The concept of modularity was explained to the assembly team as described by Baldwin/Clark and Asan *et al.* [15], [16] and [17]: ‘to divide a complex whole into decoupled and more manageable parts or modules.’ The approach defined by Ulrich [14] has been adopted during the development phase: ‘The modules can be designed and produced in parallel and still be combined with each other, as long as the interdependencies between the modules are minimized and interfaces between them are specified.’ The 2007 assembly facility was built on 800m². It had maximum output of 600 terry weaving machines per year. Total assembly time of a terry machine was 52 hours.

Quality and delivery levels increased with the lean line setup and the modularity-in-production concept. As we noticed in the gearbox pre-assembly, the explanation is that people could better see the relation between their activities and the outcome, were better motivated and focused. Pre-assembly activities can also be performed in ergonomically safe ways since they are not constrained by the physical shape of the base object. Kinutani [18] and Blackenfelt [19] found that pre-assembly activities can be undertaken at a comfortable height through the use of supportive equipment, such as lifting devices.

To improve efficiency and to reduce complexity, the basic idea was to produce the new machine on a dynamic assembly line linked to a modular pre-assembly area with dedicated assembly fixtures, torque tooling and lifting equipment. At the end of 2007, an average of 2 machines per day was reached. Overall delivery times were reduced from 12 to 10 weeks.

As a result of dispersion of activities and resources between main flow and module flows, operations had to handle disturbances quickly. Also transport modules (racks) were bigger and more complicated than before.

The warehouse was integrated into the new assembly area in order to reduce internal transport, walking distances and to minimise stock level. Bar-coding was introduced on the shop floor and linked with the MRP software in a period of 8 weeks. Its application was a key factor attributing to the successful integration.

The team was able to reduce clutter and inefficiency of the production environment using 5S. Five S is a philosophy and a way of organizing and managing the workspace and work flow with the intent to improve efficiency by eliminating waste, improving flow and reducing process unreasonableness;

5.0 Conclusion

An attempt was made to apply lean manufacturing techniques and modularity-in-production, both systems normally adapted in automotive manufacturing, to the assembly of niche market textile machines.

Defined problems were lack of knowledge of manufacturing techniques by management and operational supervisors. A reduced number of assembly activities made it more difficult to define a well-balanced work flow. Dispersion of activities and resources between main flow and module flow calls for a need to handle disturbances quickly. Transport modules were bigger than before and sometimes required special packaging.

The results obtained showed significant improvement in the production output, surface utilisation, overall delivery times, quality and ergonomics.

Flexibility in the design process and in the factory design will help ensure that the production plant can maintain competitive and profitable in the fast changing machine building environment.

Findings are useful because they form a complement to existing literature on modular process design. More research is required on operation of modular and lean assembly processes, in particular for production of niche market weaving machines.

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MATCHING HUMAN RESOURCES TO PROCESS-ORIENNTED ROLES IN MANUFACTURING COMPANIES

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Abstract

The systematic development of computer models of two real assembly situations is described. The models are created to quantify business benefits that can be generated when making manageable manufacturing engineering (ME) changes to process structures, operation procedures, work flow structures, and especially human resource assignments. The models replicate process behaviour of different configurations of assembly systems based on the use of an actual case study scenarios and plant data. Static businesses models are described in the form of CIMOSA Enterprise Models to explicitly represent the business environment of the assembly operations; this defines the business context (or 'workplace') for these operations. Causal Loop Models (CLMs) enable reasoning about cause and effects impacting on the workplace dynamics of assembly systems. Collectively the EM and CLMs inform the design of Simulation Models (SMs) that can replicate existing assembly system behaviours and can generate possible future assembly system behaviours in a systematic and quantitative way. This paper explains how an integrated use of EMs, CLMs and SMs can inform design and change in assembly systems. Also it explains how SM experiments can be carried out to support the matching of human resources to work-loaded assembly processes. The concepts and modelling method are illustrated in industrial case studies where coherent models of 'role requirements' and 'role holders' enable the design of process improvements.

1.0 Introduction

Currently managers of manufacturing industry need to plan and control an effective realization of products whilst thinking of better ways of deploying employees (5). Typically, they aim to improve productivity by managing co-operative work loads within and between different departments. Therefore, improved ways of modelling human systems (including teams, workgroups and individuals) are required that have potential to delver both business and social benefit in manufacturing workplaces that often are complex and changing (7).

This paper reports on the application and testing of a proposed integrated modelling approach in two distinctive furniture assembly processes. The research created explicit, computer executable models of process- oriented roles and matches them to explicit models of alternative role holders; here role holders were explicitly modelled in terms of competencies and performance levels that stereo-typical people can bring to the workplace. Case study models were built using Enterprise Modelling (EM), Simulation Modelling (SM) and Causal Loop Modelling (CLM) techniques.

When modelling both similarities and distinctions were drawn between people and technical resources. As significant variation occurs in the type or volume of products needed, or if there is significant variation in the number of workers available, the aim was to help production system supervisors to decide how best to re-assign available resources to roles. In general, people will need to play roles that define their dissimilar responsibilities and distinct positions when collectively they are required to realise products of various types and in variable quantities. For example, the time taken to realise any given set of products can inform 'Lean' thinking. This in turn has to do with qualities of the people deployed, the roles they play, their operation times and the consecutive steps of the process they follow. A dynamic model can help to understand and analyse unforeseen processing situations. With the help of models, managers can arrange employees so that industry can gain the biggest profits. In this paper, prime focus is on creating enterprise (static) and simulation (dynamic) models of cabinet assembly processes. Also considered in overview is the role of Simulation Modelling (SM) in support of consultative decision making by reflecting upon case study results.

2.0 Key Literature and the Approach Proposed

An assumption researched is that ME enhancements can be explicitly specified and designed, and resultant production system behaviours can be predicted using simulation technologies.

People are the prime resource of any ME, so it is vital that the interoperation of ME personnel is suitably systemised and coordinated. Suitably developed models of human resource systems can help specify, implement and maintain timely & cost effective inter working of human resources through specific ME lifetimes (1, 4).

It was decided that it would prove impractical to create general purpose models of people. However it was presumed that specific purpose models of human systems could be developed and reused. This could include models of individuals, work groups or teams created with respect to systematic work they are required to perform. To create those human systems models, CIMOSA Enterprise Modelling (EM) frameworks and tools were selected as a baseline modelling technique (5). This choice was made in order to model people and manufacture processes in a coherent way; and by so doing to explicitly model the business and work context of specific MEs. However it was observed that current EM frameworks and tools are deficient in regard to capturing competencies, behaviours and performances of human systems so that it was anticipated that extended EM concepts would be required.

As illustrated by Figure 1, previous experience of the authors had shown that CIMOSA EMs could usefully capture key structural knowledge and data about the specific ME in which any production system and its associated human resources would need to operate. Figure 1 illustrates the modeling ideas where the EM would provide means of creating a graphical model of the network of processes used by a subject ME, but that this graphical model would only encode relatively enduring ME characteristics. Hence it was decided that complementary causal loop modeling (CLM) and simulation modeling (SM) techniques would be needed to analyze current and possible future dynamic behaviors of subject MEs.

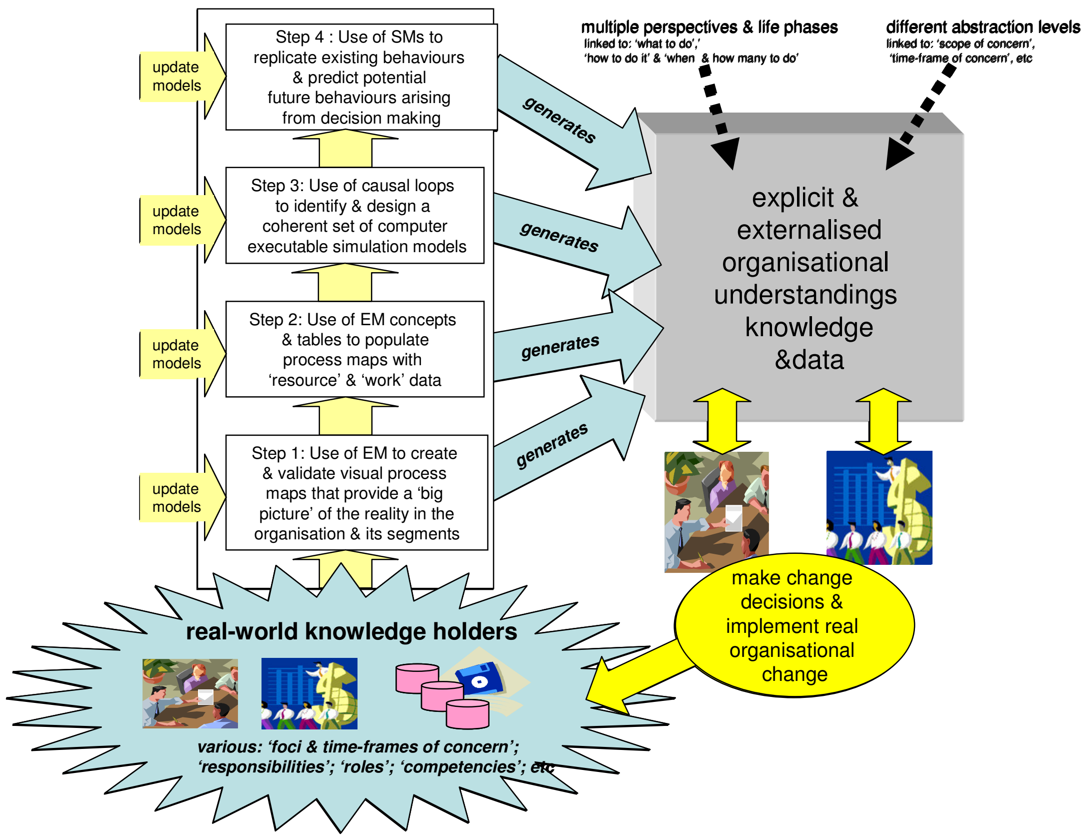

Fig. 1. Overview of systematic modeling approach

This paper explains how ideas illustrated by figure 1 were implemented and case tested when designing production systems and their associated resource systems. Here the Simul8 software tool (a discrete event simulator) was used to create SMs capable of behaviours of human systems in a virtual environment (3).

3.0 Modelling the Business Context in a Chosen Case Study Domain

The present authors observed that three business models are commonly used in the furniture industry to achieve the realisation of furniture products. These business models are illustrated by Table 1. Key features of these business models were documented. The models are termed: 'fixed furniture'; 'flat pack furniture' and 'custom furniture' business models.

The 'fixed furniture' concept (BM1) focuses on standard pre-constructed furniture items. Key to a competitive BM1 is some appropriate application of lean manufacturing principles (2); renowned for a focus on waste reduction to improve overall customer value. In the BM2 concept specialist craftsmen realised customised furniture by meeting individual desires; BM2 is based on the agility principle which complements lean manufacturing (2). The BM3 concept involves use of a 'flat pack' furniture catalogue, with a limited range of products with standard dimensions and finishes for users purchasing from 'do it yourself' stores.

Table 1: Common business models used for home furniture production

Business Model (BM)	Classes & Numbers of Actor involved in each Business Models	
***BM1 Concept**: catalogued items allow economies of scale to be realised by selling enough of each item within a range of **fixed** furniture via a retail chain Outcomes; medium priced furniture of medium quality & medium to high availability*	Material Input Supply Chain	low multiples
	Manufacturer (of fixed products)	multiples
	Retail Chain	large multiples (shops & stockists)
	Custom Builder & Fitter	not applicable to BM1-done by manufacturer
	User	large multiples
***BM2 Concept**: **customised** furniture exemplified by furniture portfolios is handcrafted to meet individual customer requirements by a highly skilled' wood worker' so as to meet specific constructional, dimensional & finish characteristics Outcomes; high priced furniture of good quality & low to medium availability*	Material Input Supply Chain	low multiples
	Manufacturer	not applicable for BM2
	Retail Chain	not applicable for BM2
	Custom Builder & Fitter	medium multiples
	User	large multiples
***BM3 Concept**: a limited range of pre-packed furniture components which conform to a range of furniture products (with standard dimensions & finishes) are sold via catalogues & retail chains; selling enough of each '**flat pack**' to realise economies of scale. In this model customers can save capital outlay by assembling the products Hemselves. Outcomes; low priced furniture of low to medium quality & low to medium availability*	Material Input Supply Chain	low multiples
	Manufacturer	low multiples
	Retail Chain	low to medium multiples
	Custom Builder & Fitter	not applicable to BM3 done by user
	User	large multiples

4.0 Simulation Modelling of Flat Pack and Fixed Furniture

Static models describing relatively enduring characteristics of the business context of flat pack assembly process were created by the authors using standard CIMOSA modelling constructs. One of the diagramming templates created (an example CIMOSA structure diagram is shown in Figure 2. Following which a simulation model of flat pack furniture assembly was created, as shown in Figure 3. The reader should note that Figure 2 is one of six CIMOSA diagram templates used to characterise the network of processes used by supply chain partners to realise flat pack furniture. Also it is important to point out that the SM shown in Figure 3 only focuses on one key segment of the flat pack process network; namely the assembly process where users of flat pack products (in this specific case that of a flat pack cabinet product) are required to assemble the product after purchasing it and before being able to use it.

CIMOSA conformant Domain Processes (DPs) of the complete flat pack business model modelled were successfully decomposed until selected process segments of reduced complexity that could be modelled effectively using a simulation tool. The process segments were also further systematically decomposed; via the innovative use of low level function based modelling concepts (called Functional Operations and Functional Entities) until viable process-oriented roles were explicitly defined. Following which competency and performance oriented models of people were built to draw comparisons between the potentials of different human role holders to perform the defined roles when subjected to different work load conditions.

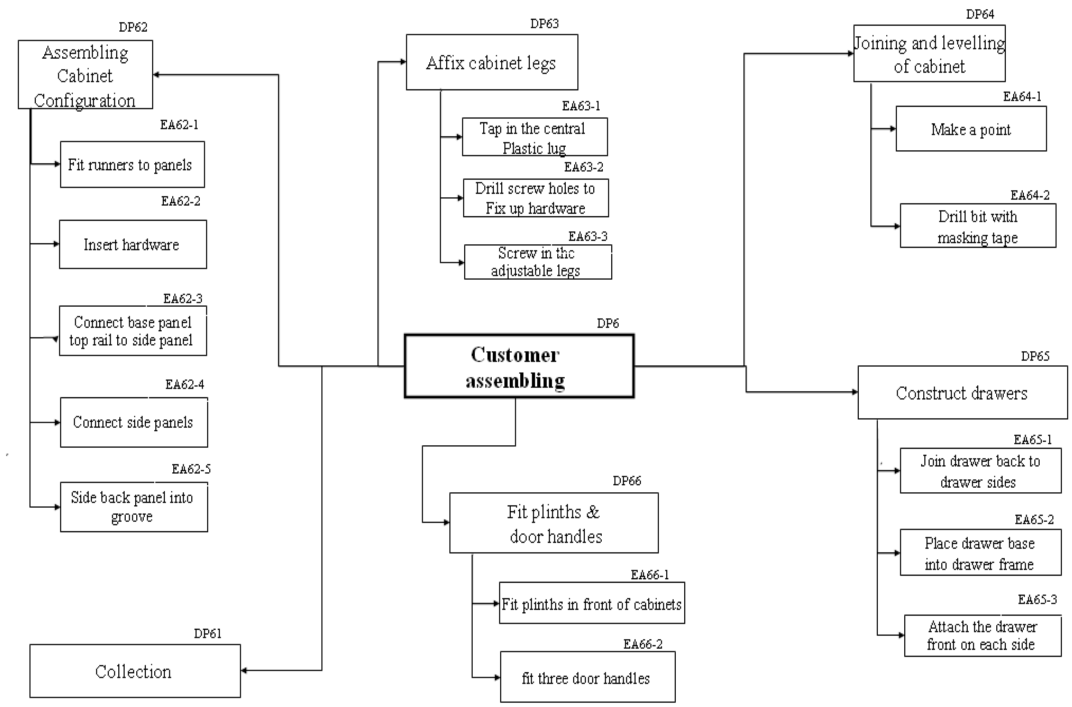

Fig. 2. Flat pack structure diagram

5.0 Simulation Model 1: Flat Pack Assembly Process

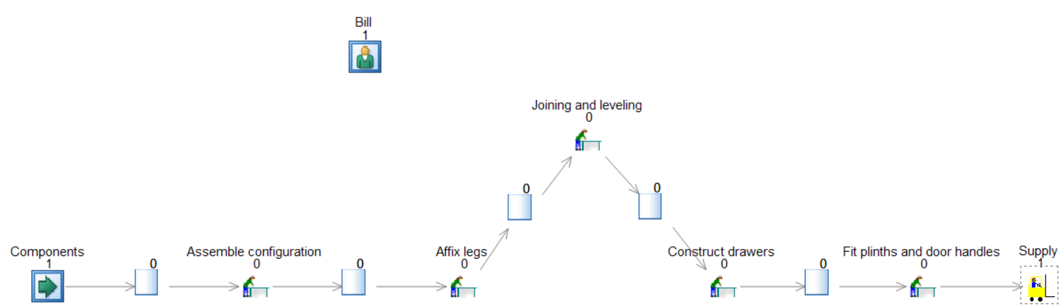

Fig. 3. Model 1 experiment 1: Flat Pack Assembly Process

Model 1 (see Figure 3) was designed to analyse the use of human resources and time and cost factors associated with the ‘in the home’ flat pack cabinet assembly case. Here it was assumed after Do It Yourself (DIY) shopping a family brings home a flat pack package. The family might comprise one person or a couple, or one parents with several kids who are intelligent and/or skilled enough to contribute positively to the overall assembling activity. However as an initial learning problem, the first author decided to feed appropriate parametric data into the first simulation model so that a set of simulation experiments could predict the time and cost involved when carrying out the cabinet assembly with different numbers of family members. Results obtained from these three sets of experiments with Model 1 are shown in Table 2.

Table 2: Predicted Total Cabinet Assembly Times: with different numbers of family members doing complementary assembly work

One product	Operation time (minute)	Utilization (average)
1 people	117	5%
2 people	78	3%
3 people	56	2%

Although at first sight the time taken by users to assemble flat pack furniture products is not a major concern to flat pack manufacturers and retailers it was observed that the kind of predictions made in by Table1 could be useful in helping BM3 supply chain partners to sell more products; if their product has competitive assembly times this could be a useful selling point. The seller should seek to improve customer satisfaction, and this might be one approach to showing quantitatively that they can do this relative to competitors. Therefore the information generated by this fairly simple SM1 could provide a competitive edge.

6.0 Simulation Model 2: Fixed Furniture Cabinet Assembly

During fixed furniture cabinet assembly at a case furniture manufacturing company, employees draw cabinet assembly work form two queues which are accessed simultaneously so that (1) frame (or carcass) assembly and (2) drawer construction is carried out. Then these semi-finished products come into one store which functions to input to the last work centre, adding the plinths and castors to them. Following which, products go to the paint shop where they are finished to meet customer specifications.

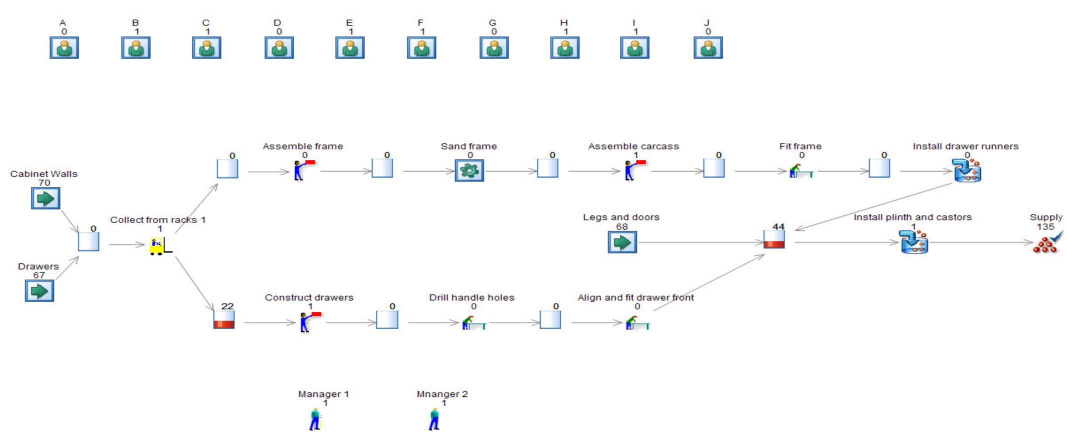

Fig. 4. Model 2 experiment 1: Fixed furniture Assembly Process

Model 2, experiment 1 (see Figure 4) was designed and run based on the assumption that all human resources would be trainees, with the same relative low level of payment. In theory there will be an expected cost saving relative to the use of skilled and experienced people. But the cycle time is expected to be longer because of a lack of key skills and possible lack of sufficient quality of work (and hence a need for rework). For Model2, experiment 2 (see Figure 5) all employees are high level trained. This means a higher salary bill but they can cut the lead time relative to trainees. With their better capability more entry points can be allowed, with greater relative work throughputs, leading to higher revenues.

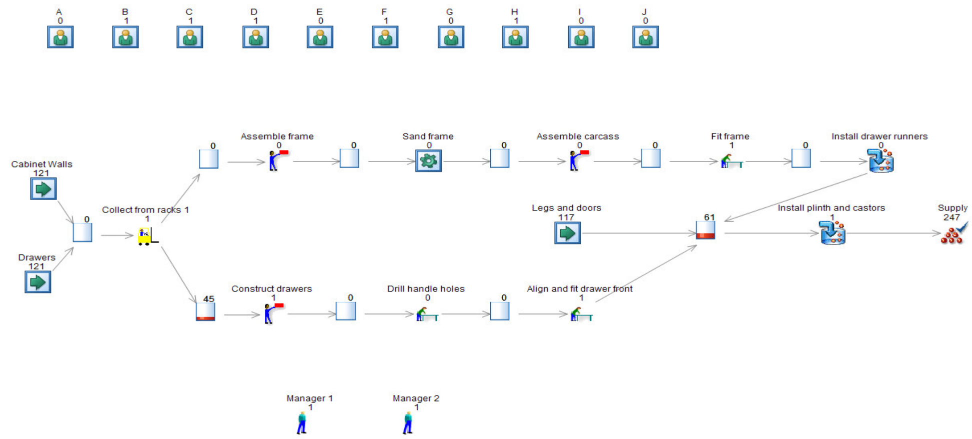

Fig. 5. Model 2 experiment 2: Assembling process with high-skilled workers

The authors observed some experimental conditions under which improved human resource utilization can be achieved by reducing the number of assemblers in the process. Hence the same work could be loaded onto fewer workers. It was understood that this might reduce the work throughput but the new arrangement was expected to save processing costs; which were posted on a final financial notice board. But it was observed that under favourable conditions the remaining people can make better use of their time (such as during times when previously they had been waiting) so that they can realise their own previous work plus the work of those made redundant.

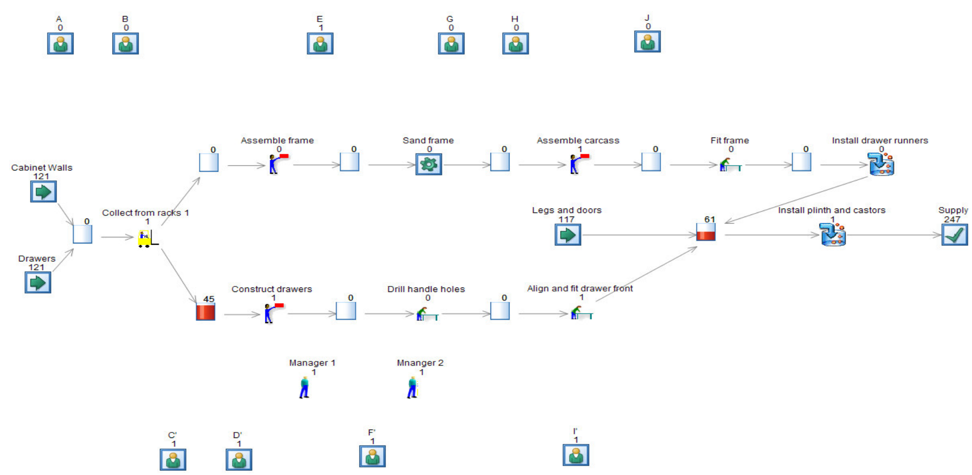

Fig. 6. Model 2 experiment 3: Modification of assembling process by deleting several workers

During experimentation it was observed that when reduced numbers of experts were allocated roles it was possible for the same operation times to be achieved as that found when experimenting with experiment 3 where a full complement of expert operators were assigned roles. Figure 6 explains this modification and suggests a possible future human resource arrangement.

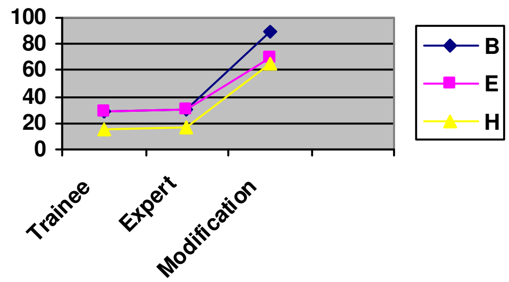

Figure 7 Results of three models by analyzing the utilization of human resource

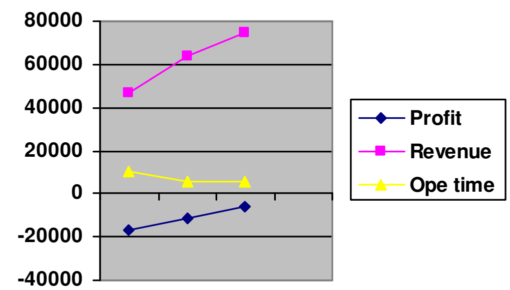

Figure 8 Results of three models by analyzing the profit, revenue and operation time

The line charts of Figures 7 and 8 illustrate the development of the new arrangement. A typical increase in utilization of assemblers B, E and H was observed. These assemblers have been assigned more responsibility including that of the now redundant assemblers. Revenue and profit improved with the higher capability of work centres and their assigned assemblers. For more entering components of the cabinet are allowed in the operation and accordingly more products are supposed to generate which bring higher revenue. Operation time was reduced with more effective use of skilled workers.

7.0 Futures Predicting

New role and competence modelling ideas were generated when modelling human resources for the two distinctive cabinet assembly processes. Consider the 'Design Specification' stage of CIMOSA modelling. Because they possess different sets of Functional Entities (FE), different people will play the same roles differently. Hence it was considered feasible to divide real people into several stereo-typical groups, such that they are modelled conceptually as shown in Table 2.

Suppose that there are 24 functional entities needed to realise all roles requirements in the complete cabinet assembling process. Then to each role a candidate resource type can be assigned, with a known level of competence and performance (designated E=Expert, P=Practitioner, or T=Trainee). Having made these assignments a simulation model can be run to predict performance (including financial) outcomes.

Table 3: people with competencies possessed at specific performance levels

	C1	C2	C3	C4	C5	……	C24
Lily	T	E	P	T	E		T
Bill	E	T	E	E	T		P
David	T	E	E	T	P		E
Mary	E	P	E	P	E		T
Ben	P	T	E	P	E		P

In the real situation multiple product types may enter the process simultaneously. If people assignments to work are too rigidly maintained, then when a variety of work comes in then more people would need to be involved in realising the different work flows through the process, and their utilisation could fluctuate significantly. Alternatively if people assignments can be modified in a flexible way then as different products types need to be realised it may be practical to realise economies of scope; because under-utilised people can be re-assigned for agreed time-frames. But this kind of flexible working generally requires the use of people with a wider range of skills, so that they can be matched to workloads which change in character. This is where the systematic approach to decomposing activities into elemental functional operations (FO's) and functional entities (FE's) recommended in this paper can lead to well defined role requirements for different work types and quantities of work types. Here for each unique product relevant activity flows can be determined and the required activities can be decomposed into their elemental FO's and FE's. Where commonality of FO's and FE's amongst product types is observed this might simplify the process of allocating people to the product oriented roles so defined. This can be followed by a broader use of tables of people competencies possessed at specific performance levels, of the type shown in Table 1. Theoretically at least this can provide a methodological and explicit way of enabling rapid and effective re-arrangement of the work-force in order, so that they have the right role assignment at the right time, to maximise value generation and minimise process costs. Normally there might be more than one assembler at each work centre, making a team, with the aim of getting higher efficiency so as to shorten the total lead time. Another resource allocation policy might be for one fitter to resource more than one work centre once someone is absent for some reason. Accordingly it is necessary to make a table listing the competency and performances of each assembler; and to use this to formalise resource allocation policies, to facilitate computer execution of alternatively resourced production system models, and to guide training regimes.

8.0 Conclusion

A method of improving the design of furniture assembly systems has been presented in this project. A tripod of modelling tools consisting of enterprise, causal loops, and simulation modelling has been used. This has provided a methodological way of building simulation models of production processes resourced by alternative human system designs and by predicting key business performance characteristics. Also the approach encourages reuse of the models created so that they can be used when alternative and uncertain product volumes and mixes need to be realised; or when process improvements need to be made on an ongoing basis. Importantly the models enable quantitative decision making about feasible and profitable re-distributions of resources

The project demonstrated case study examples of the combined use of CIMOSA Enterprise Models and Simul8 Simulation Models to support the design of two different real assembly processes, for flat pack and fixed cabinet furniture industry cases.

Future project work is necessary to investigated further the use of explicit definitions of process-oriented role requirements and of explicit descriptions of competency and performances characters of role holders. For example managerial, supervisory and co-ordination competency and performance characters could be used to specify capabilities that are possessed by candidate role holders who could be made responsible for integrating process oriented roles. While ‘change’ competency characters may be used to differentiate role holders able to switch their responsibilities and actions performed between different value streams.

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MULTI AGENT SYSTEM FOR NEGOTIATION IN SUPPLY CHAIN MANAGEMENT

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Abstract

Supply chain management (SCM) is an emerging field that has commanded attention and support from the industrial community. Supply chain (SC) is defined as the chain linking each entity of the manufacturing and supply process from raw materials through to the end user. In order to increase supply chain effectiveness, minimize total cost, and reduce the bullwhip effect, integration and coordination of different systems and processes in the supply chain are required using information technology and effective communication and negotiation mechanism. To solve this problem, Agent technology provides the distributed environment a great promise of effective communication. The agent technology facilitates the integration of the entire supply chain as a networked system of independent echelon. In this article, a multi agent system has been developed to simulate a multi echelon supply chain. Each entity is modeled as one agent and their coordination lead to control inventories and minimize the total cost of SC by sharing information and forecasting knowledge and using negotiation mechanism. The result showed a reasonable reduction in total cost and bullwhip effect.

Keywords: supply chain management, inventory management, agent technology, negotiation mechanism.

1.0 Introduction

In an era of globalisation, key account management and, products and services designed and delivered around specific customer requirements, the way supply chains are managed distinguishes between success and failure. A supply chain is a network comprising of raw material suppliers, manufacturing plants and warehouses, distribution centres and subcontractors all engaged in the transformation of material into finished products and the transportation of those within the network and ultimately to end customers (Fig 1). Supply chain management becomes however, increasingly complex as there is an increased reliance of businesses in outsourced services which include almost every activity from manufacturing to sales and distribution. This leads to increased uncertainty that must be addressed and complex and delicate business relationships that must be managed and maintained.

To address this complexity, businesses are exploring new forms of organization and collaboration mechanisms to work together with their suppliers and customers. Hence, there is a move away from traditional type of organisation in linear supply chains towards engaging in federal partnerships between a number of largely independent businesses which aim at virtually pooling and time-sharing resources. The aim is to introduce flexibility in managing and responding to uncertainty in market place by pooling competencies and sharing risks when responding to market needs. Such closely-knit federations can be in a dormant or a dynamic state at any time. These networks, however, regardless of state are always considered active and ready to respond. An arrangement such as this has been described as an adaptive value network (AVN) which is [9]:

> *"An arrangement where companies form a web of close relationships and work together as a system that delivers the right customized product and expected service at the right quality in a coordinated manner and are responsive and adaptable to changes in the environment."*

Among various activities in supply chain management, inventory management is the most important [12] and the effective management of supply chain inventories is perhaps the most fundamental objective of supply chain management [1].

The advent of software agent technology has triggered the development of new architectures and software for modelling and managing the supply chain [7, 9]. With this paradigm, activities in a supply chain such as procurement, planning, execution tracking etc. are represented by a software agent. Each agent acts based on its internal model of that particular activity and interacts with other agents in the network. For example an agent representing a particular warehouse can immediately provide stock availability information to another agent representing a particular customer when the latter queries stock availability before placing an order. This process takes place in real time and potentially without user interference.

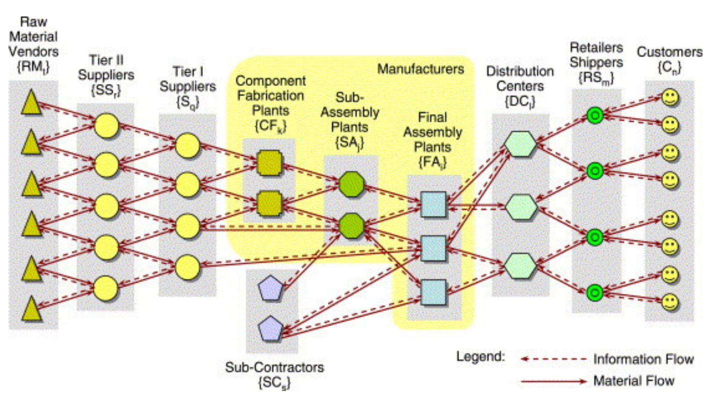

Fig. 1. Overview of a global manufacturing supply chain network

2.0 Multi Agent System for Supply Chain Management

Multi-agent system (MAS) is a fast developing information technology, where a number of intelligent agents, representing the real world parties, co-operate or compete to reach the desired objectives designed by their owners. The increasing interest in MAS is because of its ability to provide robustness and efficiency; to allow inter-operation of existing legacy systems; and to solve problems in which data, expertise, or control is distributed. The general goal of MAS is to create systems that interconnect separately developed agents, thus enabling the ensemble to function beyond the capabilities of any singular agent in the set-up [10].

The agent-based view offers a powerful repertoire of tools, techniques, and metaphors that have the potential to considerably improve the way in which people conceptualize and implement many types of software. Agents are being used in an increasingly wide variety of applications — ranging from comparatively small systems such as personalized email filters to large, complex, mission critical systems such as air-traffic control. It is the naturalness and ease with which such a variety of applications can be characterized in terms of agents that leads researchers and developers to be so excited about the potential of the approach [4].

Multi-agent systems try to solve the entire problem by collaboration with each other. In this way, MAS can help to solve complex problems and make decisions or support humans to make decisions. Therefore, agents are especially suitable for coordination of supply chains due to the following characteristics:

1. Data, resources and control over data and resources are inherently distributed [3].

2. A supply chain is adaptive and changes over time. Agents can serve as wrappers for the supply chain management components owned by a particular supply chain entity [6].

3.0 Negotiation in Supply Chain Model

Companies are required to comply with customer orders even if it may be hard to do so. Companies have to respond to the orders quickly and efficiently in the limited time available to fulfill the customer's requirements. Unexpected rush orders, however, in most circumstances causes delays in delivery and decreases efficiency in all of the supporting members [2]. To coordinate different supply chain entities and solve these problems, negotiation decisions have been identified as crucial for successful global manufacturing [5].

Negotiation techniques are used to overcome conflicts and coalitions, and to come to an agreement among agents, instead of persuading them to accept a ready solution [8]. In fact, negotiation is the core of many agent interactions because it is often unavoidable between different project participants with their particular tasks and domain knowledge whilst they interact to achieve their individual objective as well as the group goals. The importance of negotiation in MAS is likely to increase due to the growth of fast and inexpensive standardized communication infrastructures, which allow separately, designed agents to interact in an open and real-time environment and carry out transactions safely [11].

4.0 Multi-Agent Model Solution

The model proposed in this paper is based on beer game four echelons, but assumes unlimited entities at customer echelon and a single entity at others (Fig. 2). Three levels including supplier, distributor and retailer are allowed to have different inventory systems. Multi echelon agent based supply chain is simulated with multi agent systems. These agents are also capable of solving the problem of matching supply to demand and allocating resources dynamically in real time, by recognizing opportunities, trends and potentials, as well as carrying out negotiations and coordination. Operating in a multi agent environment, agent's plan explicitly represents interaction with other agents by exchanging messages. The agents are implemented as JAVA-thread objects on top of the JADE toolkit that satisfies the behavior as described above. This means that every agent is a separate computational process with its own internal control and a mailbox. Agents can communicate asynchronously using each other's mailboxes. The mailboxes are implemented as databases with records representing incoming messages. Besides that, all variables that represent the state of an agent are also stored in a model state database. The simulation model, which have been developed, is flexible enough to add new agents or to edit properties of existing agents to examine auction performance for different trading scenarios.

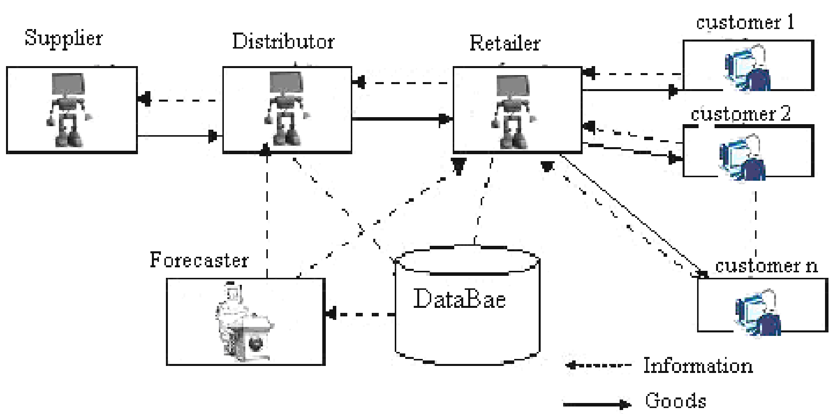

Fig. 2. abstract structure of simulated model

In this model, two types of agents are employed to respond to various types of services for the entire supply chain. One of them is a control agent and the other is a demand forecast agent. These coordinated agents have the ability to specify both static and dynamic characteristics of various supply chain entities. Customers generate random and stochastic demands at random time and only retailer give customers demand and send them goods. The same manner is employed between distributor and retailer and between supplier and distributor (Fig 2). Lead-time between echelons is deterministic and Supplier has infinite recourse. Other variables like holding and ordering cost is fixed. These assumptions are important and necessary for forecasting agent who is responsible for computing the amount of order and time to order for retailer and distributor based on Economic order quantity (EOQ).

Customer unsatisfied orders is changed to lost sale in retailer. For distributor facing a lack of inventory, retailer orders will be changed to backorder and satisfied, as goods are received form supplier. In this system, in case of lack of inventory in retailer to satisfy customers needs, retailer agent open a negotiation mechanism which help to solve this problem. By starting the negotiation mechanism retailer get new prices from customers and with the current orders and these new prices and by using a knapsack program, try to identify which customer needs have to be satisfied. In this manner, maximum benefit can be attained for retailer (Fig 3). Generally, Fig. 4 shows the schematic model of agent-based model and demonstrates all of behaviors in each agent. We can see that there is only one database which is shared for all of agents information. forecaster agent uses these information for prediction based on new data from other agents and then send new update information for retailer and distributor.

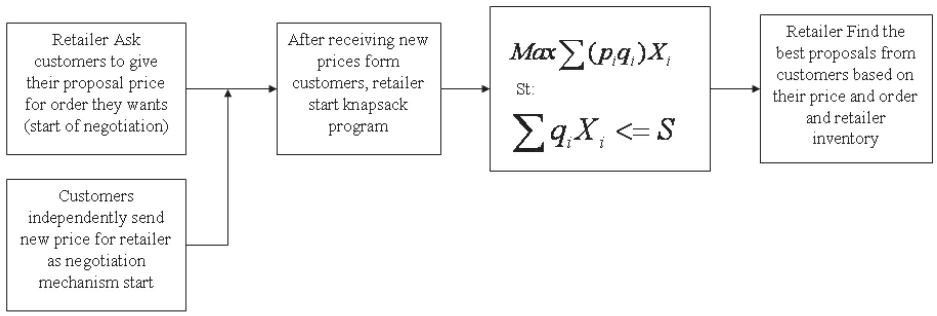

Fig. 3. Negotiation mechanism between retailer and customer

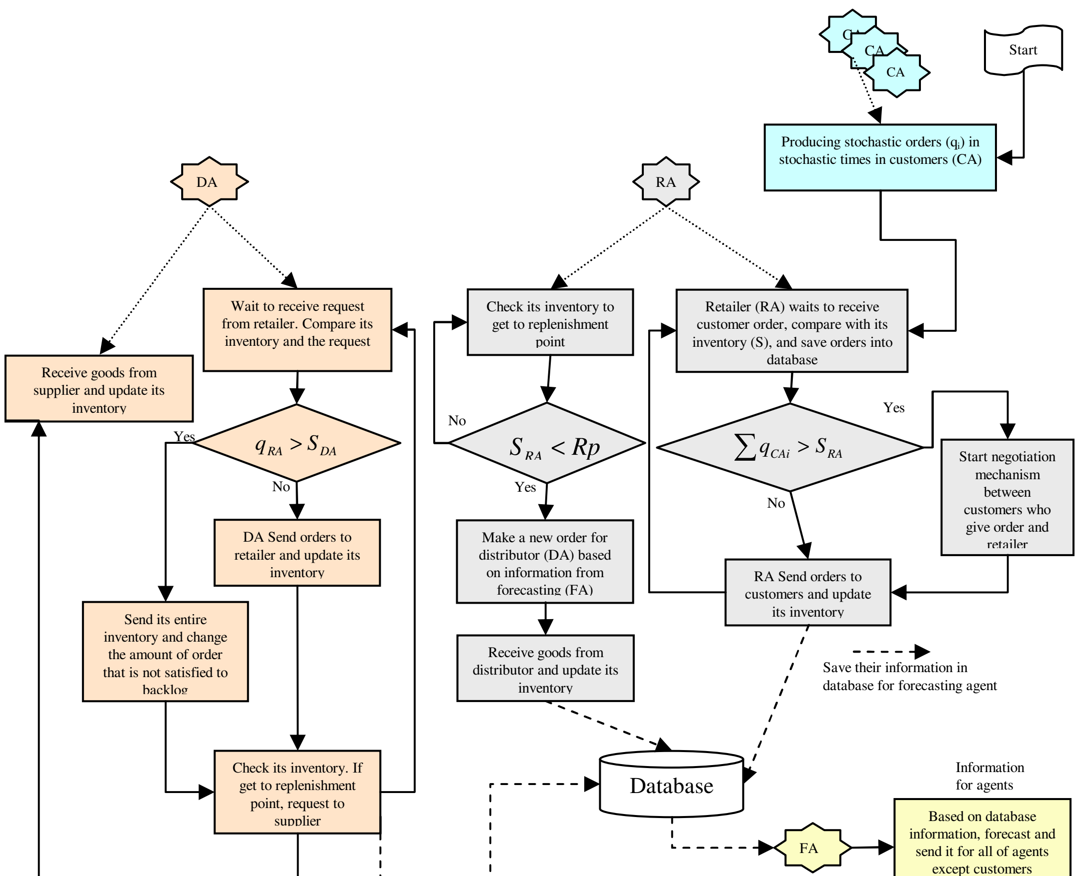

Fig. 4. schematic model of agent-based supply chain

5.0 Result and Discussion

Supply chain model as a discrete resource allocation problem under dynamic environment has been formulated, and demonstrate the applicability of the virtual market concept to this framework. The proposed algorithm facilitates sophisticated SCM under dynamic conditions. This model shows that agent technology can optimize supply chains by (a) reviewing intelligent agent's applications for supply chain optimization and (b) illustrating how a multi-agent system can optimize performance of this network.

Model benefits and saving by making use of agent-based systems for supply chain management include:

- In retailer agent, fill rate ratio (customers order satisfaction rate) calculated. All simulation runs showed 95 to 96 percent fill rate, which shows a high costumer satisfaction (figure 5).
- despite of huge and sudden demand in customs order, by agent ability, bullwhip or whiplash effect decrease in upper demand, so, total cost dose not increase so much (figure 6).

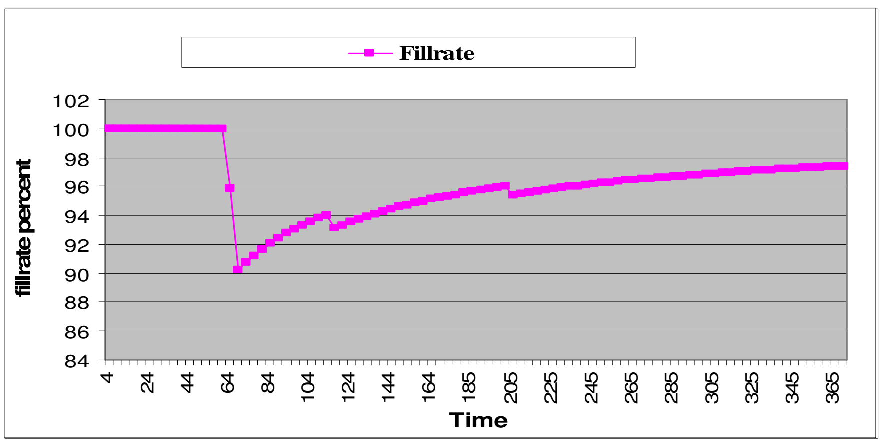

Fig. 5. Fill rate in retailer

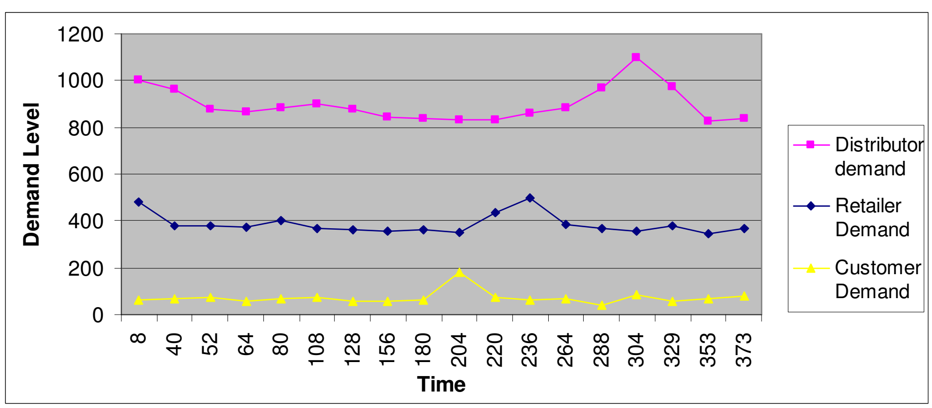

Fig. 6 Bullwhip effect in SC

6.0 Conclusion

Multi-agent system is a loosely coupled network of software agents that interact to solve problems that are beyond the individual capacities or knowledge of each problem solver. The general goal of MAS is to create systems that interconnect separately developed agents, thus enabling the ensemble to function beyond the capabilities of any singular agent in the set-up in agent model. This research can demonstrate that agent technology is suitable to solve communication concerns for a distributed environment. Multi-agent systems try to solve the entire problem by collaboration with each other and result in preferable answer for complex problems. For further works, we recommend developing this model to have multi retailer and even multi distributor and apply the auction mechanism between them.

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THE STUDY OF INFLUENTIAL FACTORS FOR DEVELOPING INDUSTRIAL AGGLOMERATION IN THAILAND

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Abstract

The focus of this study aims to identify influential factors to agglomeration and the innovation of the agglomeration by analyzing the data obtained from the survey. Twenty factors were investigated in the survey and the innovation of agglomeration was identified by check if there were any upgrading in term of technology, product and supply in the past three years. It was concluded that the industrial agglomeration of Thailand could be divided into three periods (before 1985, 1986-1998 and after 1999). The earlier was the establishment of the large firms and the later was the establishment of the smaller firms to form themselves around the large firms to become the agglomeration. Some of the factors were found significantly affecting to the development of Thai industrial agglomeration such as the large firms were attracted by investment incentives, legal systems and skilled labor while the small firms were also satisfied with the government policies in liberal trade and the system of intellectual property rights. However, the innovation of agglomeration cannot be concluded clearly since the result from the analysis showed that there were no significant common factors to explain the upgrading of industry among models.

Keywords: Industrial agglomeration, Industrial Clustering, Innovation

1.0 Introduction

Strong economic background usually comes from strong industrial section of the country that is why most of the countries try to strengthen their industries. The strength of industry in each country may come from different paths. For industrial countries, they have originally built their own technology and industrial system. Until the present time as the world becomes smaller, many companies from industrial countries seek for the new opportunity to invest outside their countries. Non-industrial countries such as many countries in Asia are their targets of investment. Many non-industrial countries have then turned up to be the new industrial countries; Thailand is one of them. Now, gross domestic product (GDP) of Thailand is depended on industrial section rather than on agriculture section as it used to be in the past. As the new comer in industry, Thailand has to find the right way to promote industry of the country in the long term. Industrial agglomeration is one of the effective ways to strengthen the industrial section of Thailand. Therefore, to understand the formation of industrial agglomeration is quite essential for the country to allocate the limited resources to promote industrial agglomeration. Not only helping in suitable resources allocating for the country but also by understanding the formation of industrial agglomeration, it can help the country to understand the needs of them. By the concept Flowchart Approach [2], the formation of industrial agglomeration can be understood stage by stage. However, the detail of each stage is depended on each country environment [1].

2.0 Research Objectives and Methodology

Foreign direct investment (FDI) has played the essential role for the development of Thai industry. With FDI at the earlier time, now some industrial agglomerations have been slowly formed. The agglomeration of industry can strengthen the industry of the country. The focus of this study aims to identify influential factors to industrial agglomeration and the innovation of the agglomeration. The mail survey conducted in November 2007 to collect primary data for statistical analysis and econometric analysis. Twenty influential factors were investigated in the survey and the innovation of agglomeration was identified by checking if there were any upgrading in term of technology of production, product, market and sources of supply in the past three years.

3.0 Descriptive Statistics from the Survey

The mail survey was conducted in November 2007 by sending questionnaires to 1,800 companies by mail, by e-mail and some of the questionnaires were distributed in person by random. The response rate was 8.8%, with 160 valid responses returned and most of them came from management people.

3.1 Profile of Questionnaire Responders

42.5% of the responders are served as Top Management such as CEO, President, Vice President, Business Owner, Managing Director, General Manager. 6.9% are served as Senior Management positions such as Financial Director, Regional (ASEAN) Manager, Manufacturing Director, etc. 23.1% are in Middle Manager position such as HR Manager, Production Manager, Sale Manager, etc. 10% are general employees such as Accountant and Engineer. 17.5% of the responders did not declare their working positions.

3.2 Year of Establishing

Based on the year of establishing, the ranges of the ages of the companies are between one year to fifty years. Figure 1 shows how long the responding companies have been established in Bangkok and/or surroundings area. The conclusion was that most companies have been established for 11 to 15 years (22%). The second most companies have been established for 16 to 20 years (18%).

3.3 Capital Structure and Major Investment and Main Business Activities

Most of the responding companies are local companies (53%). 26% of them are joint venture and 21% of them are Foreign Direct Investment (FDI) as show in Figure 2. For those who are join venture companies and foreign companies The most non-Thai investors were form other-Asia, 48%. The second one were EU investors, 21%. ASEAN and USA investors were 17% and 9%, respectively. From Figure 3 most of the companies' main business activities were involved in manufacturing while a few of them were involved in personal service

3.4 Factors Affecting Business

To understanding the formation of industrial agglomeration, the influential factors for starting the business in Bangkok, Thailand were investigated. There are several factors that might affect the investment decision of investors. However, in this study, twenty factors are selected based on from the pre-survey and interview on management people in the previous researches [3] as shown in Table I. The factors cover in three areas as social factors, governmental factors and demand/supply factors. In the questionnaire, the respondents were asked to identify the importance of factors in the viewpoint of business investors. The levels of importance were classified by five levels as "very important," "somewhat important," "not sure," "not very important" and "not important at all."

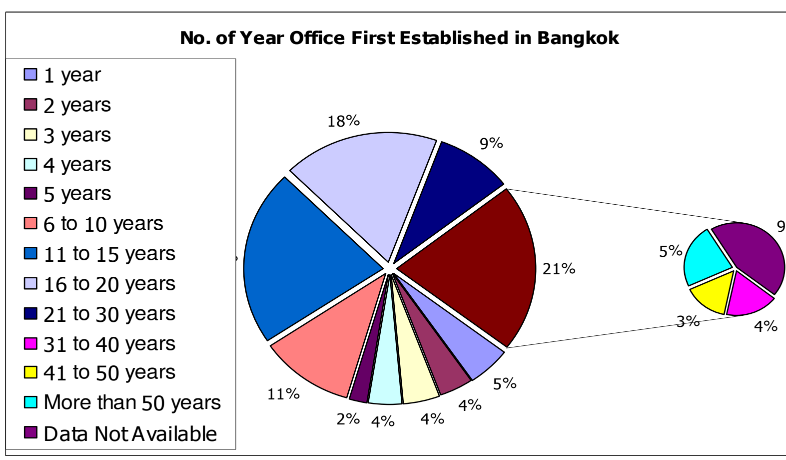

Fig. 1. Ages of the responding firms

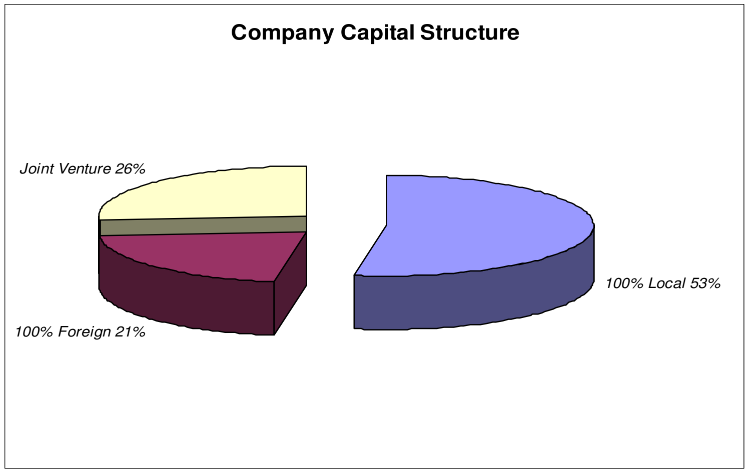

Fig. 2. Capital structures of the responding firms

Table I: Factors affecting the business for present and future

Number	Influential Factors
F1	investment incentives including tax incentives
F2	liberal trade policy
F3	customs procedures
F4	local content requirements, rule of origin
F5	physical infrastructure (roads, highways, ports, airports, etc.)
F6	infrastructure (telecommunications, IT)
F7	infrastructure (electricity, water supply, other utilities)
F8	government institutional infrastructure
F9	financial system
F10	legal system
F11	protection of intellectual property rights
F12	size of local markets
F13	access to export markets
F14	proximity to suppliers/subcontractors
F15	request by large/related company
F16	availability of low-cost labor
F17	availability of skilled labor and professionals
F18	other companies from the same country are located here (synergy)
F19	access to cutting-edge technology and information
F20	living conditions

4.0 Econometric Analysis from the Survey Data

Based on the econometric analysis, the years of establishment of firms in Thailand can be divided into three periods according to the trend in accumulation as follows: 1) before 1985; 2) 1986-1998; and 3) after 1999, as seen in Figure 3. This result agrees with the previous research done in 2005. [3] The model used to explain agglomeration in Thailand defined year of establishment of the firm as the dependent variable. Size of firms, influential factors, and functions of an office in Bangkok were used as independent variables, as seen in Equation (1).

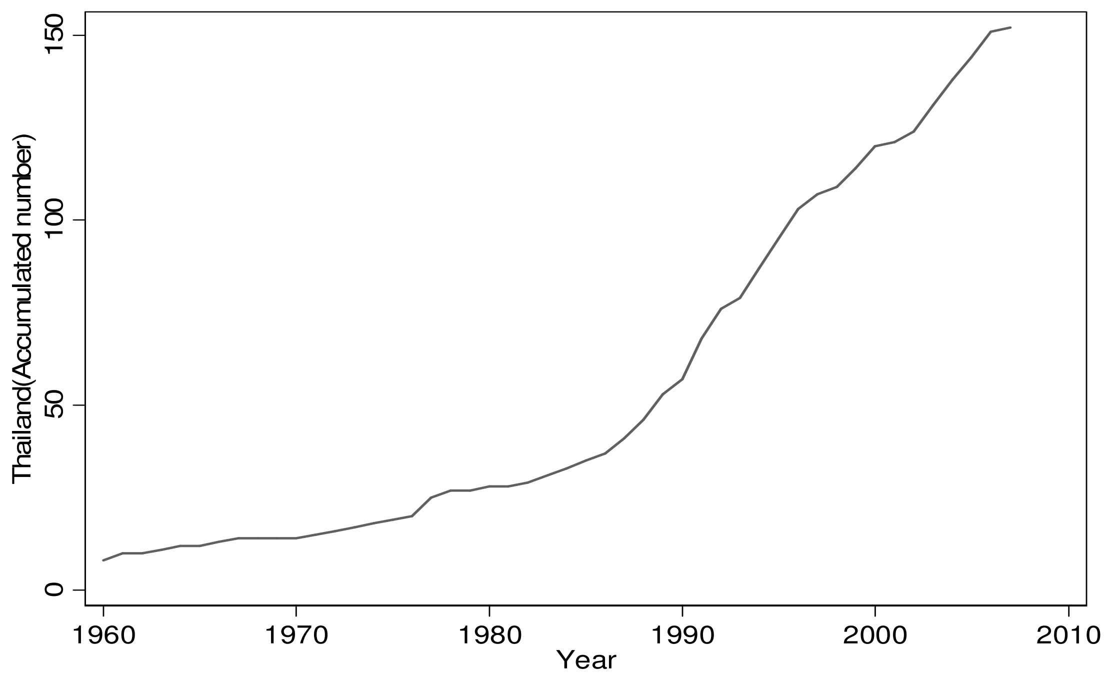

Fig. 3 Accumulated number of offices established in Thailand

YoE = f (firm's size, influential factors, function of an office) (1)

where

YoE = year of establishment

In this study, the size of firm could be represented in the function of the number of employees, firm's assets and paid-in capital. Therefore, Equation (1) can be expressed by three different ways in Equations (2), (3) and (4).

YoE = f (The number of employees, influential factors, function of an office) (2)

YoE = f (firm's asset, influential factors, function of an office) (3)

YoE = f (paid-in capital, influential factors, function of an office) (4)

Table I: Results of Estimations: Agglomeration Model

		Employees		Assets		Capital	
		Full model	Selected model	Full model	Selected model	Full model	Selected model
1	10,000-24,999(US$)/10,000-24,999(US$)		[+]				
2	100- 199/25,000-49,999/25,000-49,999			*	**	*	**
3	200- 299/50,000-74,999/50,000-74,999						
4	300- 399/75,000-99,999/75,000-99,999	*	+		*		
5	400- 499/100,000-499,999/100,000-499,999						
6	500- 999/500,000-999,999/500,000-999,999					[*]	[**]
7	1,000- 1,499/1 M-4.9M/1M-4.9M						
8	1,500- 1,999/5M-9.9 M/5M-9.9M	[*]	[**]				
9	2,000& above/10M & above/10M & above						
1	Investment incentives including tax incentives	[**]	[**]	[**]	[**]	[**]	[**]
2	Liberal trade policy	**	**	**	*	**	**
3	Customs procedures	+	*		+	+	*
4	Local content requirements, rule of origin		[+]				[+]
5	Physical infrastructure (roads, highways, ports, airports)	+	[+]	[+]	[+]	[**]	[**]
6	Infrastructure (telecommunications, IT)		**		**	+	*
7	Infrastructure (electricity, water supply, other utilities)		+			+	**
8	Government institutional infrastructure						
9	Financial system						
10	Legal system	[**]	[**]	[**]	[**]	[**]	[**]
11	Protection of intellectual property rights	**	**	**	*	**	**
12	Size of local markets						
13	Access to export markets						
14	Proximity to suppliers/subcontractors						
15	Request by large/related company						
16	Availability of low-cost labor						
17	Availability of skilled labor and professionals	[*]	[**]	[+]	[**]	[**]	[**]
18	Other companies from the same country are located here (synergy)						
19	Access to cutting-edge technology and information						
20	Living conditions						
1	Retail/ Wholesale trade	[**]	[**]	[**]	[**]	[**]	[**]
2	Production (raw-material processing)			*			
3	Production (components and parts)						[*]
4	Production (final products)						[*]
5	Purchasing/ Procurement/ Logistics						
6	R&D/ Consulting						
7	Human resources development	**	[**]	**	**	**	**
		136	143	136	145	136	142
		-110.674	-126.518	-112.496	-131.094	-109.073	-121.714
		0.199	0.156	0.186	0.138	0.21	0.184

Note 1: [ ] indicates that the coefficient is negative, and items without [] imply the coefficient is positive.
Note 2: **, * and + indicates that coefficient is at the 5, 10 and 20% significance level, respectively.

The models based on Equations (2), (3) and (4) were analyzed for the significance of the models and the summary of the result was shown in Table I, it can be concluded that for large companies who came earlier, "investment incentive," "legal system" and "availability of skilled labor and professionals" are the significant factors that encouraged investors to establish their business in Thailand. The function of the office in Bangkok for large firms at the beginning was more related to retail and wholesale trade. For smaller firms who usually came later after the large firms, the significant factors for their concerns when establishing their business are "liberal trade policy" and "protection of intellectual rights." In the Flowchart Approach, establishment of larger firms is very important since it is the starting point of agglomeration. However, the formation of the smaller firms around the large ones is important as well since this formation can develop into an industrial agglomeration later.

From the models, it can be explained that the industrial agglomeration of Thailand could be divided into two stages. At the earlier stage, the large companies due to the attractive investment incentives, legal systems and skilled labor established firms related to sales activities in Thailand. At the later stage, attracted by the country's liberal trade policy and the system of intellectual property rights, smaller firms followed suit.

5.0 Conclusion

In conclusion, the industrial agglomeration of Thailand can be divided into three periods (before 1985, 1986-1998 and after 1999). The earlier establishment of the large firms who were attracted by investment incentives, legal systems and skilled labor, the smaller firms – who were also satisfied with the government policies in liberal trade and the system of intellectual property rights – to form themselves around the large firms. Although the result of descriptive statistics show that there are several upgrading of the firms in term of new goods, new production methods and new sources of raw materials supply; the common factor that supports the upgrading is hard to find.

Acknowledgement

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HUMAN SYSTEMS MODELING IN SUPPORT OF MANUFACTURING ENTERPRISE ACTIVITIES

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Abstract

Human systems are an important part of any organization . Recently attention has been paid to modeling various aspects of people organized into production systems including production performance, efficient resource allocation and optimum resource management. In this research graphical and computer executable models of people have been conceived and used in support of human system engineering. The approach taken has been systematically decompose processes and their elemental activities into explicit descriptions of roles that potential human role holders can play. This approach facilitates quantitative analysis and comparison of different human system configurations that suit various manufacturing workplaces. The paper describes how the approach leads to the design and runtime simulation of human system. In this paper, the researcher illustrates the application of this approach and observed advantages gained from the use of simulation technologies. This paper described how the models enable prediction of the relative performance of alternative production system design comprises people and machines allocated to process oriented roles.

Keywords: Human system, manufacturing enterprise, simulation modeling, process-oriented.

1.0 Introduction

The literature review shows that ME's (Manufacturing Enterprise) are subjected to increasing dynamic impacts arising in the business environment in which they operate. To address these kinds of concern manufacturing philosophies like Agile Manufacturing[1], Group Technology[2], Reconfigurable Manufacturing Systems (RMS), Mass Customization & Postponement and Holonic[3-5] manufacture have emerged to uniform ME's how to achieve increased flexibility and responsiveness. However, on general these philosophies are only supported by limited implementation tools to quantify relative benefits of choosing alternative philosophies; and more particularly in the context of this research paper, to relative quantify benefits of alternative ways of resourcing process oriented roles in accordance with selected philosophy. Also observed is that despite significant advance in best practice complex systems engineering , as yet in industry there is no model nor coherent means of modeling organizational structures and the related time based behaviors of the human and technical (machine and IT (Information Technology)system) resources. On the other hand, various modeling techniques have been developed to characterize machines (and their competencies and behaviors) and these techniques becomes commonly implemented using virtual engineering and simulation NC (Numerical Control) and robot systems of resources. But generally because ME modeling to human system is so complex and generally the software support tools are somewhat special purpose e.g. to model kinematics and ergonomic characteristics

2.0 The Scope and Focus of the Study

This paper addresses the question: given a well defined set of process-oriented roles how best should work roles be resourced? In this respect it is assumed that either (1) people or (2) some for of machine or IT system or (3) some combination of (1) and (2) will prove most effective; and that generally these kinds of 'active' resource'; will be constrained in terms of their availability short and long term. Also assumed is that (a) the nature of roles and (b) the works loads placed on the roles will determine the most effective match of 'role holders' to 'the defined set of process oriented roles' Furthermore it is assumed that because the work loads in ME's are typically determined by customers and related factors in the ME's environment then these workloads will frequently change. This latter points provides a baseline rationale for this study in that an improved systematic method and supporting modeling tools are needed to compare the match of different choice of candidate human and technical (active) resources to process oriented roles and their workloads; and also that the request method and tools should conform short term planning of resource deployment as well as longer term strategic estimated (and risk taking) in achieving people and technical resource systems.

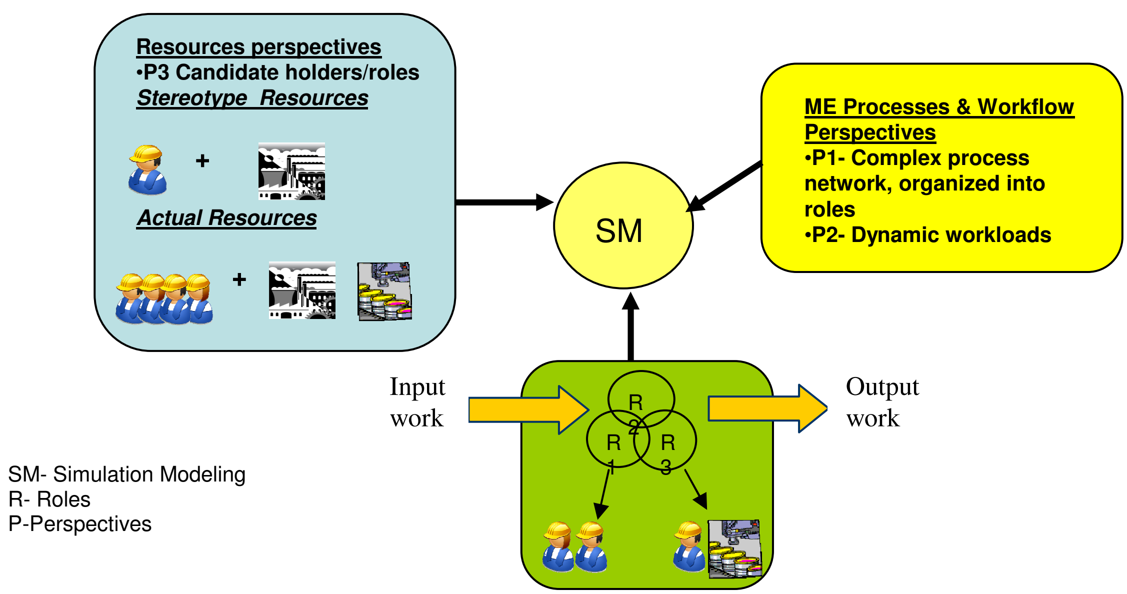

Fig. 1. Human system modelling in ME

Figure 2 illustrates the systematic modelling approach under development by the authors. The underlying idea is to create multi-perspective models that can be computer executed in the form of simulation models (SMs) such that they can provide a computer tool to inform 'ongoing planning' and 'longer term investment' decision making leading to effective use of human and technical resources. Here specific ME models related to perspective P1 are created using an EM (Enterprise Modelling) technique which is geared toward specifying sets of ordered activities (or process models) that can be decomposed into explicitly defined roles. These roles and role relationships specify a process oriented relatively enduring structure for any ME being modelled. A second dynamic workload perspective P2 is derived from (a) analysis of historical patterns of work that previously have passed through the defined roles and/or (b) a forecast or prediction of likely future workloads. The third perspective P3 relates to candidate role holders in the form both of stereotypical and actual human and technical resources. Here modelling can be with respect to (i) known competencies (of people) and capabilities (of machines), (ii) capacities and/or performance levels (of both resource types) and (iii) psychological behaviours (of people).

This multi-perspective modeling approach is designed to enable: (I) independent change to the three perspectives P1, P2 and P3; (II) reuse of models of ME's in the form of process and enterprise models; and (III) ongoing systematic reuse of models belonging to those three viewpoints, as required in support of short, medium and longer term ME decision making.

3.0 Choice of Study Domain

A bearing making company was chosen as the domain of study. The products of this company fall into four categories which relate to the shape and dimensions of the raw material used to make them. The categories are: 'Flat sheet' , 'Strip sheet', 'Round (narrow)' and 'Round(wide)' products. The product type chosen for detailed study is the 'Flat sheet'. Figure 3 explicitly portrays how the business process (BPs) and Enterprise Activities (EAs) lead to flat sheet production.

The human resource utilisation in each of the processes was determined by using the following theoretical equation:

Number of operators needed = Total Cycle Time (TCT) / Takt time

Hence predicted number of operators needed for each processing flat and round sheet product types was observed to be:

Table I: Product TCT , Takt time and number of operators

Product Types	**TCT**	**Takt time**	**No of operators**
Flat sheet	***364***	***107***	***3***
Strip Sheet	292	107	2

The TCT and Takt times were measured using time study principles at the bearing company. These time study results refer to the 'as is' process in the activity diagram as shown in Figure 3.

4.0 Enterprise Modeling and Simulation Modeling in Human System Models

The previous researchers in MSI had developed CIMOSA[6] models for the bearing company. These models 'context diagram', 'interaction diagrams', 'structured diagrams' and 'activity diagrams'. Enterprise Activities were further decomposed into Functional Operations (FO) and Functional Entities (FE). The selected process for this research is shown in Figure 3. This activity diagram concerns 'Flat Sheet' making, where at a chosen level of abstraction flat sheet making enterprise activities are defined. These activity models can be semantically enriched with models of precedence relationships and information requirements for activity execution.

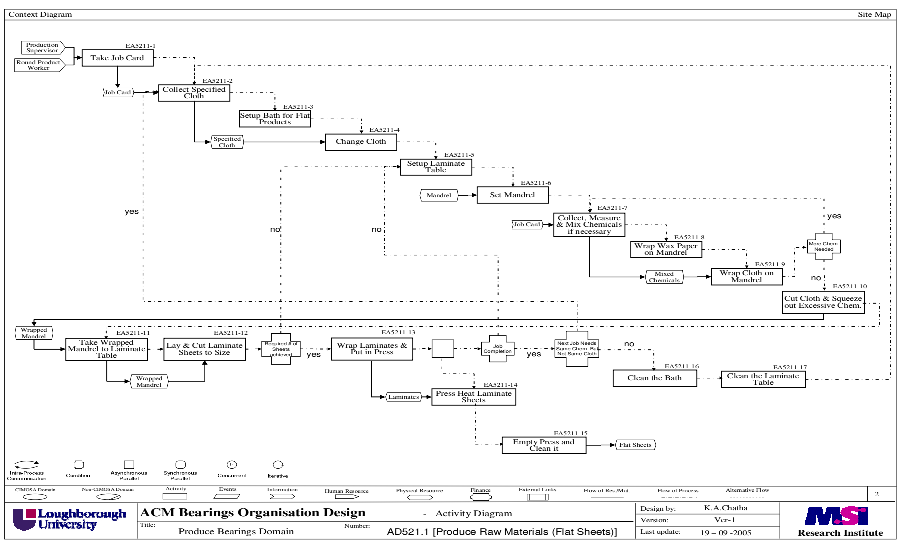

Fig. 2. Activity diagram- Flat sheet making

These processes are then used as a reference for building simulation models (SMs). Two simulation models SM1 and SM2 created in this way are described in the following, but both share a common parent process described by the activity diagram of Figure 2. This process description defines processing routes followed by workflows in the SMs. At each work centre (WC) of SMs resources (human, machine etc) are needed to realise EAs assigned to each WC. The simulation is laid out by referring to the activity diagram and these activities are represented in the simulation models with the icons such as 'single proc' for single processes, 'workstation' for work place or worker at processes, 'workpool' is for the place where all workers are gathered and assigned by a nominated supervisor known as a 'broker'. In the simulation models (SMs), enterprise activities numbered EA5211-1, EA5211-2 AND EA5211-1 are categorised into a Pre wrapping role for WC1. The process executed at WC2 are for a Wrapping role performed by EA5211-4 : then at WC3 the EAs numbered EA5211-5 to EA5211-11 are categorised together as a PreLaminate role: then at WC4 a Laminate role is performed, EA5211-12; then at WC5 the post-laminate role is performed via EAs numbered EA5211-14. Finally at WC6 the clean role is executed via EA5211-15.

The human/worker configurations for both simulations are the same. In SM1, workers are assumed to be 75% - 85% efficient leading to 'as is' processing times at each process. The throughput rates and bottleneck at each workstations were then viewed when the simulation models were run. SM2 input dynamics were changed so that the performance of the workstations and the work pool in SM2 can be compared to the previous simulation model, SM1.

The layout of the experiment is as portrayed in Figures 3 to 6:

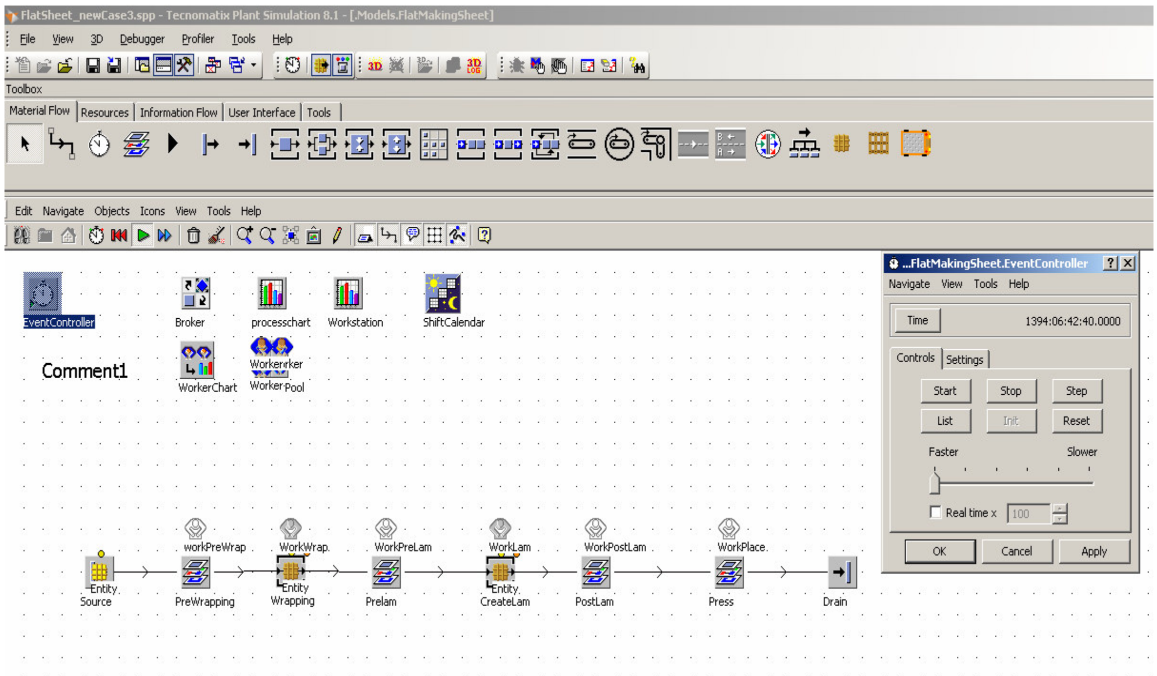

Fig. 3. Simulation Model 1 (SM1)

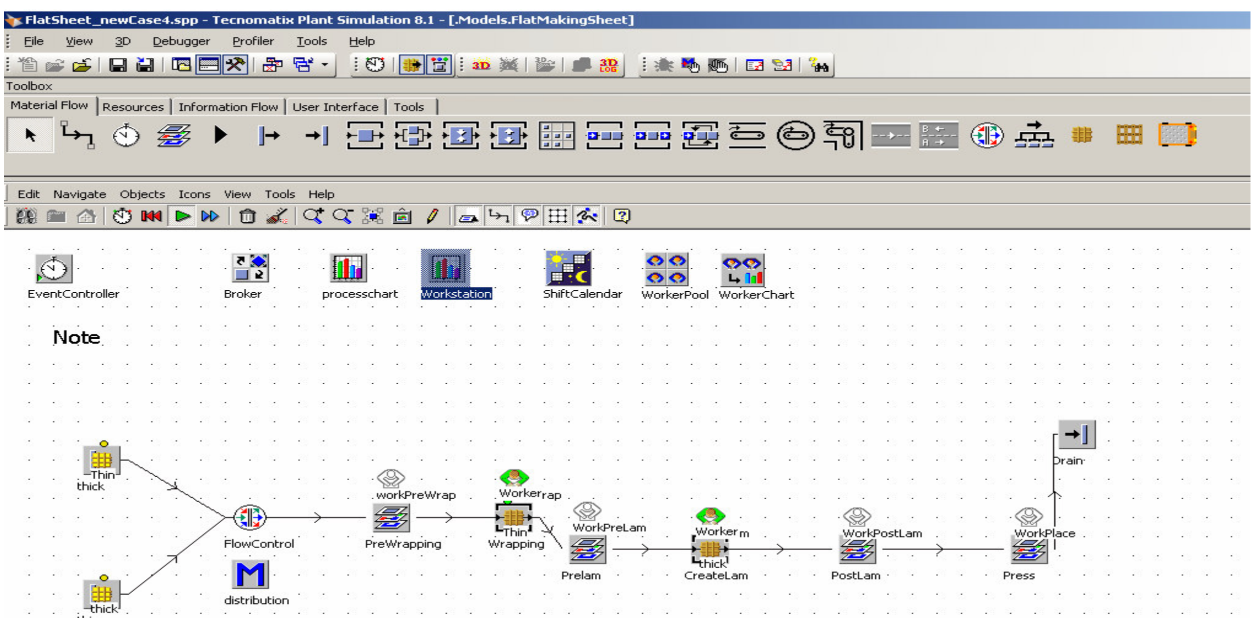

Fig. 4. Simulation Model 2 (SM2)

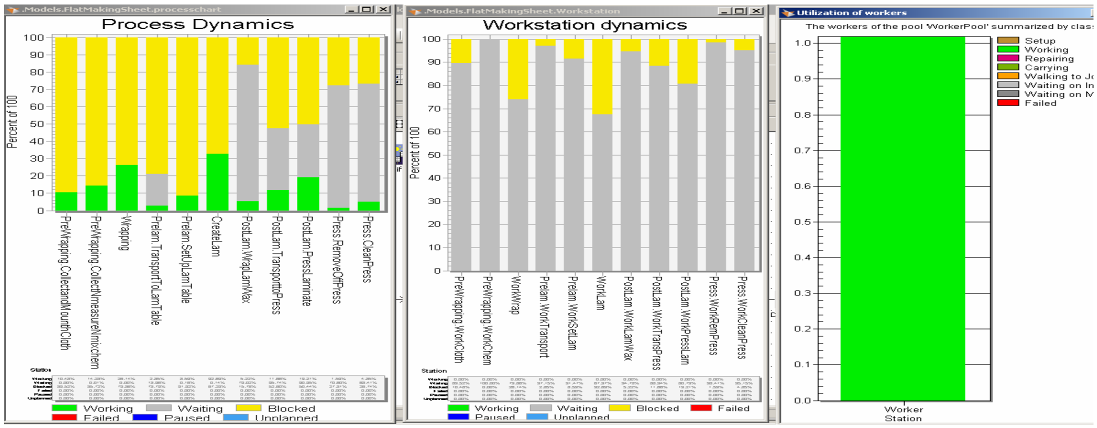

Fig. 5. Results from SM1

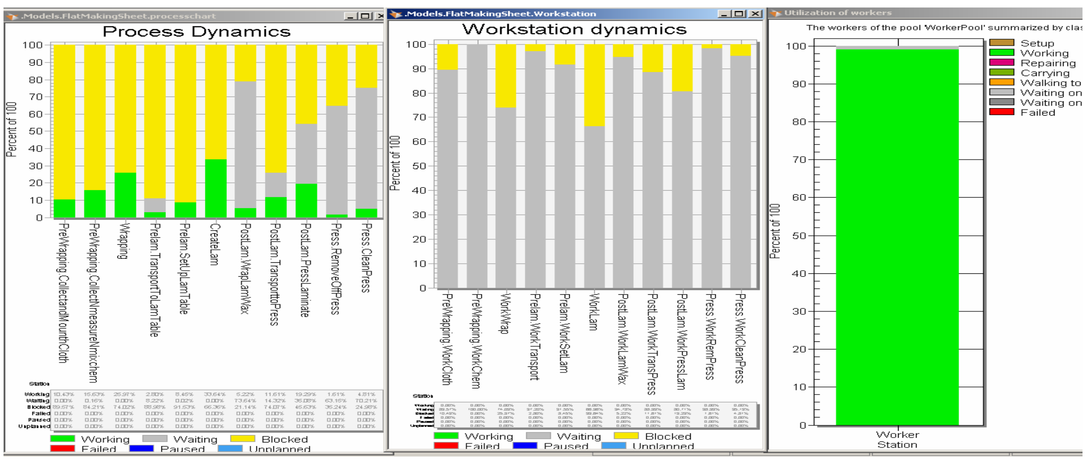

Figure 6: Results from SM2

5.0 Observation and Conclusion

The simulation experiments were found to replicate and predict overall effectiveness of enterprise activities when they deployed resources in different ways. Results obtained are shown in the graphs of process dynamics for both simulation models where bottlenecks change as the input of the processes varies. The time waiting and blocked situations increase in SM2 relative to SM1 and resource utilization in the work pool decreases by 2%.

From this research, it is found that the simulation modeling approach can build upon information previously encoded by static models represented by CIMOSA activity diagram. The approach developed new understanding that enterprise activities can be modeled and used to characterize the dynamic of the overall systems which includes human system dynamics. Thus these models can be used to predict the impact of the overall performance of manufacturing enterprise due to product variance.

Use of alternative SMs and their experimental inputs enables analysis of a particular process segment of MEs. Several candidate behaviors can be modeled by changing the resources assigned to work centre roles. Also, it was observed that both EM and SM enable the execution of 'to be' production system behaviors with different human system configurations. The study is recommended for designing or re-designing manufacturing systems such as new product development or the enhancement of existing production systems.

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THE IMPACT OF INDUSTRY GROUP CULTURE ON THE DEVELOPMENT OF OPPORTUNISM IN CROSS-SECTOR ALLIANCES

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Abstract

Over the last two decades the world economy has dramatically transformed, with strategic alliances and partnerships across industrial and global boundaries becoming an important means to maintaining and regaining competitive positioning. In spite of an increase in partnership activity, alliances continue to face problems fuelled by factors such as partner opportunism, and cultural incompatibility. This paper highlights the emergence of opportunism in alliances arising from cross-sectoral partners' differences in cultural values and norms. The literature indicates that cultural differences are important factors for understanding the behaviour of managers across sectors.

Keywords: Industry group culture, cross sector supply chain alliances, opportunism, Product service systems.

1.0 Introduction

More and more firms are realising the growth opportunities in developing alliances and partnerships both within and across industrial sectors. With this has come the recognition both amongst the academic community and supply chain practitioners, that a vital element to effective alliances is not only the ability to pick the right channel members and then establish and develop strong integrated relationships with them [1] but also to consider the cultural mindset of partners, which is shown to be critically important [2]. Indeed, much research now recognises the value of understanding the cultural context of organizations, and the importance of bridging cultural differences in buyer supplier relationships. In particular, it has become important to consider the influences that come from beyond the specific characteristics and relationship of the parties to an alliance, in the form of institutional arrangements that govern and constrain parties' behaviours (such as informal rules, roles etc,)[3]-[5]. Different 'cultural spheres' or distinct industry groupings, may share cultural values (such as trust and trust building) which may have a role in sustainability of alliances across such groupings [6] [7]. In a similar way, distinct industry groups may operate under a set of norms which lead to behaviours/attitudes that are not conducive to long term strategic partnering [5][8][9] within their own cultural spheres and with partners across sectors. Not only is a high degree of cultural consistency necessary for long term strategies to be successful [4], but also the right cultural norms, values and expectations need to be generated and endorsed by the dominant players within an industry. In the light of the diversity of cultural norms, expectations, rules etc, in cultural groupings, building and managing alliances across sectors and country boundaries can prove difficult. Even though a written agreement may be signed by each partner, the real foundation underpinning these alliances is based on trust, commitment and co-operation between the parties. Given that such alliances are based on trust, commitment and co-operation, the partners' perceptions of these attributes need to be congruent so that expectation on either side of the dyad will be reasonably similar. When alliances partners share a similar cultural background, such consistency in expectation should be a matter of course because each would most likely share the same culturally defined norms of what defines trust, commitment and co-operation. But what happens when the cultural background of each channel partner differs as in the case of alliance members across industrial sectors (PSS's), and across countries such as exporters with foreign distributors [10].

2.0 Role of Industry Group Culture

Authors from a variety of backgrounds have developed definitions and frameworks of organizational culture. Culture represents a shared set of meanings and understandings about the organization and its issues, objectives and practices [11]-[14]. Whereas culture may be visible via rituals, dress codes, stories, physical layout rules of conduct [15], these represent the overt behaviours and other physical manifestations of their organization [11]. At an even deeper cultural level, are the underlying assumptions, such as beliefs, habits of perceptions, thoughts and feelings that are the ultimate source of values and action [2].

Conceptualisation of culture remain problematic, and continue to be greatly contested in different literatures. For the purposes of this paper, a definition of group culture is presented below. Group culture has been defined as a group level phenomenon consisting of a set of shared, taken for granted implicit assumptions that a group holds, and influences how the members of the group understand and respond to their environment. The content of 'culture'- the specific assumptions, norms and values of the culture- shapes members' patterns of behaviour [13] and creates an environment in which attitudes/behaviours are generated, endorsed and tolerated [5].

This paper is concerned specifically with industry group cultures that incorporate a strong tolerance to behaviours such as opportunism. Given that strategic alliances are sites in which tensions between co-operation and competition naturally occur [16], in those alliances where players operate under different norms from one another, the result may be conflicting behaviours and attitudes, leading to an intrinsic vulnerability and inherent instability of the alliance. Post contractual opportunism in alliances can have severe costs and consequences ranging from tentativeness in commitments, to alliance dissolution [17]. The costs of opportunism don't end there as it can have a systems' efficiency cost as total supply chain loses credibility in the eyes of the end user [18]

Opportunism or cheating in the context of alliances refers to intentional self interest seeking at the expense of an other(s) assuming a prior in(formal) contract has been struck between parties. Typically in any trading arrangement, a minimum set of obligations will have been codified in a formal agreement. Under partnership, a fuller set of obligations is generally made informally. Intentionally failing to honour those obligations represents cheating, or opportunism.

The assumptions surrounding the emergence of behaviours such as opportunism seem to be generally based on the immediate or local characteristics of the alliance dyad or partnership, such as ‘lock in investments’ [19], [20] loopholes in contracts [21], difficulties of terminating long term distribution contracts easily or cheaply [22], information asymmetry [23], and performance ambiguity between partners [24] [25], decision making uncertainty and cultural inconsistency , psychic distance [26] [27] monitoring, power [28].

The predominant proponents of this approach are typically rooted in economic theories of behaviour [29]of TCE [22]; [25], [30] [24][31]-[33. Today, many supply chain theorists investigating relational risk arising from opportunism in exchange have been and still are being influenced by literature that implicitly treats opportunism as a partnership level phenomenon.

In contrast, very little consideration is given to the wider market group setting that players are part of, with little or no account of the power of ‘group culture’ that organizations knowingly or unknowingly are embedded in, which may be crucial in understanding why opportunism is more evident in some channel relations and some sectors. This is surprising given that economic behaviour, and in particular opportunism has been demonstrated to be largely constrained by social relationships or institutions, with shared beliefs, norms and mores (culture), [34][35]. Indeed, many studies demonstrate the impact of cultural norms operating within close-knit communities on the emergence of opportunism, and imply the existence of some sort of broad or local community effect on behaviour or attitude [36] [9] [37] [5]. This is significant to cross industry alliances and partnerships that operate under different cultural norms.

Despite this a limited amount of research has been conducting on understanding opportunism as a group based phenomenon, highlighting the need to examine the wider market context of economic transactions, the informal social relations and obligations that economic behaviour are embedded in, that provide the basis for behaviour, or the community pressure towards conformity and in-group norms [9].

As noted above, little theoretical or empirical attention has been paid to understanding how opportunism can emerge within and across different group cultures. Indeed, little research has examined opportunism as a result of cultural norms. One potential research aim is to explore how different industry cultures come to use opportunism as a strategy, and enact its development, both internally, (within the industry sector culture) and externally (across industrial sectors and cultures). How do different cultures’ ‘shared beliefs, ‘fabrics of meaning’ dictate (in)appropriate beliefs attitudes and behaviours about opportunism among its members? How can apparently conflicting cultural norms, beliefs or attitudes be reconciled so that trust may develop?

3.0 The Role of Industry Group/Organizational Culture in Influencing the Level of Co-operation/Competition across Supply Chain Relationships

There is an increasing amount of literature which highlights the notion that cultural differences (of a group) affect the dynamics of partnerships in different countries [39] [39]. Johnson, Cullen, Sakano and Takenouchi [40] concluded that developing cultural sensitivity and cross- cultural preparation was necessary when entering international alliances. Cultural sensitivity was the extent to which managers understood and adapted to differences in their partner firm's culture. Kim and Oh 2002 found that a supplier needed to understand the importance of societal and cultural influences on distributor behaviour, especially with regard to commitment and its impact on performance. Culture has been shown to cause differences in the perception of ethicalness of negotation tactics [54], Boone & Witteloostuijn [53] found that culture has a substantial impact on the co-operative or non-co-operative behaviour of American and Dutch participants in a Prisoner's dilemma setting.

In the US construction sector, partnering is seen as a way to achieve an optimum relationship between client and a contractor, it can be treated as a moral agreement that facilitates effective resolution of problems and conflict without destroying the harmony between the clients and the contractors. For partnering to succeed, Black et al [55] pinpointed that developing trust among partners is the most important factor. However they also indicated that "few industries suffer more from conflict than construction'. As such Hawke suggests that building mutual trust in construction is a myth, mistrust has been overwhelmingly deep seated and long standing, and seems to have become the acceptable yardstick upon which to base transactions" [52].

Similarly in the UK grocery sector also, [5],[8],[18] found opportunism and mistrust to be endemic to the sector. Hardy and Magrath (1989) identify cheating as commonplace and indeed endemic to a whole industry. In particular sectors of retailing, such as consumer grocery packaged goods, a great many sales promotions negotiated with suppliers by retailers in order to encourage pass along savings to end customers, in fact never occur [18]. Cheating on payment terms is also common in channels. This is widespread in markets where huge retailers hold great power over suppliers.

Grant's(1989) exploratory research highlighted the appearance or relative absence of opportunism within and across sectors appears to be strongly linked to variations in sector/market and sub market 'culture' characteristics, and the level of tolerance towards opportunism defined by market/group members and expectation of it. The findings reveal market members define and enforce boundaries of 'unacceptable' behaviour using unofficial rules and sanctions, unwritten penalties, standards of conduct, and concerns for reputation, which become embedded and transmitted via informal social and market networks. These differences create variations in-group member tolerance and vulnerability towards opportunism occurring not just between industrial sectors or markets, but also within sub-markets.

The Social Construction view also suggests that 'rational maximizing' (which manifests itself as opportunism) is not a fundamentally human drive or instinct, but rather a socially and culturally defined strategy. As such this perspective explicitly rejects the dominant economic notion that levels of opportunism are nothing more than the sum of individual actor's independent preferences [9], or notions of psychological or moral inclinations of individuals. The idea here is that the differences in levels of opportunism that are observed among cultural groups such as markets or sectors are explained by social conditions in each group/sector. Opportunism in some groups like all other economic behaviours, is embedded in a specific social and cultural milieu. This theory further proposes that groups (i.e. within one market), can swing between periods of opportunism and restraint. In financial markets, for instance, market makers are pulled between the short-term attractions of extraordinary profits and the long term benefits of prudence. It is a dynamic process affected by pressures shaping behaviour. On the one hand, self interest as well as competitive pressures compel traders to seek to maximize profits in the short term through the locally available strategies of aggressive trading. This aggression may sometimes slip over the line into opportunism. On the other hand, self- interest, as well as social pressures, compel traders to preserve their income stream in the longer term by maintaining interpersonal relationships and attractive markets. This elicits strategies of restraint.

Similar explanations for group opportunistic behaviour can be found in the Business Ethics literature. While ethics are basically personal, and thus have to do with the behaviour of individuals, many authors believe behaviour is influenced by the norms of the environment and the peer group to which a person belongs [41]. In business environments, Plank et al [42] suggest that purchasing professionals approach ethical decision making with a set of values related to the socialization process both inside and outside of their profession. Often in business an individuals ethics may be misaligned with the ethics of the firm market or industry. Indeed, what may be disapproved of at a personal level, is often disregarded at a business level, and even accepted without comment. This is often regarded as 'clever or sharp business'. All that matters is that the company makes the maximum profit [43]. Studies have often shown that individuals with strong personal moral and ethical values do not maintain the same values in the business community [44]. Bowman & Carroll's [45] research similarly found that people feel under pressure to compromise their personal standards in order to achieve the goals of the organization. A survey by Pitney-Bowes Inc (1989), a manufacturer of business equipment, revealed that 95% of its managers feel pressure to compromise personal ethics to achieve corporate goals. A similar study on Uniroyal managers, found 70% feel pressure to compromise ethics (which included types of opportunistic behaviour [46]. Most managers at the above companies believe most of their peers would not refuse orders to market off-standard, and possible dangerous products [46]. These and other studies suggest unethical behaviour (including opportunism) can stem from pressure imposed by superiors, absence of a corporate ethical code, the industry ethical climate and behaviour of peers [47].

Others however, within this discipline have focused on behavioural attributes as the root to unethical behaviour. For instance, Newstrom & Ruch [48] suggest managers are motivated by self interest and will therefore have a propensity to act unethically if it is to their advantage, and if the barriers to unethical practices are reduced or removed.

In addition to the influence of the climate (environment) of the organization, the role of top management, superiors and colleagues, the ethical level of behaviour is determined by the existence of limited (or a shortage of) productive resources [44]. These 'economic' considerations are echoed in the findings by Ulrich and Thielemann's [49], who suggest the majority of managers take into account both ethics as well as economics in specific decision making problems. The implication is that ethical demands must not jeopardize a company's continued economic success, as a company incapable of satisfying the requirements of the market will disappear from the scene before long. Managers reconcile the requirements of achieving economic success with the ethical demands of which they are responsible, by legitimising their activities. As such there is no average ethical profile for a manager but a whole range of thinking patterns that managers apply in the field of tension between ethical and managerial aspects [49]. In this study the authors use the concept of 'economizing' and opportunism synonymously, implying self-interest seeking is not necessarily unethical, it can be just good business practice.

Empirical findings on ethical business research reveals unethical practices arise from a variety of sources, including accepted practices within an industry. This may be the result of falling ethical standards so that practices once considered unethical are no longer viewed as such. Examples include the substitution of materials without customer knowledge after the job has been awarded; mis-representing the contents of products; scheduled delivery dates that are known to be inaccurate to get a contract [50]. Competitive pressures from outside the organization can also push ethical considerations into the background. Societal forces have also been blamed for causing lower ethical standards. These include an increase in social decay, materialism and hedonism, loss of church and home influence, competition, current economic condition, political corruption; greed, desire for gain, 'worship of the dollar' as a measure of success, selfishness of the individual, lack of personal integrity and moral fibre; greater awareness of unethical acts, and TV/communications creating an atmosphere for crime [51].

This literature highlights the implications for the sustainability of 'co-operative partnership' across players operating under diverse societal and group cultural norms and values. Indeed can 'partnerships' across sectors ever be stable and mostly free from opportunistic abuse in those markets where high levels of tolerance as defined by its members are considered acceptable? In the light of these studies, and given the continuing rise in 'partnership structures', and 'outsourcing', within and across industry sectors, and the lack of research comparing 'market culture' systematically across industrial sectors or geographical areas of a country, an extension to this work is timely and important.

In the light of the literature presented, the research proposes the following propositions:

1. Firms will tend to engage in activities and behaviours that reflect or at least are consistent with their values, culture, and predominant market group culture [5].

2. Predominant industry group culture (values, norms expectations, social obligations etc) influence a firm's relational behaviours towards its partners in strategic alliances. Market values play a role in influencing the types of relationships that will be established, and determine the level of co-operation that can exist between partners.[5].

3 Cross-sectoral 'relational exchange' partners who do not share the same or similar market cultural values are less likely to be sustainable in the long term and vice versa. This may have implications for the sustainability of cross sector/country partnership alliances.

Given the continuing rise in inter-firm co-operation within and across industry divides, and the accelerated rise of global sourcing, this new corporate paradigm of increasing firm dependency on external organizations for critical business processes, services, components and raw materials means that effective relationship management is crucial [29] [28]. Indeed, it is through understanding what causes behaviours such as opportunism to emerge, or what inhibits opportunism that practitioners are better able to predict and manage partners behaviours better. Failing to recognise the impact of industry group cultures on behaviour by managers, means the knowledge of strategies for managing potential opportunism remains incomplete. The implication for managers who disregard the wider cultural impact on behaviour (arising from group norms, obligations etc) on individual players, may result in unnecessary costs of controlling behaviour[34], loss of reputation [28] and increasing costs. Additionally, the assumptions made about a partners' behaviour will have an impact on relationship management strategies that managers select. I.e. maybe they are less open than they would normally be, wary less willing to divulge confidential information etc. The study suggests that greater understanding of the cultural and market group implications of collaborative working arrangements are needed if practitioners are to manage collaborative buyer-supplier relationships whether across the UK or globally.

4.0 Conclusions

As co-operative activity amongst organizations, both within and across national and international borders acclerates, more needs to be known about whether predominant/strong social, or market based values, obligations and expectations within which transactions are conducted and embedded can influence the risk of behaviours such as opportunism arising. Building trust, commitment and co-operation whilst refraining from opportunism among supply chain members operating in domestic channels, where the partners come from similar group cultures can be challenging. In those contexts where cultural backgrounds may be dissimilar as in PSS's for example, the challenge will be even greater. In short where cultures are substantially different, trust, commitment and co-operation are more difficult to attain [10], and sustainability in alliances more difficult to achieve. Without a sound understanding of the foundation of culture that influence behaviour, it will be difficult to successfully implement supply chain initiatives. Without the understanding of the importance and significance of cultural diversity amongst partners involved in cross-sectoral partnerships, the sustainability of these alliances cannot be guarantied.

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INTERRELATIONS OF DEVELOPMENT NEEDS BETWEEN INNOVATION COMPETENCE AND INNOVATION CULTURE?

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Abstract

The future competitiveness of organizations is dependent on their ability to innovate. On one hand, for organization's personnel to develop themselves and their innovation competence, the needs for development should be discovered. On the other hand, as the development of a positive innovation culture is regarded as a solid base for the innovations, the development requires that the management additionally discover the needs for development of the organization. The development needs, for individual innovation competence i.e. creative tension and for organizational innovation culture i.e. proactive vision, both can be portrayed with the difference between the current and the future state. The visualization can be carried out via personnel's self-evaluation of linguistic statements and results shown both numerically and non-numerically. Yet, an interesting question remains: do those results of creative tension and proactive vision have interrelations with each other? Therefore, this paper aims to find interrelations between creative tension of individual's innovation competence and proactive vision of organizational innovation culture. The paper deals with the concepts of innovation, innovation competences, innovation culture. Then the discussion goes on to describe the method of self-evaluation via software tool, creative tension, proactive vision and Friedman test for non-numeric data. And after that the results of an empirical study in organizations are presented.

Keywords: Innovation, Innovation Competence, Innovation Culture, Self-evaluation

1.0 Introduction

Arthur VanGundy [23] asks a timely question: "Where has all the innovation gone?" The future competitiveness of organizations is dependent on their ability to innovate. On one hand, for organization's personnel to develop themselves, their individual innovation competences, should be discovered for both the current state and their future objectives. On the other hand, the development of a positive innovation culture is regarded as a solid base for the innovations. For developing such innovation culture, the management of an organization should be aware in the same way of both the current state and the future vision of the innovation culture. Yet, evaluating innovation competences or culture from management top-down perspective does not give a holistic view. The needed bottom up view can be gained via self-evaluation carried out by members of an organization. Here, self-evaluation is considered as a method for a single person to evaluate [e.g. 15] subjectively one's individual competences portraying creative tension [20] and objectively the environment – this case the organizational environment thus illustrating proactive vision [e.g. 4, 18]. Those individual's innovation competences [e.g. 8, 10, 21, 25] and also organizational innovation enablers and barriers [e.g. 1, 2, 3, 7, 16, 22] have been discovered from scientific literature. In practice, this self-evaluation can be carried out with two web-based software tools using fuzzy logic [13] – one representing individual's innovation competence and the other organization's ability to support one's innovativeness, i.e. innovation culture. For holistic view the evaluations of the various individuals can be combined, thereby visualizing the needs for improvement for both individuals and their organization. The results of these two tools evoke questions; therefore, the goal of the proposed paper is to answer the research question: *"Is there interrelations between the results of self-evaluation of creative tension of innovation competences and proactive vision of organizational innovation culture?* Related to this question, the attempt of this paper is to find proof that there either is or is not interrelations between organizations individuals' innovation competence and innovation culture results. In answering this question, first the paper deals with the concepts of innovation, innovation culture and innovation competences. Then the discussion goes on to describe the method of self-evaluation via software tool. And after that the results of an empirical study in organizations are presented.

2.0 Innovation

Innovation has been defined various ways by many authors. However, the OECD [17] definition of innovation is "...the implementation of a new or significantly improved product (goods or services), or process, a new marketing method, or a new organisational method in business practices, workplace organisation or external relations." Therefore, the minimum requirements for innovation are its novelty, whether it has been developed by the organization itself, or adopted from others; and its implementation, either to the market or in use within the organization [17]. This broad definition allows studying the phenomenon of innovation from larger point of view, not only from the narrow product angle.

The link between individual creativity and organizational innovation has been found in the "Componential Theory of Organizational Creativity and Innovation" (CTOCI) [1, 2, 3]. Thus, outcome of innovation requires both individual creativity and the innovation responsive organizational environment. According to Amabile [1, 2, 3], the individual creativity is formed of three components: creativity skills, expertise and task motivation, whereas organizational innovation is a combination of resources, organizational motivation and management practises. Co-dependently, the individual or team creativity feeds the organizational innovation, whereas the work environment impacts the individual creativity.

2.0.1. Innovation Culture and Competence

Innovation has been defined both as a specific competence [e.g. 9, 24] and a collection of competences [e.g. 25]. A competence, or competences in the plural, will be used to refer to those specific characteristics of an individual that are causally related to superior performance in innovating. Several competences related to innovation have been presented [1, 5, 9, 21, 25], of which 27 have been discovered as essential to innovation. (Table 1)

All organizations have organizational culture [e.g. 19, 23]. Additionally, in the long run all organizations face changes and introduce new techniques and technologies that can be regarded as innovations. Therefore it can be claimed that all organizations have innovation culture as well. Here we see innovation culture in an organization as the part of the organizational culture that either produces innovations by enabling them – or doesn't. Many authors have presented such enablers for organizational innovation [1,2, 3, 7, 22] of which we have discovered 22 various enablers for organizational innovation (Table 1).

Table 1: Individual innovation competences and Organizational innovation enablers

Individual innovation competences	Organizational innovation enablers
Connection to innovation enablers	**Connection to innovation competences**
1. Absorptive capacity	1. Absorptive capacity
2. Accurate self-assessment	2. Constructive feedback
3. Achievement orientation	3. Challenge
4. Change orientation	4. Change-able
5. Communication	5. Communication
6. Flexibility	6. Flexibility
7. Independence	7. Freedom
8. Initiative	8. Empowerment
9. Stress tolerance	9. Stress management
10. Leveraging diversity	10. Requisite variety
11. Professional and technical expertise	11. Organization support learning
12. Relationship building	12. Networking
13. Risk orientation	13. Risk tolerance
14. Seeking information	14. Organization support development
15. Self-development	15. Seeking information
16. Teamwork and cooperation	16. Team work and collaboration
17. Trustworthiness	17. Trust and openness
18. Analytical thinking	18. Idea generation
19. Conceptual thinking	
20. Divergent thinking	
21. Imagination	
22. Intuitive thinking	
No connection to innovation enablers	**No connection to innovation competences**
Conflict management	Idea documentation
Responsibility	Idea screening and evaluation
Self-control	Understanding Strategy
Self-confidence	Situational constraints
Understanding others	

3.0 Methods

3.0.1. Self-evaluation

In this research the self-evaluation is performed using a computer application based on fuzzy logic. In practise, the subject evaluates linguistic statements describing the innovation competences and the innovation culture using a web-based graphical user interface [cf. 14]. For each statement the subjects evaluates the current and the future target level. The scale is fuzzy, for example, from continuum of strongly agree to strongly disagree.

3.0.2. Creative Tension and Proactive Vision

Zwell [24] proposes three competence cornerstones that support the success of an organization: the competence of its leadership, the competence of its employees and the degree to which the corporate culture fosters and maximizes competence. If these cornerstones are strengthened, Zwell [24] believes that an organization can improve virtually every side of its operations and come close to achieving its established vision; yet all these cornerstones do interrelate, i.e. co-evolve.

Senge [20] points out that envisioning the future in the desired destination requires realizing the present state. The present state can be clarified by involving all the members of the organization in a participatory manner. Focusing attention on oneself, an individual can bring out the current state of one's innovation competences. Similarly by focusing the attention to the outside world and its processes enables people to form their perception of how things should be related to the current situation and additionally the vision of the desired future. More specifically, at the individual level it is possible to evaluate each person's own perception of the current and desired level of organization, i.e. whether the organization's characteristics enable or hinder personal innovativeness and creativity.

Self-evaluation generates a difference between the current level (reality perceived) and the vision of the desired future (what is wanted). This difference in each individual's perception of one's current and desired future state is the individual's creative tension, as termed by Senge [20] [15]. Similar energy, or the will to develop one's organization i.e. the gap between the current and target state is referred to as the proactive vision [e.g. 4, 18]. Proactive vision activates people to mould the environment to their liking. Collectively, the individual creative tensions and proactive visions form a group level results that reveals the most critical areas in need of development in terms of organization's innovation competences and organizational culture. With the above described participatory manner, it is possible to direct the organizational inputs toward creating an innovation enabling culture in the organization.

3.0.3. Friedman Test of Non-numeric Data

The data collected with linguistic variables is by nature weakest in the statistical sense. Let's assume, that there are three different spaces in different cities. These spaces are inside a house, outside a house and in the freezer.

Next we ask from a person how cold it is in each space. The answers are given in linguistic means, with no thermometer involved. The answers may vary from “really hot” into “extremely cold”. It is impossible to define from two different person’s answers which one is warmer in June, Brunel or Pori. However, it is possible to define within one single person’s answers the rank of different spaces. In February in Pori warmest is inside and coldest probably outside. Statistically these measurements are of nominal scale, where values are used merely as means of separating the properties of elements into different classes [6].

With nominal scale, traditional statistical methods (sums, correlations, etc.) are not applicable. Our self-evaluation creates numerical values for each competence within one answerer. These values can be ranked within one answerer and there are valid statistical methods for calculating group results based on the rankings. We have used the Friedman test [6] to rank creative tensions and proactive visions. In Friedman test we have hypotheses that there are significant differences between rankings. Friedman test sums the rankings and gives us a value within which the sums should be considered equal. We have used significance level of 0.05 and divided the sums into three groups: the most significant, middle group and the least significant. With creative tensions we came into groups where the first 7 rankings were the most significant and the last 6 the least significant. With proactive vision the rankings were divided into two groups, where 11 first ones were the most significant. In empirical results we study how the corresponding innovation competencies and innovation enablers were divided into these groups and what that division means.

4.0 Empirical Results

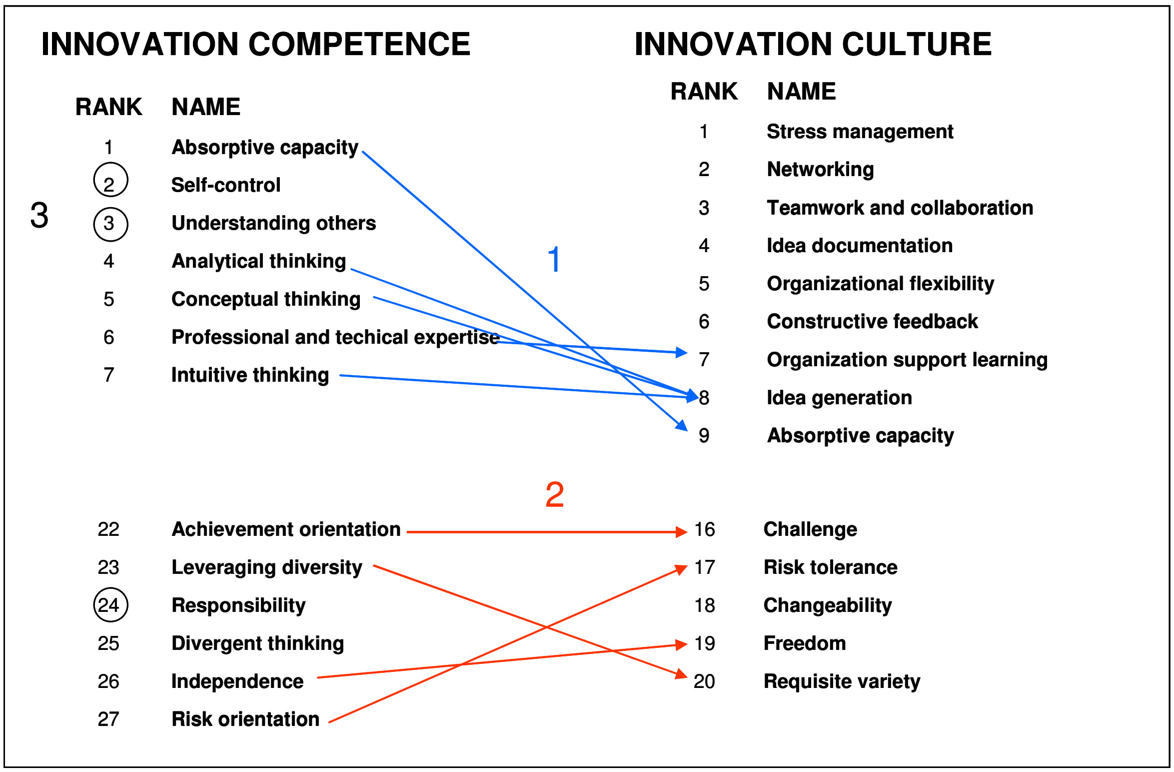
The empirical case study was conducted with test groups in two organizations in different branches: information technology and university. The test group in the information technology organization was 10 persons and in the university was 10 persons. Both groups carried out a self-evaluation of linguistic statements with two web-based software tools using fuzzy logic [10] – one representing individual’s innovation competence and the other organization’s ability to support one’s innovativeness, i.e. innovation culture. The test persons self-evaluated 108 statements regarding their 27 individual innovation competence and 94 statements regarding 22 enablers and barriers in their organization’s innovation culture that have been formulated according to the conceptual research on the literature. For collective view, the rankings of the various individual’s evaluations were accumulated**,** thereby visualizing the needs for improvement for both all the individuals in the organization and their organization. The test results of these two case organizations were analyzed by seeking interrelations.

In the first round of analysis, the average values of the collective results were compared. The results, viewed by the ranking of each competence or organizational feature, showed no specific interrelations between any competence or feature, but gave a slight indication, that with other statistical methods there might be found some interrelations.

4.0.1. Results of Friedman Test of Non-numeric Data

Thereby, in the second round of analysis, the Friedman test, a test method for non-numeric data was applied for finding statistically relevant interrelations. For this test, the entire data of the two test groups were handled together as one group (Table 2). From this data we have come up three kinds of conclusions.

Table 2: Results of the interrrelations between Individual innovation competences and Organizational innovation enablers with Friedman test



1. High score of creative tension of individual's innovation competence and additionally high score on organizational innovation culture enablers. In other words, people find a great need for development at their innovation personal competences, and as great need for improvement also for organizational culture enablers.

   This result can be interpreted so that an individual finds great need for improvement in one's individual capabilities and currently organization does not support one's innovation competences at such a level that it enables his or her individual needs for improvement to be realized at adequate level.

2. Individual's competences that the people did not find need for improvement, i.e. the creative tension was rather low. With those competences, for their counterparts in organizational level, people did not regard needing development either.

This result can be interpreted so that in those individual competences a person does not find great need for improvement, the same people do not require any organizational support either.

3. As a third group could be identify such individual innovation competences that does not have a clear counter part in organizational innovation culture enablers. Those interrelations to organizational innovation culture enablers have to be studied further.

5.0 Conclusion

The interrelations between individual innovation competence and organizational innovation culture still requires additional research. In this paper we have sought to offer a brief illustration on the problem area, though the concepts of creative tension and proactive vision.

On the basis of the discussion above, we can conclude that the creative tension of individual's innovation competence and proactive vision of innovation culture in organizations do not have clear interrelation between when compared with simplistic ranking of average values of each competences and organizational features. Yet, according to our finding with Friedman test, a statistical method for non-numeric data, there are at least two types of interrelations between individual competences and organizational innovation culture features, when compared with creative tension and proactive vision: 1. High scoring in both creative tension and proactive vision portraying both individual and organizational needs for improvement. 2. Low scoring in both creative tension and proactive vision portraying innovation competences that do not require development, thus not requiring support from counterparts in organizational innovation culture. Additionally there was found innovation competences that do not have direct counterparts in organizational innovation culture features, yet having need for development.

To conclude our findings, competences that people wish to enhance in the future have, to some extent, interrelations to those organizational features that people wish to be enhanced in the future. However, those interrelations have to be studied further with more data and also with other statistical methods.

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WSN BASED INTELLIGENT COLD CHAIN MANAGEMENT

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Abstract

This paper presents a cold chain monitoring system which is implemented by using ubiquitous computing technologies, Radio Frequency Identification (RFID) & Wireless Sensor Network (WSN). In this paper, we discuss how cold supply chain works and how we can monitor and control cold supply chain by using wireless tracking and sensing technologies. We propose a prototype design which will provide a well controlled and transparent cold chain system, which could help the users to manage their products' environmental data in real time during the life cycle. Moreover, we highlight how the availability of product trace data in combination with historical condition-monitoring data can facilitate decision-making processes enhancing supply chain's performance. Finally we discuss the integration works of these two technologies together in the cold supply chain management system. Hardware and software platform of WSN used in this system are also described in this paper.

Keywords: Cold Chain, RFID, WSN.

1.0 Introduction

A cold chain is a temperature-controlled supply chain. An unbroken cold chain is an uninterrupted series of storage and distribution activities which maintain a given temperature range. Cold chains are common in the food and pharmaceutical industries and also some chemical shipments. One common temperature range for a cold chain in pharmaceutical industries is 2 to 8 °C. But the specific temperature (and time at temperature) tolerances depend on the actual product being shipped [1]. Cold chain is very important for the supply chain management of the food and pharmaceutical industries because a good cold chain can reduce the risk and cost. The loss of a trailer of temperature sensitive products due to improper transportation or inventory will cost thousands of dollars; a pharmaceutical shipment, in millions [2]. Perishable food products must be continuously monitored for safety concerns throughout the whole supply chain. A breakdown in temperature control at any stage will impact on the final quality of the product [3]. The key to managing the cold chain is to measure product temperature at each stage. Currently, food, dairy and pharmaceutical companies are already tracking their environmentally sensitive products using temperature data loggers placed in their transportation vehicle, containers or even pallets. However, this technology only provides information for a certain part of the cold chain [4]. But for the whole life cycle tracking is still under research. To achieve the capability of monitoring and controlling of every link in a cold chain, real time data should be communicated via data retrieval devices.

Radio Frequency Identification (RFID) technology has been available for decades but it has only recently risen to prominence. Increasing competitiveness between tag manufacturers has lead to significant reductions in the cost of the technology, which in turn drives industry sectors' attention on RFID for adoption. Current RFID systems, however, lack intelligence on their operational environment such as temperature, humidity, etc. In order to tackle this problem, we have been investigating the possibility of integrating RFID with a relatively new technology, WSN. WSN are made up of many small devices with processing and sensing abilities [5].

Integrating RFID systems with condition-monitoring systems will enhance existing track and trace applications, not only the location, but also the condition of perishable and valuable products. Moreover, the availability of product trace history data in combination with historical condition-monitoring data can facilitate numerous decision-making processes [6]. In this paper, we aim to discuss the benefits that such integration could provide, whilst also paying close attention to the implementation view. In our research, we used a sensor network system based on Nano-Qplus platform which is composed of NANO HAL for abstracting the hardware part sensing and actuating, task management, power management, and message handling module. In addition, the Nano-Qplus platform includes ATmega128 MCU and CC2420 Zigbee, IEEE802.15.4 RF communication module. Based on Nano-Qplus platform, we developed the integrated system which have the functionalities of both RFID and wireless sensor network system [7]. Overall, this paper focuses on the design and implementation of the WSN based cold chain management system which monitors the condition of temperature sensitive objects during their supply chain processes.

2.0 Wireless Sensor Network Platform

2.1 Hardware of Nano-Qplus Platform

The sensor hardware which is called Smart Sensor Node focuses on low-cost, low-power, and high-modularity. The sensor node is composed of four blocks: Main, Base, Sensor, and Actuator. The main block has ATmega128 microcontroller and CC2420 IEEE802.15.4 compliant RF transceiver. The base block is used for Anchor node with RS-232 serial I/F, parallel I/O and external power source. For sensing of physical environment, the sensor block has several sensor entities, such as light, humidity, temperature, and ultra sound. The actuator block is made up several electrical switches and can be combined with electric appliances in order to turn Off/On power. In case of normal application, the sensor node is power-supplied by two AA3.3 batteries [7].

2.2 Software of Nano-Qplus Platform

The architecture of the Nano-Qplus resembles as classical modular and layered design and consists of dynamically-loaded modules included in hardware, Nano-OS, and application parts respectively. The hardware part is composed of MCU using ATmega128, RF module, which is CC2420 for wireless communication, and Sensors/Actuators. The Nano-OS part has a role as kernel scheduler and network protocol stack for handling RF messages, and it have a device driver modules, called as nHAL, for abstracting the hardware part. Furthermore, the Nano-OS part also offers the system APIs for convenient developments of WSN applications to sensor networking programmers. In the end, the application part consists of one or more modules interacting via system APIs with Nano-OS part [7].

2.3 RFID Reader Embedded Sensor Technology

As the name indicates RFID is used to identify objects using radio communication. Different applications have different demands on range, power consumption and so on. The most commonly used carrier frequencies are 125 kHz, 13.56 MHz, 868 MHz and 2.4 GHz. The tags can be either passive or active, this system uses 13.56 MHz carrier with inductive coupling, has ability to read from and write to the tag and read multiple tags simultaneously [8]. The normal reading range for the RFID system used in this system is about 5-10 cm, which means that reader and tag cannot be physically separated more than this distance in order to function. The nodes in the network include an RFID reader and RF transceiver as we have mentioned before. When the RFID reader read the tag, it will transmit the tag's information from the sensor node to the sink node, and the distance between the sensor node and sink node could be 10-30 meters [9].

3.0 Analysis of the Cold Chain

3.1 Typical Cold Chain Process

From the factory to the consumer, products follow complex logistic circuits that are subjected to intrinsic constraints. First, the required chilling time between harvest, or the end of cooking, and loading, is a constraint encountered by the producer and the carrier. The carrier's liability comes into play from the moment the products are taken over, and it is up to him to check the temperature manually during loading products, then reach the temperature-controlled distribution hub and send to the customer via supermarket or store. Temperature control needs to be improved throughout the cold chain, to ensure food safety and hygiene and to maintain the product quality [10].

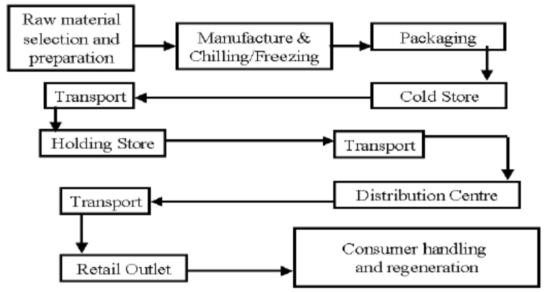

Fig.1. The sequence of events within a typical cold chain [11]

3.2 Hazard Analysis and Critical Control Point (HACCP)

A cold chain can be managed by a quality management system: it can be analyzed, measured, controlled, documented, and validated. The food industry uses the process of Hazard Analysis and Critical Control Point (HACCP) as a useful tool. Its usage continues into other fields [1]. HACCP is an important element in the control of safety and quality in food production. When properly applied, it provides a management tool aimed at complete commitment to product quality and safety. HACCP is useful in identifying problems in food production and works well for simple products and processes. There are 7 principles of HACCP as follows: 1)Identify hazards, assess risk, and list controls; 2) Determine critical control points (CCPs); 3) Specify criteria to ensure control; 4) Establish monitoring system for control points; 5) Take corrective action whenever monitoring indicates criteria are not met; 6) Verify that the system is working as planned; 7)Keep suitable records [12]. Therefore according to these principles, it is clear that we need to define the control points to monitor and keep the time-temperature history throughout the chain for products' safety and quality.

3.3 Lot Traceability and Expiration

Many process industries, notably those involving food and beverages, drugs, cosmetics, and medical apparatus, are subject to government regulation, and must maintain records that detail the lot identification of materials used in the manufacture of these products. Many businesses follow this practice to protect themselves against liability. Shelf life or lot expiration tracking systems also require supporting inventory record subsystems. Typically, they track lot creation dates and expiration dates and provide for first-in, first-out (FIFO) use of material as well as periodic aging reports used to predict material that is potentially expiring [13].

3.4 Advanced Planning Systems Adopting Cold Chain Management

Advanced planning system incorporates long-term, mid-term and short-term planning levels. With the support of effective information flows among these levels make it a coherent software suite. APS do not substitute but supplement existing Enterprise Resource Planning (ERP) systems. APS now take over the planning tasks, while an ERP system is still required as a transaction and execution system. APS are intended to remedy for the inefficiency of ERP system through a closer integration of modules, adequate modeling of bottleneck capacities, a hierarchical planning concept and the use of the latest algorithmic developments. APS is seen in its ability to check whether a (new) customer orders with a given due date can be accepted. By adopting cold chain management functions into the APS could help us to track not only where the product is but also the temperature information around it. To adapt the sensing based APS, in our cold chain management system, we can define the environmental parameters to record and transmit those in every process of the cold chain system and send back to APS and ERP system which could help us to better manage the forecast, inventories, resources, orders and distribution information [14].

4.0 Proposed System Description

4.1 RFID&WSN in Cold Chain

The monitoring of the cold chain should be from the birth of the product to its' destination with its whole life cycle. When the product is ready to be palletized, an RFID and temperature (or humidity, etc) sensor node is activated and placed on the product stack, each product item will be packaged with the RFID tag containing information such as description, destination, and date of departure etc. This information is stored in a secure database [4]. So during the whole life cycle of the cold chain from the plant to the hand of customer will be traceable by using the RFID and Sensor Networks. As RFID record the individual information of an item and sensor network could detect the environmental status, by combining the two domains we can check the status of every product in real time. The system will automatically integrate new nodes which are placed in the range of the network. RFID sensor nodes in the network will have the ability to read RFID tags of a certain type and pass that information to the sink node. The sink node will connect to a PC or Internet from which the user can collect and analyse the data. In every critical points of cold chain we deploy wireless sensor networks in which sensor node should communicate with each other (Fig .2).

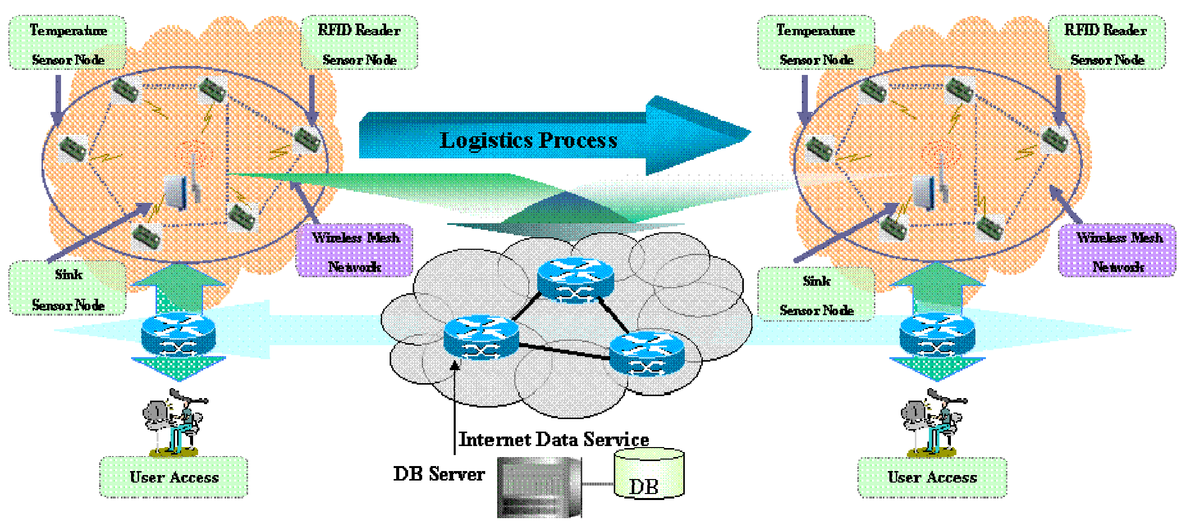

Fig.2. Integrated RFID&USN Cold Chain Management System Design

One or more RFID reader sensor is being clustered with some of the temperature sensor node. When the product have been read from the RFID reader node, the temperature data being detected from the same cluster by the temperature sensor node will be sent to the database and build up the product environment history information. By combining the RFID data and temperature sensor data in the data logger, we get the real-time temperature information of products. Also by using the web server we can make the web application in which remote users could monitor and access the cold chain data. Whenever the temperature is out of the control range in the part of the cold chain, the system could sent the SMS message to the administrators' mobile phone to give the alert by using the CDMA server and SMS service.

4.2 Supply Chain Planning and Execution

Supply chain planning refers to a set of supply chain activities that focus on: evaluating demand for material and capacity; formulating plans; and scheduling to meeting the demand and company goals [15]. Supply chain execution means set of supply chain activities that focus on fulfillment rather than planning-raw material delivery, manufacturing operations and shipments to customers. Execution functions receive requirements from the planning cycle and provide the actual data for actual measurements [16]. Obviously, supply chain planning is an important factor for the success of a company. Poor planning will result in loss of profits and revenue while accurate planning allows a company to operate smoothly and to minimize expenses. The question then is how to more effectively create business forecasts for supply chain activities and control supply chain execution [17]. In our research, the prototype system will not only act as a monitoring tool but also could be used as a planning and execution tools of the supply chain control points. As an easy example, it is easily provide the gap between planning and execution during the cold chain processes.

5.0 System Implementation

5.1 Programming Tool Description

Our prototype system is implemented by LabVIEW (Laboratory Virtual Instrumentation Engineering Workbench) which is a platform and development environment for a visual programming language by National Instruments. LabVIEW is commonly used for data acquisition, instrument control, and industrial automation on a variety of platforms including Microsoft Windows, various flavors of UNIX, Linux, and Mac OS [18]. VISA is a standard I/O language for instrumentation programming. VISA by itself does not provide instrumentation programming capability. VISA is a high-level API that calls into lower level drivers [19]. In our system, the sink node is connected to the computer by serial connecter, in order to get the data easily by using NI-VISA module. For our prototype system, we use Microsoft Access database to store the records.

5.2 Cold Chain Management System

As a part of cold chain execution tool, RFID tag should be assigned to a product and it will represent the product during the whole life cycle. For example, we assigned an RFID tag for product 'ice-cream' and its attributes (e.g. Product ID, Product Quantity, Customer, Preferred High and Low Temperature, Due Date etc.).

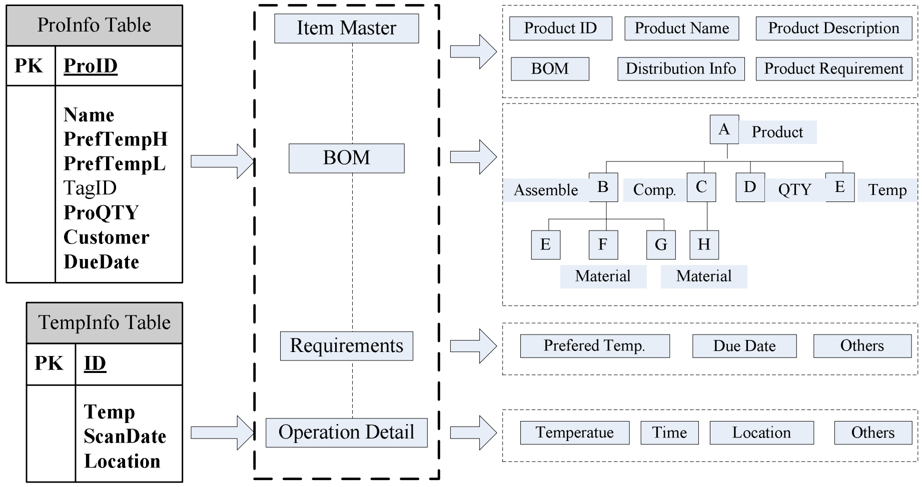

Fig. 3. Data foundation for cold chain management

Fig 3. shows example data foundation for cold chain management. After assigning the tag with product information, the next step is to identify the location of a product in the cold chain. When we scan the RFID tag using the wireless RFID reader sensor node, the system can show us the location information where the tag has been read. In monitoring point of view, we include four steps in the cold chain such as Manufacture, Inventory, Transportation and Retailing which simulate the whole life cycle of a product. In each step, there is a monitoring window that clearly shows the function of each step. We placed LED indicators to indicate whether the sensor node is working well or not, and to alarm whether the temperature is out of the range from preset interval. By using waveform chart we could clearly see the changes of temperature during monitoring process. We also designed a user interface which could help us to monitor the process visually. If the temperature is out of the range, it will also give the alarm for enabling proactive measures for our cold chain (Fig 4).

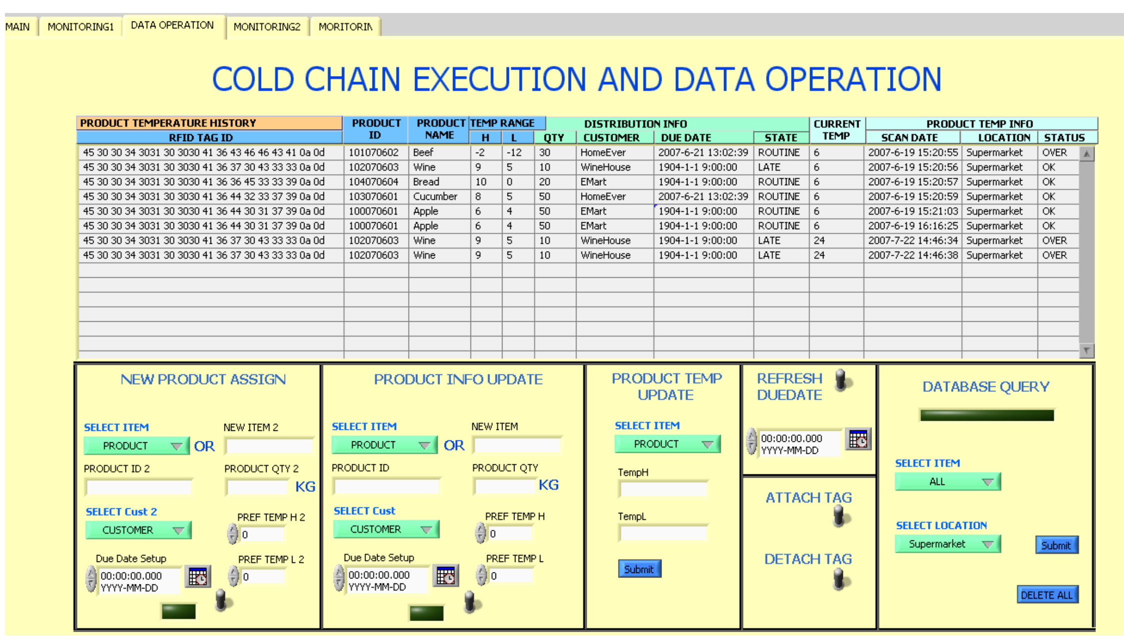

Fig.4. Cold Chain Monitoring System User GUI

6.0 Conclusion

Highly integrated and inexpensive smart nodes network is much cheaper and more flexible compared with heterogeneous network. Smart nodes read fewer tags and can be deployed densely as self-organizing WSN. They run autonomously and translate data information to the sink node. The gathered information is transmitted through multi-hops. Energy constraint is an extremely crucial problem when smart nodes are applied in industry because of battery consumption. Currently ZigBee protocol is considered as the best candidate as it satisfies reliable, low cost, low power consumption requirements [20]. For a large scale application, collecting a huge amount of data from the sensor nodes is also an issue to consider. Although we use one temperature sensor in each location, it is also possible to deploy more than one temperature sensor for multi-temperature modeling. We have presented a design model for the cold chain traceability and the concept of the cold chain. After that, the hardware and software architecture for WSN and RFID integration platform is described. Then, we have mentioned a prototype of a traceability system using Nano-Qplus wireless sensor networks and user friendly LabVIEW working environment. RFID/WSN integration works are also introduced as a challenging area of research.

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LINKING SUPPLY CHAIN MANAGEMENT CAPABILITY AND MANUFACTURING OPERATIONS COMPETENCE WITH ORGANIZATIONAL PERFORMANCE: A CASE STUDY OF THAI INDUSTRIES

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Abstract

This paper conceptualizes, develops, and validates two dimensions of SCM practices (strategically managed buyer-supplier relationships and internal manufacturing operations competence). The study is designed to identify important factors that influence a firm's internal operations and involvement in supplier development, develop reliable and valid measures of these factors, and test hypotheses on their interrelationships. Data for the study were collected from 245 companies in Thailand and the measurement scales were tested and validated using structural equation modeling. The results of this study shed light on the importance of managing the cooperative relationship between buyer and seller and its effect on the financial situation of the firm in Thai industries.

Keywords: Supply chain management, Strategic purchasing, Internal manufacturing operations, Organizational performance, Structural equation modeling.

1.0 Introduction

As competition becomes more intensified and markets become global, the challenges associated with getting a product and service to the right place at the right time at the lowest cost have been more critical to organizational performance. Organizations begin to realize that it is not enough to improve efficiencies within an organization, but their whole supply chain has to be made competitive. It has been pointed out that understanding and practicing supply chain management (SCM) has become an essential prerequisite to staying in the competitive global race and to growing profitably. Many firms have responded to these conditions by focusing on their core competencies, and outsourcing non-core activities that were previously performed in-house.

As a result, there is a need to achieve the right balance between internal and external outsourcing activities. The successful implementation of SCM requires integrating internal functions of a firm and effectively linking them with the external operations of its partner firms in the supply chain. Largely missing from this body of knowledge has been a full and complete understanding of how cooperative supply chains are effectively managed overtime and whether internal manufacturing operation efficiencies within an organization can contribute to such cooperative relationships as well as to the organizational competence.

Our study is an attempt to fill this gap in the research by developing and testing a framework that looks into how these relationships function and contribute to the firm's success. This paper has three objectives: (i) to establish linkages between some aspects of firm's internal manufacturing operations with some aspects of supply chain management: (ii) to study the impact of these linkages on an organization's performance: (iii) to study the effects of these linkages in the context of Thai industries. It is hoped that the results of this study will help senior management to better understand these inherent relationships. For researchers, this case study of Thai industries may provide a stepping stone towards examining the impact of the relationships between manufacturing and supply functions on organizational performance.

2.0 Theoretical Framework and Hypotheses

This section focuses on organizational measures in terms of financial performance of the firm in an effort to place supply chain management's capability and internal manufacturing operations' competence in a theoretical context. The factors under study are conceptually categorized as follows:

Supply chain management capability factor: This includes strategic purchasing (SP) and buyer-supplier relationship (BR). These components influence the firm or the purchasing function within the firm to adopt a strategic perspective on long-term cooperative relationships.

Internal manufacturing operations competence factor: This includes quality expectation (QC) and production and inventory management (PIM). These components are an integral part of the firm's internal manufacturing operations.

Organizational performance factor: This includes the firm's financial performance (i.e., return on investment, profits as a percentage of sales, net income before taxes, and present value of the firm), which is considered to be the main criterion for judging the organizational performance of the firm.

The following hypotheses and the model depicted in Figure 1 specify the antecedent factors and their interrelationships.

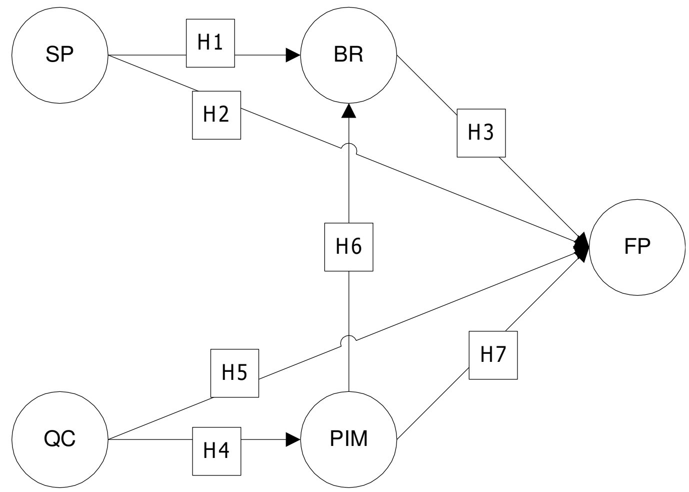

Figure 1: Research Hypotheses

2.1 Supply Chain Management Capability in Relation to Organizational Performance

Hypotheses 1 to 3 propose that strategic purchasing (SP) has a positive impact on buyer-supplier relationships as well as the firm's financial performance. These hypotheses are based on the idea that firms that practice long-term planning and considered strategic purchasing are likely to build long-term cooperative relationships with their key suppliers which eventually benefit the firm's financial performance. Two dimensions of the effective supply chain management were measured: strategic purchasing and buyer-supplier relationships. Buyer-supplier relationship architecture is conceptualized as being information sharing and trust between buyer and supplier, and aspects relates to centralized planning which is referred in terms of JIT as "supply chain proximity". The following hypotheses are purposed:

H1: Strategic purchasing (SP) has a positive impact on buyer-supplier relationships (BR)

H2: Strategic purchasing (SP) has a positive impact on the buying firm's financial performance (FP)

H3: Buyer-supplier relationships (BR) have a positive impact on the buying firm's financial performance (FP)

2.2 Relationships of Internal Manufacturing Operations Competence and Organizational Performance

Hypotheses 4 to 6 postulate that positive relationships between the independent factors of the internal manufacturing operations can impact on the organizational performance. According to Fogarty *et al.*[1], in spite of the media attention devoted to the development of supply chain, two mistakes are far too common. First, developing effective internal manufacturing operations may seem mundane next to strategy formulation, but these methods are critical to long-term survival and competitive advantage. Second, many analysts assume that implementing sophisticated manufacturing operations will solve all problems. These analysts may achieve a high level of efficiency by optimizing given the lead time and demand variability the firm observes. However, they do not understand that this efficiency is insignificant compared to the benefits available by changing the givens. Therefore, the following hypotheses are purposed:

H4: Quality expectation (QC) has a positive impact on production and inventory management (PIM)

H5: Quality expectation (QC) has a positive impact on the firm's financial performance (FP)

H6: Production & inventory management (PIM) has a positive impact on the firm's financial performance (FP)

2.3 Relationship of Production and Inventory Management Capability and Buyer-Supplier Relationships

Hypothesis 7 suggests a positive relationship between internal manufacturing operations competence (production and inventory management) and buyer-supplier relationships. To attain the quality in the supply chain, it is essential to develop a stable buyer-supplier relationship, which requires that the firms involved work beyond organizational boundaries to improve performance throughout the supply chain. The stability of relationships goes beyond a simple, positive evaluation of the other party based on considerations of the current benefits and costs associated with the relationship. It implies the adoption of a long-term orientation towards the relationship-a willingness to make short-term sacrifices to realize the long-term benefits of the relationship [2]. Therefore, it is hypothesized that production and inventory management has a positive impact on buyer-supplier relationships

H7: Production and inventory management (PIM) has a positive impact on buyer-supplier relationships (BR)

3.0 The Survey

A survey was undertaken to gather data for testing the research hypotheses. The survey included multiple scale items for each of the factors. The sample was drawn across industries. A relatively large pool of respondents was necessary due to the number of variables in the model. From the 1,000 subjects in the target sample, 245 responses were received. Twelve surveys were excluded from the analysis because of incomplete information. Thus, the response rate was about 24%. To achieve as high a response rate as possible, telephone calls and company visits were used to remind potential respondents of the questionnaires.

The respondents were drawn from a variety of industries and industrial areas drawn from the membership list of the Federation of Thai Industries (FIT). In order of frequency, industries most frequently represented were automobile, plastics and packaging, electronics, and consumer products. Registered capital investment was used as indicator of the firm's size. The response sample was comprised of high ranking plant mangers and purchasing executives. The responses were recorded using a five-point Likert-type scale (1 = strongly disagree to 5 = strongly agree) on 5 groups of the questions representing each node of the hypothesis.

This paper uses Structural Equation Modeling methodology with Statistical Analysis Software (SAS) to analyze the research hypotheses. SAS provides a wide range of statistical analysis ranging from traditional analysis of variance to exact methods and dynamic data visualization techniques. Then, Structural Equation Modeling is performed by using a two-step procedure. The measurement model is developed; this is followed by development of the structural model [3]. The measurement model examines the relationship between the underlying variables and the factors they are supposed to measure. The structural model differs from the measurement model because it includes causal paths based on hypothesized relationships between specific factors in the model.

4.0 Results

Confirmatory Factor Analysis (CFA) was used to validate measures of constructs for developing the measurement model. CFA is a more effective method for assessing unidimensionality than exploratory factor analysis, coefficient alpha, and item-to-total correlation. The purpose is to ensure unidimensionality of the multiple-item constructs or low item-to-constructs and to eliminate unreliable items [4]. Items that loaded on multiple constructs were deleted from the model prior to testing. The measurement model was analyzed using the SAS program and CALIS procedure. An adequate fit was achieved for the measurement model. The chi-square to *df* freedom ratio = 1.756, the Bentler's Comparative Fit Index (CFI) = 0.9027, Bentler and Bonett's Non-normed Fit Index (NNFI) = 0.9, all of the *t*-statistics for the indicator variables were greater than 2.576, significant at $p<0.01$, and no standard errors were near zero. The confirmatory factor analysis resulted in the elimination of a few individual items (V5 and V18) because of low factor loadings or high residuals. This result was not surprising because many of the survey items had been developed specifically for the study, and other items had been adapted from other literature streams.

Table 1: Measurement model: unstandardized coefficient, standard error, *t*-value and standardized coefficient for each item

Individual items, their respective factors and coefficient alpha for each factor. (All scales were 5-point Likert scales where 1 = Strongly disagree – 5 = Strongly agree)	Unstandardized coefficient	Standard error	*t*-value	Standardized coefficient
Production and Inventory Management (PIM) (α = 0.6658)				
V1: The firm has never experienced supply shortage in the past 6 months	0.4388	0.0787	5.5741	0.3926
V2: The firm has never experienced late order delivery to customers in the past 6 months.	0.6056	0.0812	7.4605	0.5118
V3: Demand forecasting of the firm is quite accurate and has a high potential to be used for its production planning.	0.6603	0.0639	10.3358	0.6823
V4: The firm has managed its inventory control system effectively so that its level of inventory is suitably set and managed.	0.7143	0.0671	10.6486	0.7010
Buyer-supplier Relationships (BR) (α = 0.7861)				

V6: The firm has firm policy to build a long-term relationship with key suppliers.	0.4909	0.0594	8.2658	0.5347
V7: The firm has frequent face-to-face planning/communicate with key suppliers.	0.8036	0.0618	13.0011	0.7688
V8: The firm has frequent face-to-face planning/communication with its customers.	0.6955	0.0635	10.9547	0.6738
V9: There are direct computer to computer links with key suppliers.	0.8075	0.0852	9.4806	0.5999
V10: The firm has exchanged important information with key suppliers such as supply/production/delivery plans, current inventory level, etc.	0.7685	0.0710	10.8245	0.6674
Strategic Purchasing (SP) (α = 0.8507)				
V11: The firm has an effective supplier certification program	0.6812	0.0483	14.1144	0.7880
V12: The firm has a formal **program for evaluating and recognizing suppliers.**	0.7350	0.0502	14.6463	0.8082
V13: Purchasing plan is effectively established by considering various types of relationships established with suppliers	0.5837	0.0502	11.6198	0.6845
V14: Purchasing plan is reviewed and adjusted to match changes in the firm's strategic plans on a regular basis.	0.6740	0.0504	13.3597	0.7582
V15: The firm is currently satisfied with key suppliers.	0.5313	0.0541	9.8179	0.5997
Quality Expectation (QC) (α = 0.7100)				
V16: The firm gives the highest regard to the quality of its products.	0.3108	0.0394	7.8912	0.5145
V17: There are effective quality control tools to monitor and control the quality of its products.	0.7075	0.0566	12.4931	0.7494
V19: There is no complains from our customers about the quality of our products.	0.4761	0.0737	6.4573	0.4307
V20: The firm has an effective equipment and machine maintenance program so that all machines and equipment are always in good conditions.	0.7025	0.0566	12.4109	0.7455
Financial Performance (FP) (α = 0.8960)				
V21: Return on investment	0.7986	0.0474	16.8591	0.8693
V22: Profits as a percentage of sales	0.9094	0.0487	18.6789	0.9259
V23: The firm's net income before taxes	0.8863	0.0517	17.1504	0.8788
V24: The present value of the firm	0.5776	0.0567	10.1916	0.6055
Note that V5 and V18 were eliminated during measurement purification				

Table 1 provides unstandardized coefficients, standard errors, and *t*-values for each individual item. These numbers provide information about the local fit, that is, how well each individual item related to its respective factor. Each of the coefficients is large and significant at the $p<0.01$ level. Table 2 also provides coefficient alphas for each factor after the measure purification process. The coefficient alphas ranged from 0.6658 to 0.8960. De Vellis [5] noted that alpha levels below 0.6 are unacceptable.

Goodness of fit is determined by comparing the structural model (full maintained model) to alternative models. One tests alternative models by sequentially deleting or adding paths [6]. The measures of goodness-of-fit are shown in Table 2. After deleting 2 paths representing Hypothesis 7 and Hypothesis 2, the results of the test of the overall fit of the model in Figure 2 are provided below. The chi-square statistic is significant. Other goodness-of-fit indices indicate an acceptable fit of the structural model to the data, especially given the exploratory nature of the study. Bentler's Comparative Fit indices (CFI) and Bentler and Bonett's Non-normed Index (NNFI) are above the desired 0.90 level [7,8] and thus indicate good fit. The ratio of chi-square to degrees of freedom is 2.138, which is below the recommended 3.0 threshold [8,9], which indicates a good fit. The adjusted goodness of fit index is above the desired 0.80 threshold [9-11], although below the conservative 0.90 threshold recommended by Bagozzi and Yi [12].

Table 2: Measures of goodness of fit for the structural model

Model	χ2	*df*	χ2 /*df* ratio*	CFI**	NNFI***
Null model	2355.1991	210	-	-	-
Uncorrelated factors	1360.2646	209	-	0.4997	0.4470
Full maintained model	431.8911	201	2.15	0.8997	0.8847
H7 path deleted	431.9934	202	2.14	0.9000	0.8857
H2 path deleted	433.5983	203	2.14	0.9004	0.8858

* χ2 /*df* ratio < 3 (Hartwick and Barki [9]; Hair *et al*. [8])
** CFI > 0.9 indicates a good fit of the data to the model (Bentler and Bonett [13])
***NNFI > 0.8 indicates an acceptable fit (Wheaton *et al*. [10]; Segars and Grover [11]; Chau [12])

These results are indicative of an acceptance fit of the model to the data, especially given that many of the measures used in this study were either developed for the study, or adapted from other scales. The R^2 values for the three structural equations, which represent the variance explained by the endogenous factors of FP, PIM, and BR, are 0.23, 0.52 and 0.4 respectively. For example, 0.4 is the variance in buyer-supplier relationship (BR) explained by strategic purchasing (SP) and production and inventory management (PIM). The results of the hypothesis tests, represented by individual paths between factors within the model, are included in Table 3, shown in Figure 2 and addressed in the following paragraphs.

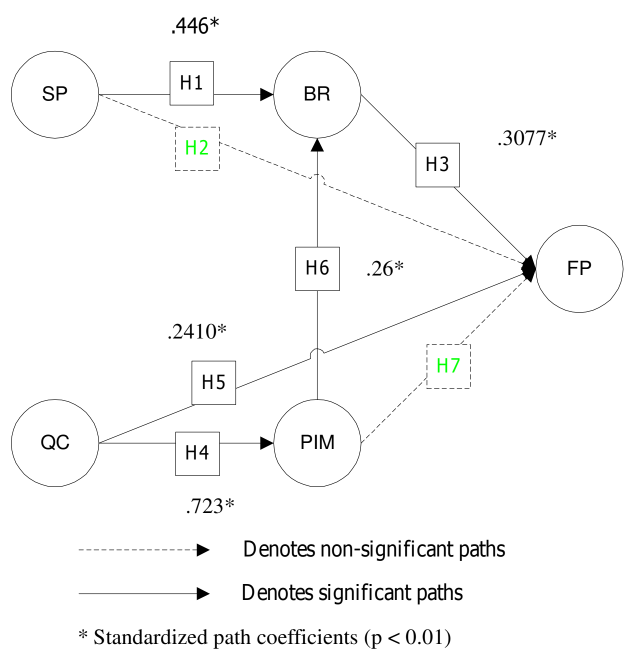

Figure 2: Structural Model

Table 3: Test results of the structural model

Hypothesis	Path from	To	Regression weight	Standard error	*t*-value
1	SP	BR	0.4180	0.0907	4.6074*
3	BR	FP	0.4031	0.1176	2.5933*
4	QC	PIM	0.7424	0.1012	7.3338*
5	QC	FP	0.3185	0.1162	2.7417*
6	PIM	BR	0.2554	0.0985	2.5933*

* Significant at $p < 0.01$

H1, representing the path from the strategic purchasing factor (SP) to the buyer-supplier relationship factor (BR), was positive and significant (p<0.01). This result supports the hypothesis that as strategic purchasing increases, it is expected that the firm will increase communication, cooperation, and coordination with key suppliers. Firms that do long-term planning and consider purchasing to be strategic are also likely to build long-term cooperative relationships with their key suppliers. This trend has also shown in Thai industries where the purchasing firm seeks to identify potential suppliers and determine their qualifications as a supplier of the firm either through formal or informal supplier evaluation systems.

H2, testing the effect of the strategic purchasing (SP) on the factor of the firm's financial performance (FP), was not significant and recommended to be dropped during the Walt test, which analyzed the fitness of the structural model to the data, there was no significant increase in the model chi-square. This may reflect the fact that SP does not appear to have a direct impact on FP. However, it appears to have an indirect impact on the firm's financial performance via the factor of BR (as path H1 is positive and significant). This suggests that improving strategic purchasing without building cooperative buyer-supplier relationship may not improve the firm's financial performance.

H3, testing the effect of the buyer-supplier relationships (BR) on the factor of the firm's financial performance (FP), was significant and positive (p<0.01). This result lends support to the notion that when buyer-supplier relationships become more cooperative with key suppliers, these firms will also have higher levels of financial performance with respect to return on investment, profits as a percent of sales, net income and present value of the firm.

H4, representing the path from the quality expectation (QC) to the production and inventory management factor (PIM), was positive and significant (p<0.01). Defective units from a production line need to be returned for rework or rejected as scrap. Appropriate control mechanisms are then required to integrate the returned defective units into the producers' production planning. From a production management point of view, these activities are no different from other production processes.

H5, representing the path from the quality expectation (QC) to the firm's financial performance factor (FP), was significant and positive (p<0.01). This result lends support to the notion that quality practice can generate a sustainable competitive advantage. In the traditional paradigm, firms are concerned with company-centered issues such as price, product quality, and delivery time. In the new supply chain quality paradigm, supplier-customer relationships and co-making quality products have evolved as the major issues.

H6, testing the effect of the production and inventory management (PIM) on the factor of the firm's financial performance (FP), was not significant and should be discarded as during the Walt test, which analyzed the fitness of the structural model to the data, there was no significant increase in the model chi-square. This result is surprising in that it suggests that the production and inventory management has little direct impact on the firm's financial performance. Moreover, this result contrasts with the result of H5, which suggests that the QC has a direct effect on FP. The results of the analysis indicate that the linkage between specific internal capability factors and overall financial performance is not always clear. As this study reflects an extension of the manufacturing enterprise to encompass the entire supply chain as the competitive unit, other factors may have a stronger effect on it. As a result, improving this individual performance does not necessarily imply immediate improvement in organizational financial performance, since there are many other intervening factors, which may have an impact on organizational results.

H7, testing the effect of the production and inventory management (PIM) on the factor of buyer-supplier relationships (BR), was significant and positive ($p<0.01$). It reflects an extension of the manufacturing enterprise to encompass the entire supply chain as the competitive unit. High levels of process integration across firms are characterized by greater coordination of the firm's logistics activities with those of its suppliers. This blurs organizational distinctions between the production and inventory management activities of the firm and those of its suppliers. Thus, a single construct termed "logistics integration" is used to describe the study of the steps taken by firms towards process integration along the supply chain.

5.0 Conclusions

The study provides empirical evidence for ever-growing strategic nature of supply chain management functions in Thailand. It reemphasizes the critical role of strategic purchasing functions in building strategic and collaborative buyer-supplier relationships. It also shows that internal operational aspects including production and inventory management can impact on strategic alliance formation. This strategic alliance formation, in turn, exerts a significant impact on the financial performance of the firm. The significant positive link of strategic alliance to performance constructs reaffirms the importance of collaboration in a supply chain context.

Cooperation between buyers and suppliers is a key factor for successful integration. To successfully manage a buyer-supplier relationship, a firm may need to develop a strategic purchasing function. In addition, to achieve business success, it is imperative for firms to excel in their internal operations, on which the efficient and effective flows of goods and information in the supply chain depend. The internal manufacturing operations function is related to the goals of a business, the types of resources it utilizes, and the tasks of management. It organizes, plans, controls, and improves the use of process, inventory, work force, and facilities and equipment in order to appropriately determine the ranking of the competitive priorities – price, quality, dependability, flexibility, and time – thereby providing short-term profit, long-term profit, and improved market share.

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EXPLORING THE ADOPTION AND IMPLEMENTATION OF INTEGRATED AND DISCRETE IT SYSTEMS -A FRAMEWORK FOR ANALYSIS

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Abstract

This paper critically reviews the literature on the determinants of IT adoption, specifically differentiating between discrete IT and integrated IT systems. Integrated IT is exemplified by ERP; discrete IT is represented by the wide variety of discrete IT/IS examined in the adoption and implementation literature, including advanced manufacturing technology (AMT), CAD/CAM and expert systems. The central argument of the paper is that integrated IT systems differ markedly from discrete systems, and that differences exist in the organisational factors that determine the successful implementation of each. A taxonomy of proposed differences between the determinants of integrated and discrete IT implementation is presented.

Keywords: Information systems, Integration, Adoption, Implementation.

1.0 Introduction

Advances in business software are supporting greater integration within organisations of previously discrete functional IS. Since the mid-1990s, the interfacing of functions that were previously programmed and tested separately has led to the growth of systems such as enterprise resource planning (ERP), customer relationship management (CRM), supply chain management (SCM) and digital manufacturing (DM). Prior to these developments, research on technology adoption and implementation focused primarily on single, discrete new technologies, producing perhaps the most mature stream in IS research [1]. In general, this research has led to broad consensus on the factors important in the implementation of discrete IT/IS. However, with the growth of integrated IS, research on the factors influencing implementation and adoption [2]-[3] has been less consistent than that for discrete IT/IS [4].

Research on the adoption and implementation of integrated IS/IT, and on ERP in particular, has tended to study its implementation in a similar manner to that of discrete IT systems [5]-[6]. This approach however ignores the integrative dimension of such a system, which defines and elevates it above a legacy system servicing a single department [7]. It is arguable that ERP in fact belongs to a different category of IT than the standard legacy system (that of 'integrated IT'), and that a distinction should be drawn between ERP implementation research and IT/IS implementation research [8].

In this paper we review the literature on the determinants of IT adoption and implementation, specifically differentiating between discrete and integrated IT systems. Discrete IT is represented by a range of IT/IS in the literature including advanced manufacturing technology (AMT), CAD/CAM and expert systems, while integrated IT/IS is exemplified by ERP. The central argument of the paper is that integrated IT systems differ markedly from discrete systems, as reflected in the organisational factors determining the successful implementation of each. The remainder of this paper is structured as follows. In Section 2, we highlight the range of factors identified in the research that influence the adoption of discrete and integrated IT systems. In Section 3 these factors are discussed, considering in particular, if these factors differ for discrete as compared to integrated IT systems. Finally, a taxonomy of differences is presented in the concluding section with some consideration of the organisational implications of this.

2.0 Determinants of IT/IS Implementation & ERP Implementation

A review of the literature reveals that the determinants of adoption and implementation of IT/IS and ERP fall into three categories (Fig. 1). First, decisions made prior to adoption lay the foundations for the project and, as such, strongly influence its ultimate success or failure. Second, the inherent characteristics of the organisation determine its receptivity toward change [9], and therefore its capacity for successful uptake of IT. Finally, the appropriateness of the managerial approach to the project is believed to strongly influence successful implementation.

In this process (Fig. 1), no distinction is made between discrete and integrated IT. Rather, factors are classified according to the nature of their influence, which closely parallels with the stage of the process during which they are most important. Initial selection is determined by technology characteristics and by the constraints of the project. After the adoption decision, the organisation's characteristics become critical in determining the initial interface between technology and organisation. In the implementation phase, success becomes a function of how effectively the project is organised and managed. In Section 3 we consider how specific determinants differ for discrete and integrated – as typified by ERP – adoption and implementation.

3.0 Comparison of Determinants of IT/IS Implementation & ERP Implementation

3.1 Pre-Adoption: Preliminary Decisions

After deciding to introduce IT, managers select a technology with the specific features addressing the perceived need. Rogers [10] identifies five technology constructs as determinants of 'innovation diffusion': relative advantage, compatibility, complexity, trialability and observability (Table I). With the exception of 'complexity', the greater the extent to which an IT possesses these traits, the smoother will be its adoption and implementation. Goodhue and Thompson's [11] concept of 'task-technology-fit' is analogous to Rogers' 'compatibility', advocating selection of IT which is equal or suited to the task for which it is being adopted. Rogers' construct, however, also incorporates "compatibility with what people feel or think" [12, p. 33]. Davis *et al.*'s [13] perceived usefulness and perceived ease of use concepts, meanwhile, correspond to Rogers' 'relative advantage' and 'complexity' respectively. An IT's position along Rogers' constructs has implications for adoption and implementation success; as such, managers should evaluate the complexity, trialability, etc. of the various options before selecting an IT solution.

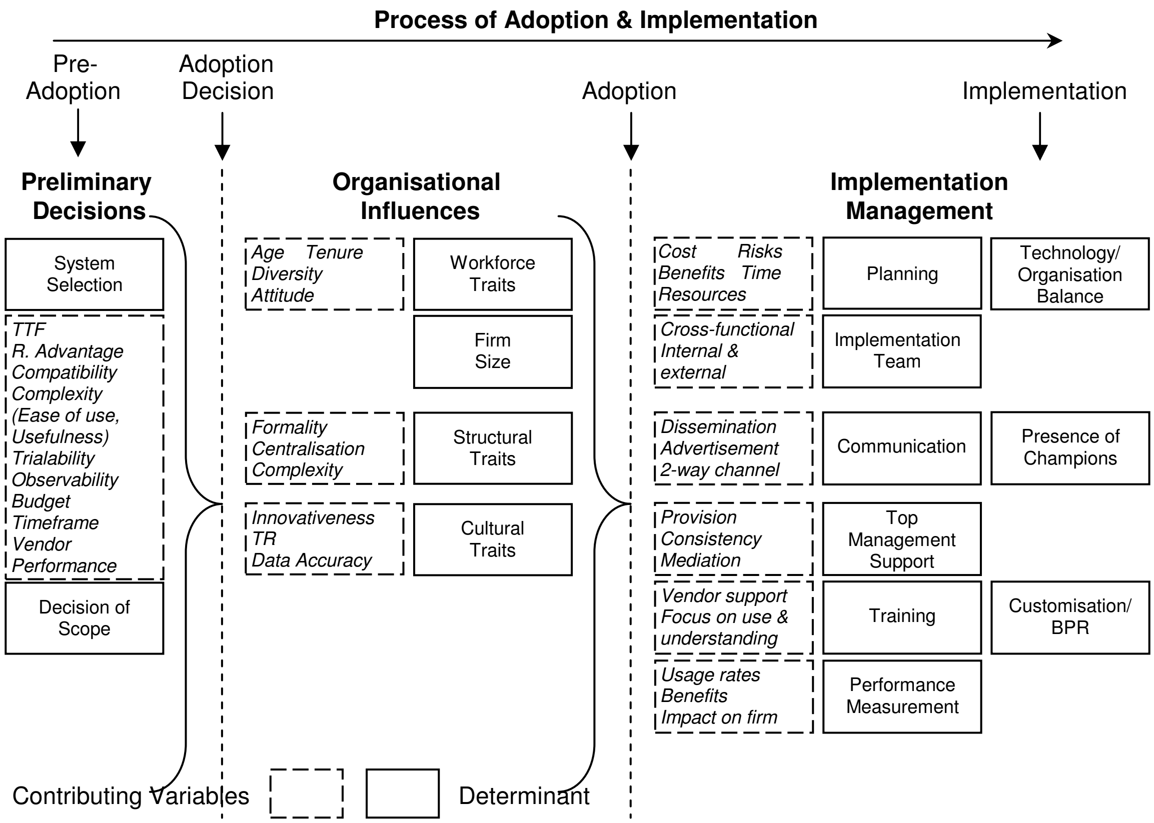

Fig. 1. Consolidated determinants of IT/IS & ERP adoption & implementation by category

Table I Technology Characteristics and IT Selection Decisions

Technology Characteristic	Issue for Consideration in Selecting IT
Relative Advantage (Perceived Usefulness)	*Is it superior to the preceding technology?*
Compatibility (Task-Technology Fit)	*Does it fit with tasks for which it is needed & staff attitudes?*
Complexity (Perceived Ease of Use)	*How easy/difficult is it to adopt and use?*
Trialability	*Is it possible to experiment & try it out?*
Observability	*Is the technology visible & are its benefits visible?*

Source: [10]-[11]-[13]

With regards ERP, Somers and Nelson [4, p. 260] suggest that applications should be selected based on projected "budgets, timeframes, goals and deliverables". In addition, it is also important to consider potential vendors [14], and to take into account the number and experience of previous adopters [15] [4]. As is also found with discrete IT, compatibility is important in terms of acquiring high-performance modules for the critical areas of the firm [16], and matching the software to the business' needs [17]. Yet, due to the larger scale of ERP systems and the IT vendor's role in implementation success, selecting a suitable integrated system is more complex than in cases of discrete IT. As well as selecting a system, in ERP projects the scope of implementation must be determined, often in terms of the number of modules needed [3]. In contrast, the scope of discrete IT implementation is more fixed, typically comprising one application within one function. ERP system selection therefore requires greater consideration, particularly in terms of the scope of implementation and the potential support of vendors.

3.2 Post Adoption Decision/Pre-Adoption: Organisational Influences

3.2.1 Workforce Characteristics

Research suggests that a workforce with a high proportion of younger employees [18] from diverse backgrounds [19], who have worked in the firm for longer [20] is most suited to IT adoption and implementation. The workforce 'complexity' of the organisation (i.e. the extent to which the workforce is specialised, highly educated and professional) is also positively linked to IT implementation success [21]. Successful IT adoption and implementation also depends on the support of a "critical mass of stakeholders" [22, p. 98], so monitoring and understanding workforce attitudes is important. This helps ensure that the IT fits with stakeholder needs and that the necessary 'energy' for implementation is present [23]. These workforce characteristics, and fostering a positive attitude towards implementation, are important for both discrete IT *and* ERP adoption and implementation.

3.2.2 Firm Size

Larger firms are consistently found to be more capable of adopting and implementing new technology [24]-[25]. These firms perceive less risk in the decision to adopt new technology and as such, tend to be more willing, and better equipped, to adopt [24]. At the same time, Robinson [26] suggests that in smaller organisations with greater physical and cognitive proximity of functional areas, more effective inter-function coordination and communication can be achieved without integrating their systems. The pressure to adopt an ERP system therefore increases as firm size increases. The feasibility of both discrete and integrated IT adoption and implementation therefore increases with firm size.

3.2.3 Structural Characteristics

In general, structural complexity (e.g. the number of different divisions within the organisation) is positively correlated with IT adoption and implementation success [27]. An organic, informal organisational structure is found to facilitate IT/IS adoption [28]-[29]. In other words, less centralised authority and decision-making within an organisation is conducive to workers adopting the unfamiliar [30]. However, it is suggested that a centralised organisational structure is more conducive in the implementation stage, when tight control leads to more optimal and faster implementation of the IT [31]-[32].

Essentially, formalisation and centralisation determine how suited an organisation's structure is to adopting IT. Optimum ERP implementation, however, involves *changing* the organisation to fit with the new system [4]-[33], so pre-existing organisational characteristics should have a lower effect on implementation success. Therefore, organisational structure would be expected to be less important in ERP adoption and implementation, where the choice of IT ought to dictate the company's level of centralisation and formalisation, not vice versa.

3.2.4 Cultural Characteristics

An organisation's culture is the "commonly held beliefs, attitudes and values which...provide...rules for behaviour" [34, p. 70]. Looking at certain imbedded cultural features of an organisation can help inform IT adoption decisions. Morrison's [35] concept of 'organization dispositional innovativeness' (ODI), for example, gauges how inherently innovative and receptive to new technology the firm is. 'Personal innovativeness' (PI) [9] and the Technology Readiness Index (TRI) [36] are similar constructs, but they cumulatively measure receptivity to technological change at the individual, as opposed to organisational, level. Higher levels of these constructs mean less inherent resistance to new IT, and a smoother implementation [23].

While culture influences IT/IS adoption and implementation in general [37], it is regarded as "the unique factor affecting ERP systems implementation success" [17, p. 57]. An underlying predisposition to integration, high TRI [36], positive attitudes to change, and an existing capability for computing are found to reduce the upheaval of integrated IT implementation [3]. ERP users are required to input data in a timely and precise fashion [17]: a culture of data accuracy is therefore more important for ERP implementation success than for discrete IT [26].

3.3 Post-Adoption: Management of Implementation

3.3.1 Organisation/Technology Balance

IT implementation is determined not only by the benefits of the IT, but also by how it links to the specific objectives of the organisation, and by how effectively the organisation is reconfigured in order to accommodate the IT [23]. As such, understanding and appropriately modifying the organisational context in which the technology is implemented is of great importance [2]; this may mean training and reskilling of workers, or new managerial approaches [23]. Benjamin and Levinson [23] advocate an approach to planning IT implementation in which the organisation's current state, desired final state and a number of transitional states are set out. The target final state is one of equilibrium, so the change process can be thought of as a quest to rebalance the *organisation*, and its *processes*, in line with the *new IT*. IT/IS implementation success therefore requires that changes made in one of these three areas be offset by change to one or both of the other areas [23].

Successful management of ERP implementation also depends on maintaining equilibrium between technical and organisational issues [38]-[39], with neither dominating implementation decisions. Success depends on optimising the fit between the ERP *application* and the *organisation*; this requires effective monitoring and management on both fronts. The greater scope of an ERP project and the obligation to change the organisation in line with the new system [4] make it even more important and more difficult to achieve this balance.

3.3.2 Planning

Planning is deemed crucial in discrete IT/IS implementation [40] with research tending to focus on pre-implementation planning, i.e. measures to ensure that adoption is justified and that the best technology is selected. For example, assessing the organisation's current level of IT sophistication [41]-[42] and searching for appropriate technologies [37] is advised, but planning how the technology is then to be implemented is not a prominent consideration. An explanation for this may be that, if an appropriate IT is selected and a timeframe set, the actual adoption and implementation will, to some extent, 'take care of itself'.

A thorough implementation plan is also considered critical to ERP success, preferably detailing the "proposed strategic and tangible benefits…costs, risks and timeline" of the project [3, p. 291]. The resources required for implementation should be carefully calculated, and the anticipated benefits set out for different areas of the organisation [2]-[16]. The needs and best interests of the organisation should be kept at the heart of the project plan [16], which should, in turn, be kept at the heart of the ERP implementation [2]. Studies have shown greater rates of ERP success in firms who formulate and adhere to an implementation plan and adhere to it [16], and poor performance in cases of inadequately planned ERP implementation [43]. In contrast with the IT/IS implementation literature, ERP findings emphasise the need for detailed planning of *post-adoption*, implementation activities, as these are much more complex and unpredictable [33]. Pre-adoption planning is necessary for both discrete IT and ERP implementation, but detailed planning of the actual implementation process is much more important in cases of integrated IT.

3.3.3 Implementation Team

Cross-functional implementation teams are found to facilitate discrete IT/IS implementations [40]-[44]. These almost invariably involve staff from diverse disciplines, and allowing these staff to co-operate and collaborate means all interests are represented and fully discussed [23]-[28], leading to optimal implementation.

The use of dedicated cross-functional teams is also consistently linked to ERP implementation success [23]-[45]-[46]. ERP is, by nature, a cross-functional concept, so it stands to reason that its implementation should be coordinated among the members of different functions. Implementation team membership ought to reflect both business and technical interests within the firm, in order to achieve balance between organisational factors and issues arising from the IT itself [2]. All divisions involved in or affected by the implementation should be represented [46], and managers placed in teams alongside lower-level personnel [45]. Also, effective implementations involve careful use of external consultants [4] alongside the firm's own best staff [47]. This juxtaposes expertise on ERP systems and their implementation with expertise on the organisation and its processes [17], optimising the interface between the ERP system and the organisation and leading to successful implementation [46]. As with discrete IT implementation, concurrent input from all stakeholders will ensure all interests are represented, and is shown to shorten the ERP implementation period [16]. However, while cross-functional teams are *desirable* for standalone IT implementation, they are *indispensable* for successful ERP implementation.

3.3.4 Customisation / Business Process Reengineering (BPR)

The best discrete IT/IS system for an organisation can generally be chosen from among a wide range of standard alternatives, which are essentially sold customised. As such, there is good fit between the technology and the organisation from the outset, and customisation and BPR are therefore of little concern.

ERP, on the other hand, is a "packaged solution" [3, p. 286]. Optimum performance occurs when it is applied exactly as it was developed and programmed, and the organisation's processes are moulded to fit with it, while altering the software will preclude the future adoption of newer versions and updates, eroding value for money and risking obsolescence [3]. As such, keeping customisation of the ERP software to a minimum should be a priority during introduction and implementation [4]. Successful adoption of new IT requires balance between designing the IT to fit with the organisation and restructuring the organisation to accommodate the IT [48]. The implication of there being no changes to the ERP software is that all the changes necessary to align the firm and the new system must be made to the organisation's processes [17]. Optimal ERP implementation is therefore characterised by low levels of software customisation and high levels of BPR [4]; failure is linked to underestimation of the need for organisational change [17]. The greater range of tailored discrete IT solutions, meanwhile, makes alterations to the technology or the organisation less of a necessity.

3.3.5 Communication

Effective communication is shown to support discrete IT/IS implementation [37]. Pre-implementation, strong communication among those installing the IT will optimise its deployment; in the implementation phase, organisation-wide communications become more important, as the effective dissemination of information about the technology can help train, persuade and reassure staff members [49].

Communication is also emphasised as a determinant of ERP implementation [3]. Initially, the implementation must be justified to stakeholders [16]. There should be clear communication from management of the functionality and benefits of ERP [2], of what the workforce should expect from the system [4], and of what is, in turn, expected of the workforce [3]. Informing workers helps to minimise resistance to the new application [4] and build enthusiasm. As well as communicating general information about the ERP system, it is important to specifically 'advertise' the progress of implementation and associated improvements within the firm [33]. Provision for two-way communication should be made [3]-[23], ideally extending to user involvement in key decisions about ERP implementation [16]-[33]. This creates the impression among users that they are in control of the implementation [17], and maximises fit between system functionality and user needs. Ignoring users' "needs and expectations" is linked to IT implementation failure [2, p. 509]. All stakeholders must be consulted; otherwise, the project will be biased towards the interests and agendas of certain groups, and long-term implementation success will be jeopardised [2].

These ERP communication factors are generalisable to cases of discrete IT/IS implementation [37]-[49]. However, there is likely to be no precedent for, and therefore little knowledge of, ERP within the organisation, so a greater volume of information may need to be conveyed. Also, the scope of communication will need to be broader than for discrete IT/IS implementation, as potentially every division of the organisation will be involved in or affected by the implementation. Communicating justification, features, benefits and progress is important for success in any IT implementation project, as is provision for user feedback, but more intense communication with a greater proportion of the workforce is necessary during ERP implementation.

3.3.6 Champions

A champion is a manager "who is intensely interested and involved with the overall objectives and goals of the project" [50, p. 15]. Their role is to promote the IT to their superiors and subordinates [51], and to provide, or encourage the provision of, necessary funding and resources for the implementation project [23]. Champions may be appointed or adopt the role voluntarily, but it is argued that the *appointment* of a champion is symptomatic of a lack of spontaneous support, and of problems with the implementation as a whole [23].

The visible support of champions is found to facilitate implementation across a range of IT [52], including ERP systems: Sumner [46], for example, advocates the appointment of an individual to promote the integration initiative to the whole organisation. The role of champions is particularly important in earlier stages of ERP implementation [4]: the positive messages conveyed will then disseminate and take hold due to the reputability of the source. The presence of a champion is strongly correlated with implementation success for both discrete IT and ERP systems.

3.3.7 Top Management Support

The support of top management for any newly adopted IT is consistently cited as crucial to its successful implementation [53]-[54]. It is ultimately managers who decide whether to adopt a technology or not [42], so their backing is instrumental from the outset. However, managerial support should not be limited to initial enthusiasm: it is important that managers continue to show their commitment, and that they periodically 'energise' the implementation [53]. Their advocacy of the IT can serve as an example to the rest of the organisation, radiating through the workforce and boosting the chances of successful implementation [21].

Top management support has also been correlated with successful ERP implementation; Somers and Nelson [4], in fact, rate it as the greatest predictor of ERP success. Senior managers should emphasise the significance of the project, while demonstrating their own commitment and involvement. This will involve allocating sufficient resources and time to the implementation effort [33], and generally providing strong leadership [16]. Several factors make management support and all-round effective management particularly important for ERP implementation. Implementing ERP requires cooperation and coordination among members of many divisions: strong management will help settle disputes and give cohesive direction to all those involved [17]. Also, major organisational change is often a part of ERP implementation, and effective management is crucial in such times of change [17]. Top management support is critical for any IT implementation, but attentive and effective management is more important in the context of the disruption and broad scope of an ERP project.

3.3.8 Training

Training in new IT is among the most direct and effective ways to encourage adoption [37]. In particular, expert training and support from onsite staff of the IT vendor is linked to successful implementation [52]. IT/IS training supports implementation by optimising use of the new system, but also by increasing understanding thereof [2].

ERP system training is similarly important, but must focus even more on increasing understanding [17]. It must encourage proper use of the software, but this first requires that users develop personal understanding of, and enthusiasm for, the integrative dimension of ERP [3]. As such, effectively training integrated IT users is even more challenging, and arguably more important, than discrete IT training. Negative outcomes are recorded in cases where efforts are not made to promote optimal use and clear understanding of new ERP systems [17]. Somers and Nelson [4] recommend initiating training and education as early as possible in ERP implementation (even prior to adoption), and continuing it throughout the process. However, while ongoing training is important for *any* IT/IS implementation, it is the need to focus on reinforcing understanding which sets ERP training apart from the more practical focus for discrete IT.

3.3.9 Performance Measurement

As discussed in Section 3.3.5, any discrete IT/IS implementation should be preceded by a meticulous cost/benefit analysis, in order to justify and get backing for the project. This is, regrettably, as far as the evaluative efforts of many IT adopters go [2]. However, by then comparing predicted versus actual post-implementation costs and benefits, managers can monitor how effectively the IT is operating [16], how successful it is [17] and whether it should be persevered with. What is more, failure to adequately specify and evaluate the anticipated benefits from an IT is blamed for heavy financial losses in IT/IS implementation [55].

Clear procedures for performance measurement are also linked to successful ERP implementation [56]. Usage rates provide the most basic and reliable measure of the system's success: whether it is used by its intended users [2]. It is equally important to gauge and coordinate "how the organization should operate behind the implementation effort" [3, p. 291]. Performance should therefore also be gauged in terms of the management of the project and of its contribution to firm performance [3]. It is crucial to set out desired benefits, performance levels and usage rates for any discrete or integrated IT prior to adoption, and to subsequently measure how the implementation project itself is going, and how the IT is affecting other areas of the firm.

4.0 Conclusion

Somers and Nelson [4, p. 270] conclude that "some of the players and activities that are critical during any IT implementation play an equally crucial role in ERP implementation". This review of the IT/IS and ERP implementation literatures supports this position. However, the key point to focus on is not the *parallels* between the determinants of discrete and integrated IT adoption and implementation, but the significant *differences* that appear to exist in the influence of certain factors on one or the other. These differences fall into one of two categories.

Firstly, there are those factors which influence all IT implementations, but which are of *greater* importance during integrated IT adoption and implementation. For example, organisational culture determines an organisation's predisposition to change, and is therefore determinative of any IT adoption and implementation. However, because the level of change required during ERP implementation is much greater, organisational culture is more influential on the process. Similarly, communication is critical to the success of any IT implementation, but more so in cases of ERP, when more information must be conveyed to more people. System selection, implementation planning and top management support also fall into this category.

Secondly, certain differences arise due to fundamental disparities between discrete IT and ERP. The fact that the scope of an ERP implementation (i.e. the number of modules to be adopted) is variable, adds extra decision-making responsibility, for example. Also, ERP systems are inherently cross-functional, so a cross-functional implementation team is a necessity, where it is merely desirable in cases of discrete IT implementation. The uncustomised nature of ERP software gives rise to further differences: changes to either the organisation or the software are inevitable; the influence of existing organisational structure is less due to the obligation to change the organisation; and maintaining balance between organisational and technical considerations is more difficult than in cases of discrete IT/IS implementation.

The implication here is that ERP adoption and implementation is at least partly subject to different considerations than discrete IT adoption and implementation, and that managers therefore need to approach such projects with a different configuration of factors in mind. It is arguable that the typically high ERP failure rates during the last decade [4] have, to some extent, been due to managers' persistence in managing ERP implementations as they would manage any *discrete IT* implementation, where they ought to have been managed as *integrated IT*.

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CHARACTERISATION OF SME MIGRATION TOWARD ADVANCED TECHNOLOGIES

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Abstract

British SMEs are seen to be migrating toward higher value markets, by utilising advanced technologies. In the face of competition from low labour cost economies, manufacturing best-practices are being promoted which reduce cost and/or increase profit. However, it is not clearly understood by SMEs how increased product value can be offered without compromising control of material, labour and investment costs.

One possible solution is the introduction of Advanced Manufacturing Technologies (AMT) in order to improve product quality, reduce lead times, and offer additional functionality or customisability. Cost must be controlled through careful selection, detailed preparation and planning, and swift implementation and development stages. As part of a 3 year investigation, 300 companies were surveyed in order to determine their attitude toward AMT. Subsequently the companies were categorised into three levels of technological capability, and an ideal AMT implementation model created. The companies were revisited with a view to identify what changes had been adopted toward the end of the project, and how they had influenced bottom line performance.

Whether it was due to implementation of the model, or other sources, it was seen that companies were migrating toward the higher categories of technology utilisation. There were also significant numbers of companies falling between the previously described categories; either side of the level two category, due to discrepancy between attitude and associated achievement, hence the categorisation itself needed to be re-developed. By considering the characteristics of these transitional companies, a revised strategy for AMT implementation should be developed for the future to tackle the weaknesses being revealed.

Keywords: SMEs, Advanced Manufacturing Technology, Management, Survey.

1.0 Introduction

SMEs in manufacturing must recognize the threat of half-heated approach to change, and particularly the potential for failure incurred by ineffective technology development. This will not only result in financial loss, but more importantly a loss of ground in the race to lead the market. As competition from low labour cost economies continues, EC manufacturing companies must continue to move toward advanced technologies to remain competitive (Ettlie [1], Beaumont et al [12]) by offering higher levels of customisation and technical service while maintaining Quality Cost and Delivery (QCD) performance against the global manufacturing market.

At a base level, the requirement to keep abreast of technological developments in order to improve productivity, quality, range of products and other performance measures is now paramount (Quarashi *et al* [2], Jhang et al [13]) Despite the clear evidence for a need to acquire technical skills and implement new and effective technology into SMEs to ensure survival and sustainable growth, many companies are reluctant to move towards major investment to enable competitive advantage through technological capability. Furthermore, many companies are especially reluctant to invest in technology pertaining to Automated, Intelligent and Computer Aided Engineering systems. The reasons for this are many. Primarily, companies are initially deterred by the extensive capital investment required to develop such technologies and secondly, the capabilities of the technology and the advantages it brings to the average SME are not fully appreciated by the companies concerned. This, along with the fact that many SMEs do not have the technical and manufacturing infrastructure to support AMT severely limits their success in various technology transfer initiatives (Thomas [3]).

2.0 Methodology

300 manufacturing based SMEs were targeted for assessment over a three-year period. A questionnaire was devised that identified accurately the current technological platform of the SMEs as well as defining their aspirations towards developing their operations, company infrastructure, financial strength, skills base etc. It was decided that each SME would be visited by a researcher rather than rely purely upon questionnaire feedback since this allowed for a more realistic analysis of the company's operations. The companies were selected from a range of industrial sectors and all were registered as Small to Medium Manufacturing Enterprises.

2.1 SME Categorisation

The companies were profiled at an initial survey visit, considering the above aspects, and the detailed results were published by Thomas et al [4]. This described a three level categorisation of the surveyed SMEs, which is outlined below.

Category 1. Companies

These were companies that were happy with their current customer base and had no significant aspirations to develop their companies through the use of AMT. These companies tended to be sceptical about the benefits of AMT and the benefits that it could bring by way of increased customer base, improved technology quality, reduced product cost and improved delivery performance etc. It can be argued that the development and implementation of AMT into such companies may not simply be relevant to the markets they operate in. (22% of companies were considered to fall into this Category)

Category.2. Companies
These were companies who constantly try to improve and develop their company operations. These companies in general could see the long term benefits of using AMT in developing their product or process but, did not have the in company skills base, financial resources and knowledge on how to introduce AMT into their companies. (65% of companies were considered to fall into this Category)

Category.3. Companies

These were companies who had considerable experience of introducing AMT into their company and as such had a financial model which returned a large amount of their yearly profits into the purchasing of technology to continually develop their manufacturing operations. Without exception it was these companies that achieved a greater market share and mostly had contracts with the larger manufacturing industries producing products in high value markets. (13% of companies were considered to fall into this Category)

2.2 Technology Implementation Model

Subsequently, a model for AMT implementation was proposed to the companies as a composite model of aspects seen in best practice throughout the lifecycle of a technology implementation project, these were seen to be largely common to improving, and especially cat.3, companies. The model is described in full by Thomas et al [4] but essentially comprises the following 5 stages:

Stage 1 - Company Analysis and Planning Stage
Stage 2 - Technology Planning Stage
Stage 3 - Technology Selection Stage
Stage 4 - Technology Process Engineering Stage
Stage 5 - Technology Development Stage

- Technology and Resource Capacity Building
- Knowledge Development and Management
- Technology Performance Enhancement
- Technology Improvement

Once this model was proposed, some companies naturally selected elements of the model as particularly pertinent to their business and adopted those practices, while others chose to adopt the carefully structured hierarchy to use the model as a chronological 'road-map' for technology development, and as expected a number of companies chose to ignore the model completely. This begs the question; could this mixed response be monitored to try and evaluate the overall effectiveness of the model?

The initial answer was that the spread of application was seen to be too varied, and the nature of the mixed industrial sectors proved to be too broad, such that there was no like-for-like comparison. However, a number of test companies were examined and the results proved favourable for those adopting the model, which correlated directly with the character of the company as profiled by the initial categorisation. Gains were seen in on-cost delivery, on-time delivery and right-first-time delivery of technology development projects. Each of which yielded tangible improvements to the company in QCD performance, hence bottom line profitability.

However this was a sample, hence a fairly superficial view and continuity of project management is not assured, regardless of success experienced historically. In order to review what progress was being made by the SMEs surveyed, a second Phase review survey was undertaken by means of a second round of visits. In the interests of research integrity, the survey reports were similar in format so that the categorisation of the SMEs could be compared directly with the initial results.

3.0 Results

The results of the second phase survey are shown in the summary table, table I, and indicate that there was some variation against initial findings; cat.1 and cat.3 companies reduced, as a percentage of the total, while cat.2 companies increased, as a percentage of the total.

It is important to note that the percentages given in the results, see table I, do not demonstrate that the overall number of companies surveyed in the second phase was lower than original. This was different due to two additional conditions, which could be demonstrated as ‘virtual’ categories zero and four: a small number of category 1 companies had ceased trading when the lack of ambition had led to the demise of that company (there were 5 instances), and a similarly small number of companies had been merged/acquired by larger partners when the level of development had made them a prime candidate for acquisition before becoming a threat to the larger corporations (there were 3 instances).

In Addition to the three fundamental categories identified, the review survey highlighted a distinct split in the cat. 2 companies into three factions:

- Category 2.1 Companies; is a mixture of previously cat.1 and cat.2 companies. The cat.1 companies are those which have realised that survival of the business may rely on adoption of new technologies, to prevent competition from low cost economies and high product specification from cat.3 competitors continuing to erode the customer base beyond that which will support the company. The old cat.2 companies are those which have previously performed well on the basis of a strong product or process portfolio, but have failed to maintain an effective succession plan and obsolescence has led to a reduction of company performance. The key for these companies is to recognise this and that action is required to update the business capabilities.

- Category 2.2 companies; are the same in characteristic to those seen before, but less in number, and more significantly consists of the same companies as before, i.e. many companies judged to be underachieving in terms of failing to maximise the effect of the development they are implementing are still not learning from mistakes and continue to invest in new short term developments to cover gaps in capability which could already be tackled with fine-tuning of existing technology, as opposed to the 'leapfrog' developments that will promote them to become market leaders.

- Category 2.3 Companies; are completely made up of cat.2 companies who have learned from their mistakes and have made the transition toward forward-planning of AMT development with a view to leading the market and ensuring sustainability of the business. The factors affecting the success of these companies, essentially the 'to-do' list for the cat.1.1 companies are detailed in the following discussion section.

In each of these sub-categories there is a profile of company that fits comfortably with each of the three possible trends in category change; improved attitude to AMT and associated improvement in performance (promotion from cat.1 to cat 2.1 and from cat. 2.2 to cat. 2.3), maintenance of a stable operation (cat. 1, cat. 2.2 and cat. 3) and decline in business profile due to a lack of activity in implementation (cat. 2.2 to cat 2.1). It was seen that there were no clear ‘relegation’ companies moving from cat.3 to cat.2 or cat.2 to cat.1), which indicates that once the practices included in the implementation model are truly incorporated into the operations management of a company then they are robust enough to be self-sustaining, which is the key to continuous improvement, or at least continuous activity.

4.0 Discussion

The survey highlighted that in general, SMEs still did not fully appreciate that the effective implementation of AMT could assist the company in improving business performance and customer satisfaction. Furthermore, of the companies that had implemented AMT, all stated that the implementation phase was the most problematic area of the process. This can have two effects; of deterring companies from further investment, as they do not perceive that value for money has been realized, or alternatively of necessitating additional resource to meet the original expectation, preventing optimization or specialization which would provide greater performance.

These difficulties must be overcome to prevent companies falling into the 2.1 and 2.3 categories. However, it is now seen that to move between the basic three categories, a significant change process has to be undertaken beyond that of using applied tools and techniques. While a difficult implementation can lead to a lack of top-end performance, hence progression to a higher category, it is a symptom of the more cultural issues in the business.

For example, precision engineering companies that have been founded on traditional machine-shop (often family owned) business values are happy to move toward higher technology as followers, minimising risk, but less likely to develop the unique capabilities that would make them a cat.3 company. While a precision engineering company that has been more recently established on the strength of a particular skill set or capability will already appreciate the value of this, and will be both more likely to dedicate resource to developing a faster, more flexible and cost effective technology and also more able to do so through application of a simpler management framework to maintain this advantage

Table I: Summary of Results; SME Categorisation

	Business Type	Technology Strategy	Business Strategy
Cat.1 Low tech' SMEs with static progress (22% of original survey result, 19% of review survey)	Single-process based business using conventional production techniques which are unchanging. Has the single advantage of being flexible in small batch sizes.	Very little interest in technology development and equipment is initially replaced with improved conventional equipment. Lack of management vision.	SMEs in craft activities with slow technical progress, often with highly skilled labour, reducing profits. AMT is viewed as a financial burden, unable to retain specialist staff or customers.
Cat. 2.1 Cat.2 companies falling behind / cat.1 companies catching up (12%)	Sales are being lost to competing economies. These companies have usually relied on particular product or process strength with little succession planning.	Understands that a core capability needs to be quickly re-established but inexperience in technology management prevents meeting the required pace of change.	Lack of clear understanding of what is required to maintain market share. There is often a discrepancy between business strategy and customer requirements which must be addressed.
Cat.2.2 Growing SMEs profiting from basic technology development (65% of original survey result, 47% of review survey)	Higher-performance business which purchases technology without really managing or understanding it. Technology can be low cost but is underutilised due to limited knowledge and lack of workforce development.	Believes technology is essential to development of company but do not tend towards forward planning and an ability to match the technology to company needs. Tend to be taken by 'technology fashion'. Results in technology being under-utilised.	Business with a relatively traditional mode of production. See that technology implementation as the key to success but no real idea of how to implement. Financial risk is seen as an issue but not one that will prevent AMT implementation.
Cat 2.3 Cat. 2 companies who have experienced success and are developing unique AMT. (10%)	Cat. 2 companies that are achieving increased performance, but consistency is required before competitive advantage is sustained. These companies have developed an AMT implementation strategy in light of success, or just increased experience.	Increased performance of the business is capitalised in terms of continued development of product or process capability. Management attitudes are changing toward 'front-end' activities, appreciating the full potential benefits of AMT in terms of sustainability.	Business performance is improving as customer base is extended, achieved by change from a reactionary attitude (to particular customer demands) towards a proactive development plan designed to extend scope of the company.
Cat.3. Innovative SMEs with high tech' profile and culture (13% of original survey result, 12% of review survey)	Business marked by its strong capacity for technological innovation and enterprise, offering new products or innovative processes, creating new markets and customers. On the fringe of losing SME status.	Continuous technological innovation strategy. Forward thinking with MD's who will devote limited resources to implementing technology in house hence maintaining knowledge base.	Independent innovative SMEs focusing on process in order to manufacture the product with high quality. Tend to be able to keep workforce who develop skills that keep company ahead of competitors. Culture of continuous performance.

4.1 Factors Affecting Technology Implementation

The ancillary benefit to interviewing the companies after the initial categorisation, and proposing the subsequent technology implementation model, is that companies can more accurately assess themselves in terms of performance and attitude. This makes the process quicker the second time round, but also provides a deeper insight into the areas for improvement and what factors are preventing promotion to a higher category by increasing the effectiveness of technology development.

As mentioned, the implementation phase was stated to be the most difficult, but almost all companies agreed that this could be overcome in part by a tighter front-end specification and a more detailed return on investment (ROI) calculation which should drill-down into expected QCD improvements to identify potential problem areas. Burcher [5] also proposes that this will prevent missed opportunity / not realising capabilities of technologies, as closer interrogation of suppliers and the existing knowledge base will expose aspects which may not be commonly utilized by the competition, or better still areas of weakness that could be overcome to provide the critical competitive edge. Commercially this is also important to align market requirements with new technology capabilities. Small [6] advocates an approach to identify selective factors in order to create a selective technology portfolio,

In addition, the need for a disciplined approach to technology planning through close adherence to a detailed project plan prevents deviation from achieving the core objective, a view supported by Salimi [7], and also precludes unrealistic expectation about the implementation time-scale and the associated cost of TI. In combination, the specification and planning assesses all possible risks of failure and deals with issues before they happen (Smith and Reinertsen [8]).

To achieve this, on an operational front, there are several common features which have led to sub-optimisation of new technology. Failure to integrate existing conventional and advanced technologies can lead to unbalanced process chains and potentially little improvement in overall lead-time, which is supported by Beatty [9] and Singh et al [14]. Support for the development of a new technology can leave it isolated through inadequate organizational planning, again compromising this integration of this key technology to the core of the business where it should quickly become a unique selling point. This also calls for capacity building of the human resource so that the technology can be fully developed and expanded upon into the future (Castrillón & Cantorna [10]).

Therefore, it is suggested that as a development of the Technology Implementation Model (TIM) proposed, there could be a more flexible Technology Implementation Strategy (TIS) which diverges across a range of approaches depending on existing constraints/parameters/characteristics. The TIS will continue to provide a framework for the tools and techniques at each stage, but in an optimised progression, weighting activity by requirement. Cooper [11] and Hutchison & Das [15] propose that this must also incorporate detailed peer review, including top level management, at suitable decision points to provide commitment to expected results.

5.0 Conclusions

It is important that implementation of AMT is not viewed to be a panacea for all production related manufacturing problems, but it is believed that a companies specific attitude toward AMT reflects its strategy for achieving long term economic sustainability. To this end, it is seen that there are three main categories of SME: low tech' companies with low ambition, growing companies which are undertaking AMT development but not optimizing potential, and also high tech' companies that are high achieving and largely stand-alone.

In addition to this, there are two additional sub-categories of category 2 companies: those failing to keep pace of growth and development, and those who are changing attitude to development of new technology and developing unique skills, but still not realizing company performance increases which will take them to the next category.

Future work identified includes creation of an analysis tool for companies to be able to self-assess, against the characteristics identified through the surveys, in order to place themselves into this improved performance matrix. Subsequently, a decision tree structure can be created to identify a critical route for progression to the next category, incorporating which TI tools and techniques are required to achieve this. Which will ultimate result in fine-tuning and refinement of the TI model proposed by Thomas et al [4].

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ENTERPRISE MODELLING IN SUPPORT OF METHODS BASED ENGINEERING: LEAN IMPLEMENTATION IN AN SME

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Abstract

Popular 'methods-based' approaches to engineering enterprises include: BPR, Continuous Improvement, Kaizen, TQM, JIT, Lean and Agile Manufacturing. Generally the industrial application of such methods-based approaches leads to long lead-times, high costs, and poorly justified engineering projects that do not prepare the organization for future change. These outcomes are to be expected because (1) invariably Manufacturing Enterprises (MEs) constitute very complex and dynamic systems that naturally require complex design and change processes and (2) current methods-based approaches to organizational design and change are not analytically well founded.

Therefore the authors argue that a framework and modelling toolset are required to facilitate ongoing and integrated application of methods-based engineering approaches, providing underlying modelling structures and concepts to 'systemize' and 'quantify' key aspects of organization design and change. Unless suitable decomposition, quantitative and qualitative modelling principles are used to underpin an approach such as a Lean Manufacturing, deficiencies will remain. Often, MEs adopt the "we need be lean" mindset without holistic understandings of causal and temporal impacts of such philosophies on ME processes, resource systems and current and possible future workflows. Enterprise Modelling (EM) partially addresses the aforementioned problems and can support the development of robust understandings about current enterprise processes and potential capabilities of systems. However in general, current EM techniques are geared best to capturing and organizing relatively enduring knowledge and data about any given organization but are themselves deficient in respect to replicating and predicting dynamic system behaviors.

This paper presents a model driven approach to organization design and change in support of methods-based engineering, applying Lean Manufacturing principles, with a UK based bearing manufacturer. EM and various derivative Simulation Modelling (SM) views were generated to display system behaviors under changing scenarios.

Keywords: Lean, Takt Time, Manufacturing Enterprise, Enterprise Modelling, Simulation Modelling

1.0 Introduction

In recent decades technological innovation has induced very significant change on the way that Manufacturing Enterprises (MEs) operate and compete. To support MEs in coping with changing business and production requirements, 'method-based' approaches to organization design and change including: BPR, CPI, Kaizen, TQM, JIT, PPM, Lean Manufacturing, Agile Manufacturing, etc, have been proposed and applied in many MEs. However, none of these management philosophies and production approaches could be said to be a panacea for success. With increasing pressure on MEs to remain responsive to changing market demands, whilst maintaining operational efficiency, arises the need for robust process understandings to enable effective implementation of improvement philosophies.

In general MEs are very complex entities: designed, managed and changed by people, by deploying people and technological resources in systematic, timely and innovative ways that generate competitive behaviors. Prerequisites to respond such change and deal with complexity are firm understandings of; the processes that are the focus of improvement and effects of change decisions. However, implementing change and dealing with associated effects can prove difficult when such an understanding is not intrinsic i.e. domains lacking structure and documentation.

This paper presents a model driven approach to organizational design and change. An Enterprise Modelling and Integration (EM&I) approach was deployed to model aspects of a Small to Medium sized Enterprise (SME) collaborating with the Manufacturing Systems Integration (MSI) research institute. The resultant models, especially in their simulation views provide basic frameworks for reasoning about enterprise systems behaviors under changing scenarios. The case instance reported is an SME that makes composite bearings to order, namely ComBear composite bearings. The focus objectives of the ComBear improvement project include (1) to create enterprise models (static & dynamic) to enhance the understanding of the enterprise processes and systems, and (2) to bring to bear on the process and systems models created elements of Lean Manufacturing concepts and tools with a view to achieving improved performance in the critical areas of lead time, process efficiency, resource utilization and consumption, and increased value generation.

2.0 Lean Manufacturing Philosophy Background

The Lean Manufacturing philosophy originated from Toyota Production systems in Japan and was pioneered by Taiichi Ohno (1912 -1990). The prime purpose of Lean Manufacturing is to eliminate manufacturing wastes (muda). Tapping [1] describes manufacturing wastes in terms of the so called seven deadly manufacturing wastes, namely: overproduction, waiting, transport, over processing, inventory, motion, and defects. Wastes in manufacturing are activities which absorb resources but create no value in return and they includes: mistakes which require rectification, production of items no one wants, unnecessary inventories, processing steps which are not needed, movement of people and transport of goods without purpose, people waiting because the upstream activity has not promptly delivered, goods and services that do not satisfy customer's requirements [2]. Lean Manufacturing is a systematic approach to identifying and eliminating wastes through continuous improvement, flowing the product at the pull of the customer in pursuit of perfection [3]. Hence the goal of Lean Manufacturing is to eliminate wastes by:

- Producing what the customer needs
- When required by the customer
- In the exact quantity needed
- Using resources only when needed

Womack & Jones [2] suggest five principles steps towards achieving Lean Manufacturing benefits namely:

1. Precisely specify value by specific product
2. Identify the value stream for each product
3. Make value flow without interruption
4. Let the customer pull value from the producer
5. Pursue perfection

The application and testing of some of these Lean Manufacturing principles in ComBear will be discussed later in this paper.

3.0 Enterprise Modelling and Simulation

Enterprise Modeling (EM) approaches and supporting tools provide a structured view and grounding for change decisions, enabling the systematic hierarchical decomposition of an ME's processes, allowing contextual problem definition and specification. CIMOSA (Computer Integrated Manufacturing Open Systems Architecture) was developed by the AMICE consortium during a series of ESPRIT projects [4]. CIMOSA aims to help companies manage change and integrate their facilities and operations. It has been emphasized by [5], [6], and is considered by many authors to be the most comprehensive of current public domain EM approaches [7]-[9]. CIMOSA introduced a process-based approach to integrated EM, ignoring organizational boundaries, as opposed to various function or activity-based approaches, described in terms of their; function, information, resource and organizational aspects, and designed according to a structured engineering approach that can then be plugged into a consistent, modular and evolutionary architecture for operational use [7]. It presents a model-based approach to design, operationalize and manage an enterprise. The authors and their colleagues have been using CIMOSA in numerous research and industrial projects. Sets of CIMOSA conformant models are generated during projects and presented to industrial partners for verification. This serves three purposes; (1) to enable enterprises to understand, model, analyze their processes and operations, (2) to provide model developers with an accurate benchmark from which improvements can be derived, (3) to provide the management team with information to make effective decisions in response to change. For the constraints of this paper, the authors will not go in to great details and illustrations of CIMOSA models, but briefly introduce main modeling procedures followed and the model types produced.

3.1 Establishing a Focus Modeling Domain, the Context Diagram

After the broad aims and general problems for a case company have been identified, the modeler must define a scope within which the existing modeling tools will be deployed. EM in this case uses decomposition principles to handle model complexity, this constrains the modeler to model in abstraction and avoids modeling of the infinite complexity inherent to real systems. The modeling priority and emphasis is established through a model depicting the global objective, which is reasonably simple in structure and content. The primary focus is central and surrounded by the most relevant domains involved in objective realization. This is termed the Context Diagram, and is the first type generated. Additionally, it is necessary to have specified an area of concern when drilling down and to demarcate immediately unconcerned domain(s) to provide succinct models, representative of entry point and problem concerns. Marked domains are then treated as 'black box' thus not further detailed during model development nor when creating modeling scenarios for case companies.

3.2 Problem Domain Decomposition, Interaction Evaluation and Structure Building

The next modeling step deploys a mechanism for decomposition to break down the primary focus domain, CIMOSA modeling specifies a diagram to show relationship networks between those involved domains. The relations are interpreted in terms of inflow and outflow of; information, human resources, material and finance. Thus when a particular domain is subjected to internal change, one can deduce the inter-domain effects on connected flows and responses. This outlines the purpose for the Interaction Diagram. A subsequent type of diagram, termed the Structure Diagram, is used to decompose and build structure. This can also be used on each of the associated domains which have been identified to model in CIMOSA in the Context Diagram. The Structure Diagram takes each domain as a focus for further examination and decomposition in to a hierarchically structured set of processes. Both types of diagrams can be built on a subsequent level i.e. it is possible for a particularly complex domain to have several Interaction and Structure Diagrams for the purposes of providing a sufficient level of detail as required by the modeler.

3.3 Sequential Precedence of Process Operations, the Ultimate Respondents to Change and Where Decisions Need to be Made

Procedural steps thus far have served to decompose and structure domain contents. Now a more detailed level is reached, here actual sequences of process and constituent operations are assessed. Complete end-to-end process networks, comprising activities with associated information and resource inputs and outputs are represented using the fourth CIMOSA diagram type, the Activity Diagram. A numbering convention is followed to identify activities listed with their dependencies and routings. Also, an approximate duration is given through means of a timeline indicating when each step of operation will initialize and how long they operate.

From a model developer and theoretical perspective, the concepts, methodology and technology used in CIMOSA modeling and diagrams, can usefully decompose complex process networks into their component process segments. CIMOSA also serves to provide a means of documenting and visualizing associated flows of; activities, material, information, controls and so forth. Such model diagrams can support an ME's decision makers (i.e. company management teams and direct associated operators) who require increased information support from models. To achieve this, the models need to enable; (1) appropriate presentation format and structure to be readily understood by users (i.e. the decision makers) (2) efficient and equivalent information which can be quickly obtained from models, (3) quick, responsive and efficient development, if original model data is available, as per the end users' reference requirement, (4) a model format and building procedure that is flexible to various model iterations, transfer, and re-use.

3.4 Systemizing Methods-Based Engineering Using CIMOSA

The authors propose that the use of EM, in particular CIMOSA and conformant approaches developed at the MSI Research Institute [10], in conjunction with methods-based engineering approaches will fulfill a two-fold requirement, these being: (1) the provision of a structured route to implementation of methods-based engineering philosophies, and (2) EM based improvements to be informed through well defined philosophies. Such static models can then inform the analysis of time dependant simulation models, allowing for the quantification of improvements with respect to: throughput, time in the system, resource efficiency and utilization.

4.0 Case Study

4.1 Company Background

ComBear is a rapidly growing SME based in the UK with global customers and stakeholders. Recently, ComBear completed a major enterprise engineering project when it created a second production facility, similar to its UK operational base, which is now located in South Korea. Further production facilities are being developed in other parts of the world including the US with a view to increasing market share. At both of its current manufacturing sites, ComBear manufactures a range of advanced composite products suitable for agricultural, marine, mechanical, pharmaceutical and food processing applications. In general terms, composite products are manufactured from reinforced plastic laminates composed of synthetic fabrics impregnated with resins and lubricant fillers. Final products are delivered to customers in a variety of form factors including, but not limited to: structural bearings, washers, wear rings, wear pads, wear strips, rollers, and bushes.

4.2 Problem Definition and Case Study Objectives

ComBear's growth in the market of composite bearing manufacture has put the company under increasing pressure to produce products in larger volumes, shorter times, and at reduced costs. Approaching such challenges without considering organizational design and change has lead ComBear to compromise metrics fundamental to the customer i.e. on time delivery, product quality, and product costs.

The focus objectives of the case study were to: (1) create enterprise models to enhance the understanding of the enterprise processes and systems, and (2) bring to bear on the process and systems models created elements of Lean Manufacturing concepts and tools with a view to achieving improved, quantifiable, performance in the critical areas of; lead time, process efficiency, resource utilization and consumption, and increased value generation. Whilst Lean activities with ComBear are ongoing, to remain concise, the establishment of a 'pull signal' and reducing materials wastage will be discussed in this paper with particular emphasis on the raw materials production process.

4.3 Enterprise Modelling and Simulation at ComBear

CIMOSA modelling constructs and representational formalism support decomposition of complex systems, in this case ComBear's processes, into sub systems that can be analyzed independently and later recomposed into a collective whole. The key processes in ComBear were identified and encoded to enable the realization of enterprise models. These were then validated by their management and production teams as being representative of the enterprise processes and associated resources. Exemplar diagrams follow, figure .1 shows a Context Diagram which was described in section 3.1. Figure .2 depicts an Interaction Diagram, described in section 3.2, of ComBear's 'plan and control production' process, showing the flow of information and resources between associated processes, and also flow and control logic. Domain Processes (DPs) external to the domain under study are depicted as 'black box' representations. Control Production (EA5.1.1.1) receives the job card from the Technical process (DP4) and produces appropriate production schedules according to scheduling rules deployed at ComBear. The job card provides both technical product information, i.e. engineering drawings, as well as order details i.e. due date, quantity. The job card informs BP5.2.1 through to BP5.2.5 along with further inputs of raw materials and human resources. BP5.2.1 produces round and flat raw materials that are then used by BP5.2.2 and BP5.2.3. Products are packaged and dispatched, at which point DP4 receives notification and feeds back dispatch details to BP5.2.5. A number of control nodes indicate where EA5.1.1.1 will consult the production schedule to prioritize jobs accordingly.

Having developed similar static models of ComBear processes, at the further detailed 'activity' level, the next step in the project sought to operationalize the models by applying selected Lean Manufacturing measures to the processes in a simulation environment in order to observe current 'as-is' process behaviors and performance of the resource systems. The initial simulation environment was realized using Simul8® and further investigation is being carried out by another software, Lean Modeller®, to establish values (this is mentioned for completeness but is not within the scope of this paper).

Through analysis of static and simulation models in conjunction with discussions with ComBear's management and production teams, it was decided that the focus of improvements should be in the production of raw materials that supply later processing shops. This was supported by the simulation model in figure .3 which indicates a very low percentage utilization of resources in the histogram as well as a large deviation in the time round narrow raw materials spend in the raw materials processing shop. Additionally, this part of the manufacturing process was manually intense hence offered the most scope for improvement.

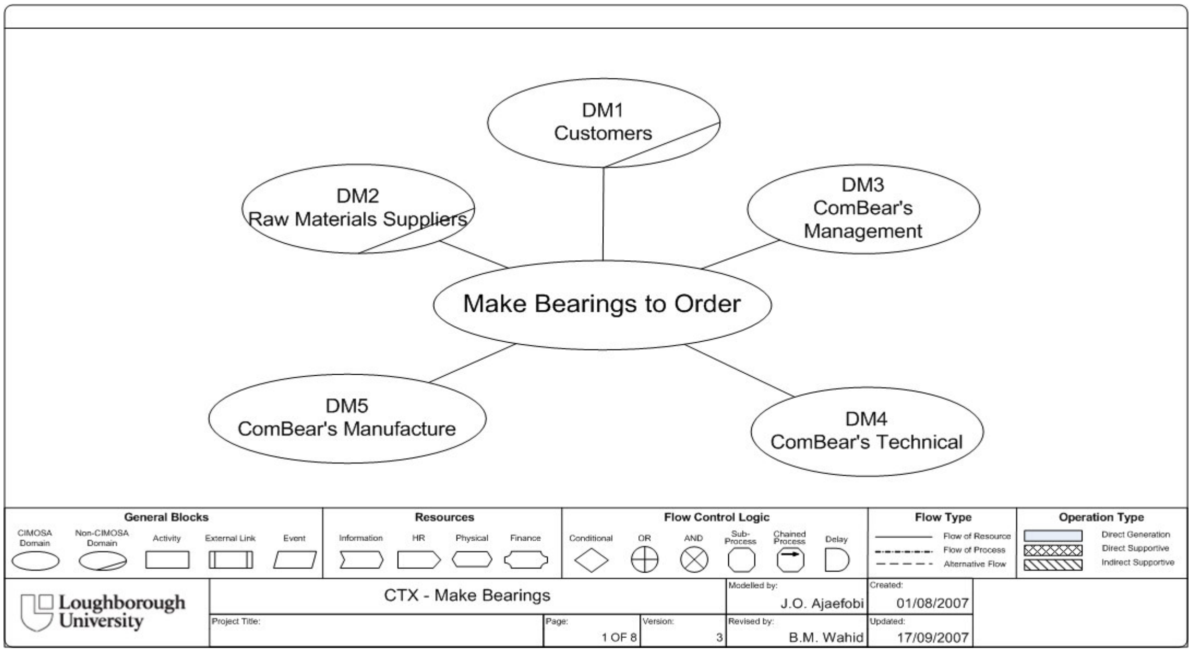

Fig. 1. Establishing a focus domain using the Context Diagram

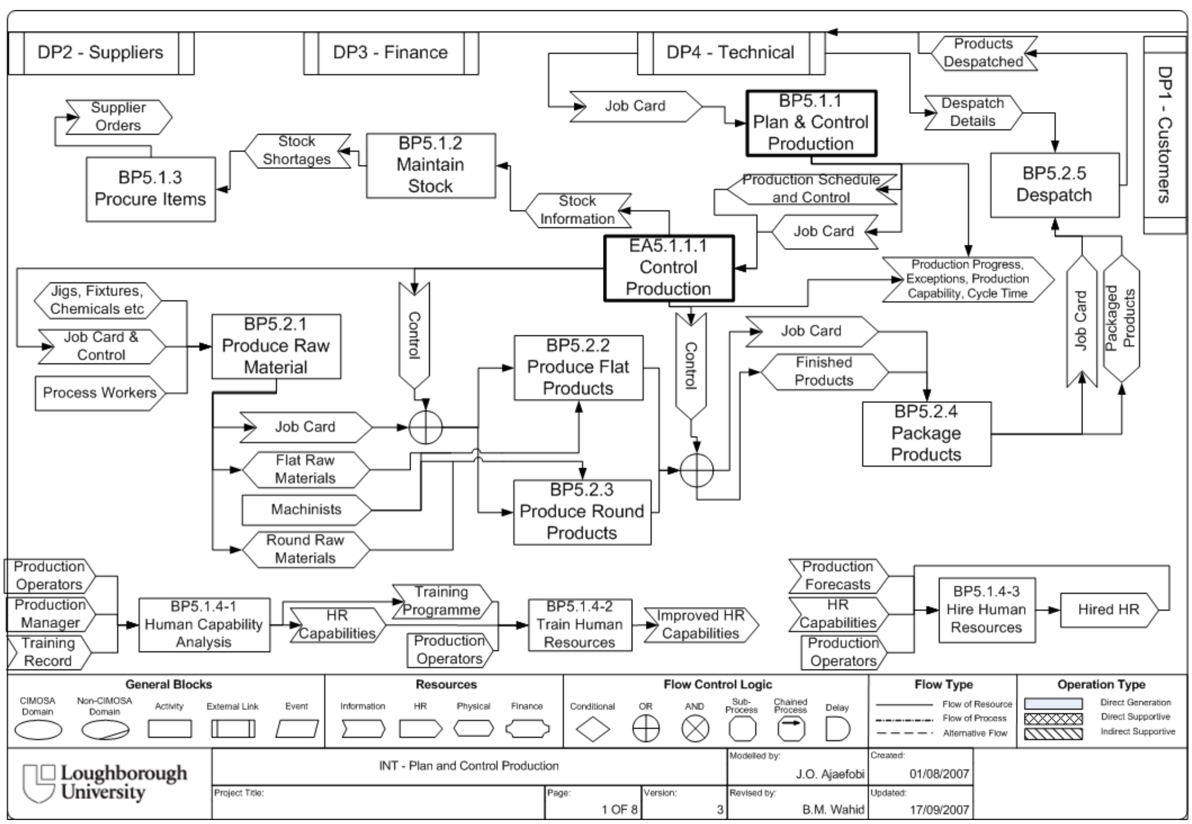

Fig. 2. Process and resource flows within a domain, the Interaction Diagram

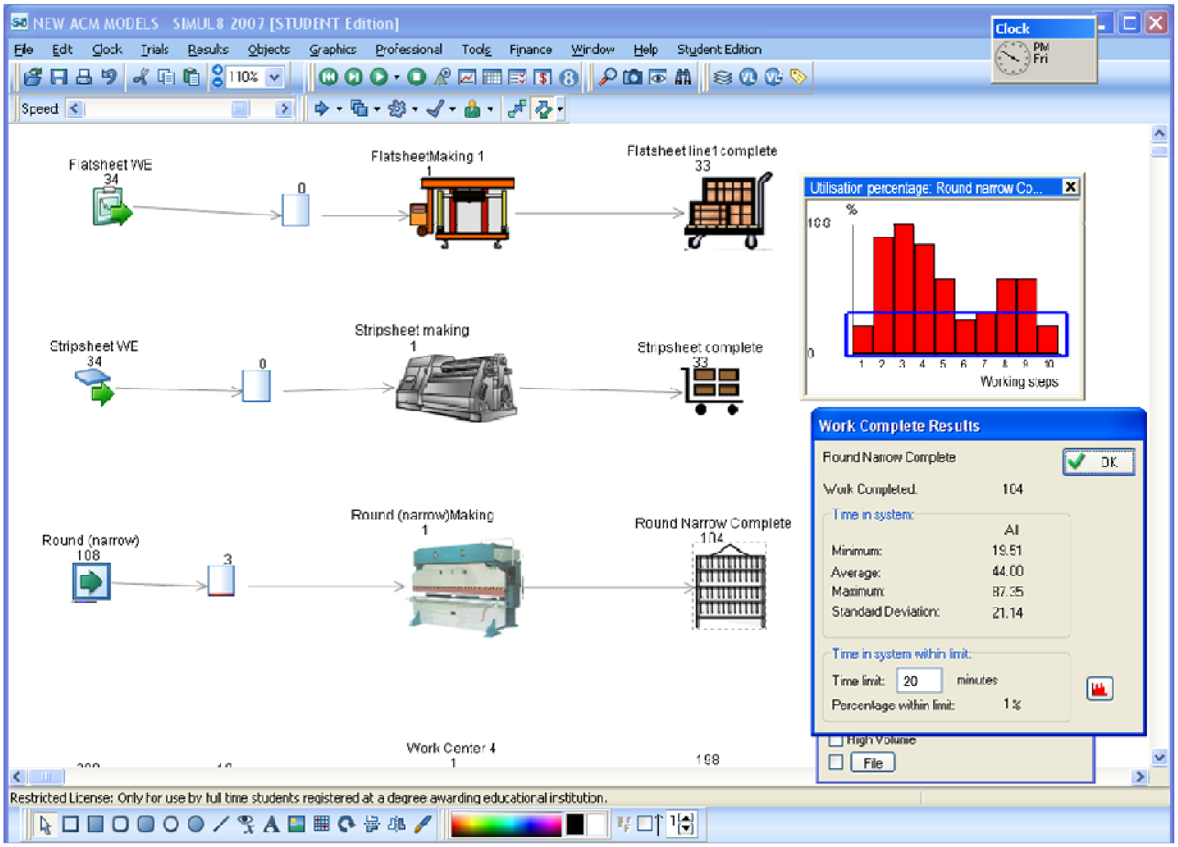

Fig. 3. Initial simulation model

The company's production systems are a mix of make-to-order and engineer-to-order, despite the order book consisting of repeat orders. Whilst these are representative of pull systems, the pull signal itself i.e. the job card, is issued to the raw materials processing shop i.e. the start of production. This indicates that whilst production is based on firm orders, within the factory products are produced in a way more representative of a push system. ComBear had highlighted that there were increasing problems with late deliveries and also product quality, with products leaving site that were then found to be of insufficient quality by the customer.

Having created static CIMOSA models, to depict processes and provide common understandings, and simulation models to introduce time dependencies and thus quantify current practice (in terms of output, time in the system, and resource efficiency and utilization) indicating where to focus lean improvements, the next step was to deploy methods-based engineering to target improvements. Whilst improvements were targeted and made across flat, strip, and round raw materials, for the purposes of this paper only those made with respect to round narrow will be discussed.

4.4 Lean Manufacturing Principles Deployed

Through use of analytical methods, guided by the model structures developed using EM principles and diagramming techniques, improvements were targeted to provide; effective process resourcing, product and tooling rationalization, reduced materials wastage, and workplace organization.

4.4.1 Implementing Pull and Product Rationalization

In order to implement a pull signal within the organization, it is necessary to establish takt times for products i.e. demand driven requirements of ComBear. This can only be achieved if sound product classifications exist, these were established through the use of activity diagrams. It was noted that of the product classifications used by ComBear, processing characteristics provided an alternative and generalized classification of round, flat, and strip products. These general form factors exhibited distinct processing routes in the raw materials processing shop. This rationalization of products allowed complexity to be minimized when establishing takt times.

Analysis of historical order information allowed takt times to be developed and broken down in to constituent takt times for each of the newly defined classifications by key processes i.e. produce raw material, produce flat products, produce round products, as defined in previously created enterprise models. With these times understood and visible to the production team, decisions could be exercised to enable adequate resourcing of processes to support production of what the customer needs, when required, in the quantity needed.

4.4.2 Materials Wastage and Tooling Rationalization

The processes deployed in the production of raw materials require that the tooling, thus working dimensions, be within 2mm of finished dimensions to minimize the amount of subsequent machining effort required and material wasted. However this must be balanced with cost, space, and demand constraints. Currently, tooling is highly product specific and whilst this reduces material wasted, it does induce waste in terms of tooling stock. Other than dimensional constraints, there is no sound justification for the tooling sizes stocked in the raw materials shop. A distinction must therefore be made between the frequency of tooling use and a justification must be made for holding particular sizes and quantities. With the aforementioned points in mind, stepwise improvements have been delivered through the categorization of products in to; those that occur on a continuous basis and are core products (runners), those that occur regularly (repeaters), and those that are manufactured to specific requirements (strangers). The associated requirements for tooling sizes and quantities were extrapolated and as a result of these grounded considerations for stocking of tooling, significant scope for rationalization has been indicated. The authors would like to state that this is still an area of continued work, with similar improvements targeted for the other product types produced at ComBear along with effects on scheduling of production within the organization.

4.5 Quantifying Improvements Through Simulation

The quantified effects of changes to the production of round narrow raw materials, as a result of implementing Lean compliant improvements and resourcing strategies, can be seen in the simulation model in figure .4. Comparing this with figure .3 shows that the worker utilization has increased as has the overall productivity of the system, this is now regularly achieved with 71% within the limit. The histogram indicates that a higher resource utilization percentage has been achieved, this is attributable to the increased availability of tooling i.e. operators are not waiting. The implementation of a pull signal (takt time) means that operators are more clear and informed as to the proceeding job, this is reinforced by the standard deviation which indicates that the production rate is more predictable.

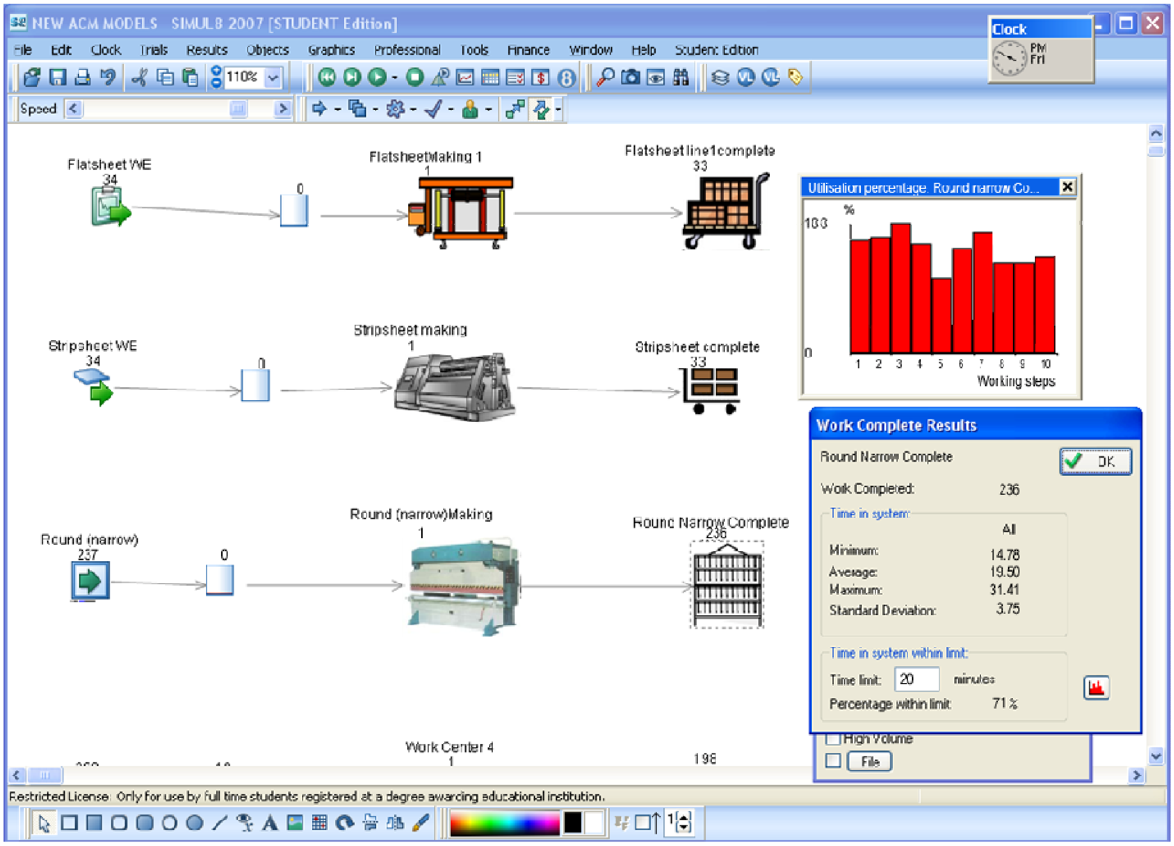

Fig. 4. Simulation model to quantifying improvements

5.0 Conclusions

The combined use of Enterprise Modelling (EM), Simulation Modelling (SM), and methods-based engineering allowed the authors of this paper to conduct a quantified, systematic and targeted Lean implementation based on; improved and verified process understandings, establishment of a pull signal, resource (human, tooling, raw materials) and product (establishing groupings) rationalization.

Whilst it is acknowledged that the research in the areas of Lean Manufacturing is well documented, it is however lacking in a structured and integrated means to realizing improvements. The authors can see the real benefits in the development of systematic support for methods-based engineering that guides users with generalized routes to implementation. The case study conducted has shown that the key to successful Lean and similar improvements is largely dependant on understanding of current practice and the causal impacts of change. Through the use of static and simulation modelling approaches developed at the MSI research institute, many of these impacts can be enacted and thus mitigated.

Improvements and methods-based engineering conducted were done so in abstraction from the real system, using EM and SM approaches. The project work with ComBear is ongoing and the next steps are to work on product classes to inform different stocking strategies based on the product type i.e. runner, repeater, or stranger. For example it may well be necessary to make-to-stock raw materials for less frequent products. Additionally, the interfaces between the raw materials shop and subsequent processes needs to be explored to further inform takt times thus fully implement a pull signal. Whilst classifications break complexity, there is a degree of variation within them, hence further variables will be used in order to further inform product sub-types.

Further suggested improvements are to be implemented and areas of investigation researched, the results of these efforts will be reported on in further conference and journal publications.

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LOW CARBON MANUFACTURING: CHARACTERIZATION, THEORITICAL MODELS AND IMPLEMENTATION

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Abstract

Today, the rising of carbon dioxide (CO_2) emissions is becoming the crucial factor for global warming especially in industrial sectors. Therefore, the research to reduce carbon intensity and enhance resources utilization in manufacturing industry is starting to be a timely topic. Low carbon manufacturing (LCM) can be referred to the manufacturing process that produces low carbon emissions intensity and uses energy and resources efficiently and effectively during the process as well.

In this paper, the concepts of LCM are discussed and the LCM associated theoretical models, characterization and implementation perspective explored. The paper is structured in four parts. Firstly, the conception of low carbon manufacturing is critically reviewed then the characterization of low carbon manufacturing is discussed and formulated. Third part, the theoretical models are developed with initial models by using the theory from supply chain modeling and linear programming solutions (LP). The models show the relationship of resource utilizations and related variables for LCM in two levels: shop-floor and extended supply chain. Finally, the pilot implementations of LCM are discussed with two approaches: desktop or micro machines and devolved manufacturing. The paper is concluded with further discussions on the potential and application of LCM for manufacturing industry.

Keywords: Low carbon manufacturing (LCM); Micro manufacturing system; Devolved manufacturing; Energy efficiency; CO_2 emissions

1.0 Introduction

Currently, global warming is extensively discussed as one of the most important global issues because of the rising of the amount of carbon and carbon dioxide contents emitted from industrial sectors. Many sectors have been trying to develop the solutions to solve and prevent this problem e.g. carbon emission analysis, software based prediction on economic factors and physical implementation using micro manufacturing system and microfactory. However, most of previous solutions does not mention about the configuration of the procedures to reduce carbon emission. Therefore, the effort to reduce carbon intensity and enhance resource utilizations is stated as a timely topic. The purpose of this paper is to develop an industrial feasible approach to implementing LCM including its theoretical models, methods and application perspectives.

2.0 Literature Review

2.1 Carbon Emissions Analysis

In the past decade, many countries have been conscious to develop the procedures for reducing carbon emissions. Fan et al. [1] have presented the model for prediction of carbon dioxide (CO_2) emissions based on the input of population, economy and urbanization. In 1996, Golove and Schipper [2] introduced the analysis of the tendency of energy consumption which can cause CO_2 emissions from manufacturing sectors based on the input of the gross domestic product (GDP) changed to economic output and process intensity. Although, these methods have been developed to deal with the global warming problem from carbon contents, the procedures to analyse is still focusing on the wide range and depending more on economic factors such as GDP. The procedures for reducing CO_2 emissions in manufacturing systems and the associated manufacturing processes have not been introduced yet.

2.2 Operational Model

In the area of production research, most of the research focuses on the objective such as cost minimization, quality assurance and the level of customer satisfaction as the objectives of the process optimization according to Gugor and Gupta (1999)[3]. Carbon emissions and energy efficiency have never been a critical factor in operation optimization. However, Mouzon et al. [4] have developed the operational model by using the theory of multi-objective mathematical programming in order to minimize energy consumption from equipments in manufacturing system. In the operational model, the constraints are focusing on completion time and total power per unit time. Even though, the production research for reducing total energy consumption has been introduced at this time, the operational model for reducing carbon contents from manufacturing processes need to be further developed.

2.3 Desktop and Micro Machine

The concepts of micro-factory and desktop machines for micro manufacturing purpose have been explored in the wide range. For the definition and concepts of the micro-factory and desktop machine, Yuichi [5] explain it as small scale manufacturing systems which can perform with higher throughput while resource utilization and energy consumption rate can be reduced simultaneously. In addition, Mishima [6] suggests that the concept of micro-factory and desktop machines should also concentrate on low heat generation and less energy consumptions of the systems. It is concluded that the innovation of desk-top and micro machine can be applied to the LCM by reducing the unnecessary carbon contents from manufacturing systems.

2.4 The Novell Approach: Devolved Manufacturing

The high proportion of carbon dioxide emissions not only comes from manufacturing systems and processes but also from the transportation while working on extended supply chains manufacturing. Bateman and Cheng [7] have introduced in a novel approach called Devolved Manufacturing (DM) which integrates main three elements together for future manufacturing systems: web based (e-manufacturing), mass customization (MC) and rapid manufacturing. The aim of this approach is to provide “factory-less” which customers can receive their products at the nearest location. In other words, this approach can be applied to minimize the transportation in associated with manufacturing systems set up. It is concluded that Devolved Manufacturing can be considered as an approach for reducing carbon contents emissions particularly for LCM in supply chain based manufacturing systems.

3.0 Characterization of Low Carbon Manufacturing

Low carbon manufacturing (LCM) can be described as the process that emits low carbon dioxide (CO_2) intensity from the system sources and during the manufacturing process. In addition, the term of LCM can be broadly not only for environmental aspect but also the energy conservation and effective production because the process uses energy excess available capacity/constraint (low energy efficiency) simultaneously without optimal algorithm to run process or system can lead to the high volume of carbon dioxide intensity to atmosphere (Figure1). Therefore, the main characterization of LCM can be categorized into specific five terms as follows:

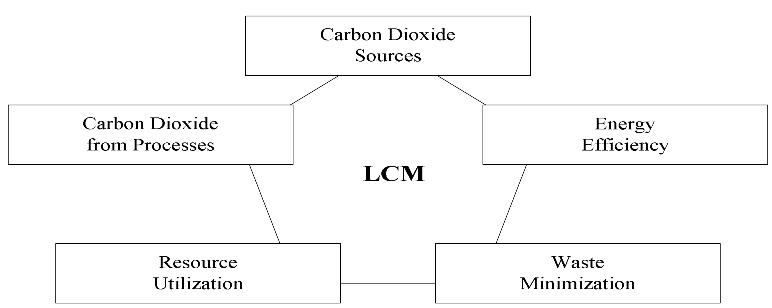


Fig. 1. Characterization of Low Carbon Manufacturing

1) Low carbon dioxide from source: currently, almost all equipment and machines in modern industry use electricity as a main energy to operate if machines or equipment can be adjusted or improved to use less energy, the carbon dioxide intensity from the machines and equipment sources will be reduced.
2) Energy efficiency: energy efficiency can be explained as a percentage of output of energy from process (in watt or joules) divided by the input of energy to the process [8]. Hence, this parameter in LCM concept should be higher than conventional industrial processes.
3) Waste minimization: This term can be meant as how waste can be dislodged or minimized according to the reference [9]. If the third criteria above are categorized into carbon dioxide emissions due to machines and equipment, it is emission from imperfect operation because waste can occur in the process. For example, many wastes can appear in the turbulent manufacturing process: idle time, waiting time and queuing time etc. Therefore, the optimal solution and algorithm (for example, optimal time to run machines and equipment which can conform to operational constraint) for the manufacturing process should be installed into LCM in order to minimize waste energy and thus carbon dioxide emissions.
4) Resource utilization: Sivasubramanian et al. [10] described that resource utilization in today industry can be typically observed from raw material usage and queue/waiting time in the process and priority rule in the process chain. These factors can become as constraints in problem formulation in order to create optimal production algorithm. The percent of carbon contents can be reduced when percent of resource utilizations are increased because unnecessary energy for CO_2 emissions is also reduced.

4.0 Implementation of LCM

Three implementations have been explored at Brunel University for LCM. The configuration of implementation of LCM is shown in Figure2.

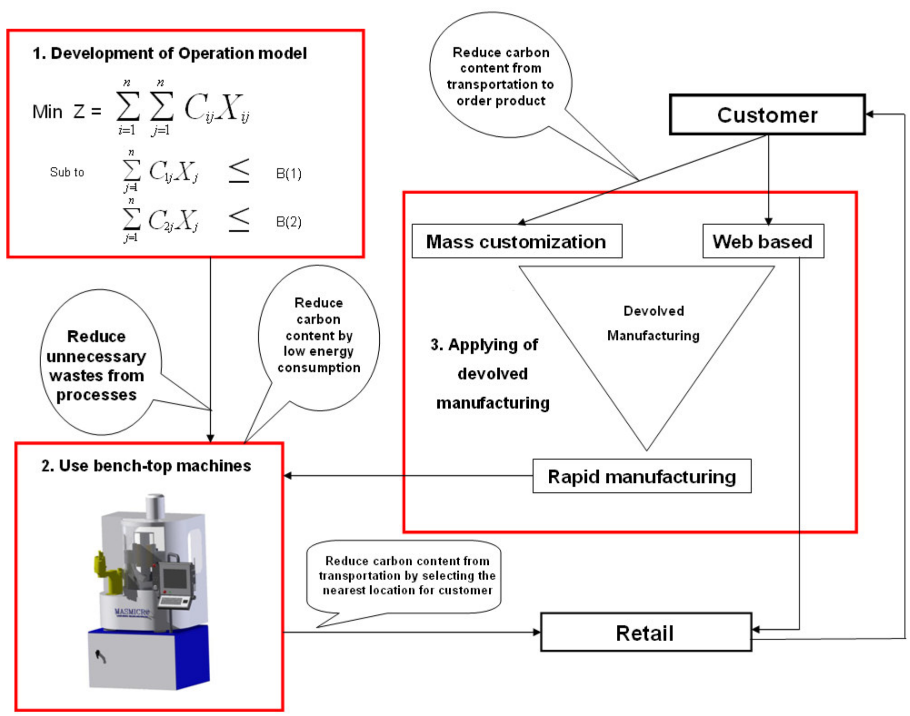


Fig. 2. Implemented Concepts for LCM

1) Development of operation models: this method is developed for establishing suitable objective function which can reduce carbon content from manufacturing processes. All resources causing carbon emissions are considered as constraints in the operation model in order to prevent unnecessary wastes occurred in idle and down time while the finished products can conform to customer's demand. Therefore, it could be described in another way that this method is specific for carbon minimization.
2) Using bench-top/micro machines: These kinds of machines have been developed in the concept of less energy consumption and small space requirement for processing. The reduction of carbon content of this method is specific on machines/equipments (locations). At Brunel University, bench-top machines have been developed for micro manufacturing purposes. However, it can be also used for LCM by taking advantage of their low energy consumption, resource efficiency and small foot print.
3) Applying of Devolved manufacturing: Bateman and Cheng have introduced the concept of Devolved Manufacturing which aims at achieving mass customized rapid manufacturing in a devolved web-based manner [11]. This method can be applied to the concept of LCM by minimizing carbon emission from make to order product (upstream) by customizing product via Internet-based instead through the nearest location (downstream) to pick-up finished goods. It can be explained in another words that this approach is focused on reducing carbon emission from supply network.

5.0 Operation Models for LCM

In this section, the operation models for LCM system are presented at two levels which concentrate on minimization of total used energy. The operational models are concerned with supplied chain level and shop-floor level respectively.

5.1 An Operational Model at Supply Chain Level

The model formulation was established based on the supply network presented by Taha [12]. The objective function sums up of total used energy in unit of joules to produce electricity of electrical flow in the supply network operation (source: power plant to sink: specific shop floor). The goal of this formulation is to minimize carbon intensity in supply network by finding the optimal electricity from (X_{ij}) between node i and j in unit of kWh. The formulation can be described as:

$$\text{Min } (f = \sum_{(i,j)\in\Omega} En_{ij} X_{ij}) \tag{1}$$

$$\text{Subject to} \quad \sum_{\substack{k \\ (j,k)\in\Omega}} X_{jk} - \sum_{\substack{i \\ (i,j)\in\Omega}} X_{ij} = f_j \qquad \forall j \in Z$$

$$C_{ij:\min} \le X_{ij} \le C_{ij:\max} \qquad \forall i,j \in \Omega$$

$$X_{ij} \ge 0 \qquad \forall i,j \in \Omega$$

where

Z - set of node (location) in network = {A, B, C, D, E}
Ω - set of arc (path) in network = {(A,B), (A,C), (C,B), (C,D), (B,D), (B,E), (D,E)}
En_j - energy factor coefficient for flow X_{ij} (joules)
$C_{i,j:max}$ - maximum electrical capacity of arc (i,j) (kWh)

$C_{i,j:min}$ - minimum electrical capacity of arc (i,j) (kWh)
f_j - total net flow at node j (kwh)

5.2 An Operational Model at Shop-Floor Level

This formulation is developed by using the theory of linear programming solution (LP) [12]. The goal of this formulation is to minimize primary energy used during the manufacturing process by finding the optimal time (X_{ij}) to produce product i on machine j. The problem formulation can be described as follows:

$$\text{Min } (f = \sum_{i=1}^{n}\sum_{j=1}^{\phi} En_{ij} X_{ij}) \tag{2}$$

$$\text{Subject to} \quad \sum_{i=1}^{N} S_{ij} X_{ij} \geq P_j$$

$$\sum_{i=1}^{N}\sum_{j=1}^{\phi} C_{ij} X_{ij} \leq E$$

$$\sum_{i=1}^{N}\sum_{j=1}^{\phi} \delta_{ij} X_{ij} \leq L$$

$$X_{ij} \geq 0; i \in B; j \in A$$

where

A - set of machines in the system {1, 2, …, Φ}, Φ is the maximum number of machine
B - set of products {1, 2, …, N}, N is the total number of product type
En_{ij} - coefficient of energy used to produce product i on machine j
δ - coefficient of lubricant used to produce product i on machine j
C_{ij} - coefficient of electricity consumed to produce product i on machine j
S_{ij} - processing time for producing product i on machine j
P_j - demand of total finished goods on machine j
L - total lubricant per period that equipment can resist
E - total electricity in specific area per period that shop-floor's fuse can resist

6.0 Experiments and Results

6.1 The System and Processes

There are five machines in the system: cutting machine, milling machine, machine centre, inspection machine and packaging machine. Each machine has two basic devices of the motor and oil tank to enable it in operation. The system starts operation at 8.00 am and ends at 10.00 pm. The process operates as job shop sequences by producing two products: gear and spindle. Processes of gear are cutting, milling, machining, inspect and packaging. Processes of spindle are machining, cutting, milling, inspect and packaging. Processing time of both two products is listed in Table 1 and energy consumption rate in Table 2.

Table 1. Processing time of the gear and spindle on each machine

Product	P:M1	P:M2	P:M3	P:M4	P:M5
Gear	15	15	15	15	15
Spindle	15	15	15	15	15
	30	30	30	30	30

Table 2. Energy consumption rate to produce the product on each machine

product	e:m1	o:ot1	e:m2	o:ot2	e:m3	o:ot3	e:m4	o:ot4	e:m5	o:ot5
Gear	1	1	1	1	1	1	1	1	1	1
Spindle	3	2	3	2	3	2	3	2	3	2
sum	4	4	4	4	4	4	4	4	4	4

M1: cutting machine; M2: milling machine, M3; machine centre; M4: inspection and M5: packaging; P:Mj = processing time on machine j (j = 1,2, …., 5); e:mj = electricity rate (kwh/cycle time) on motor j (j = 1,2, …., 5); o:otj = oil rate (litre/cycle time) on oil tank j (j = 1,2, …., 5). Energy is still provided to the devices although they do not perform any work (down and idle time) with E = 90 kWh, L = 65 litres. If total amount used electricity and lubricant are consumed over their limit, all motors and oil tanks will be shut down for 5 hours. If total electricity and oil used are over their limits, the value of these two variables will be reset to 0.

6.2 Optimization Procedures

Operation model aims at the optimal value by using optimization function in MATLAB programing. Optimal values can be the optimal time to turn-off each device. Secondly, optimal values can be used to establish operational shift for each device. In this research, two systems are established with same conditions and simulated to observe energy used from the process on ProModel simulations. The configuration of the systems in ProModel is illustrated in Figure 3. The first system is run normally but the second system is run with LP (shop-floor) model. Operational shift for the second system is presented in Table 3.

Table 3. Operational shift for each device

Device	Time
Motor 1, 2, 3, 4 and Oil tank 1, 2, 3, 4	16.30 pm
Motor 5 and Oil tank 5	13.00 pm

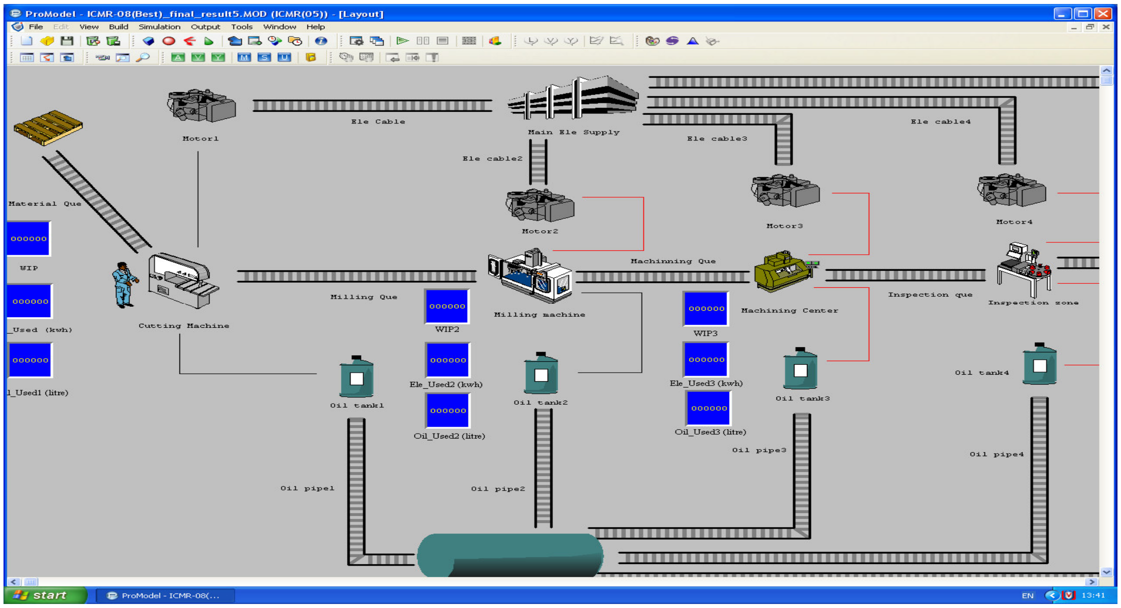


Fig. 3. The configuration of the systems in ProModel simulations

6.3 Results

Both systems are operated from 8.00 am to 1.00 am (to get results at steady state) in the same condition including inter arrival time of entity and operating algorithm. After running system simulation by using ProModel, the comparison of location states single between two systems are shown in Figure 4 and 5. Running the system with shop-floor model, the second system can eliminate percent of down time from operating period.

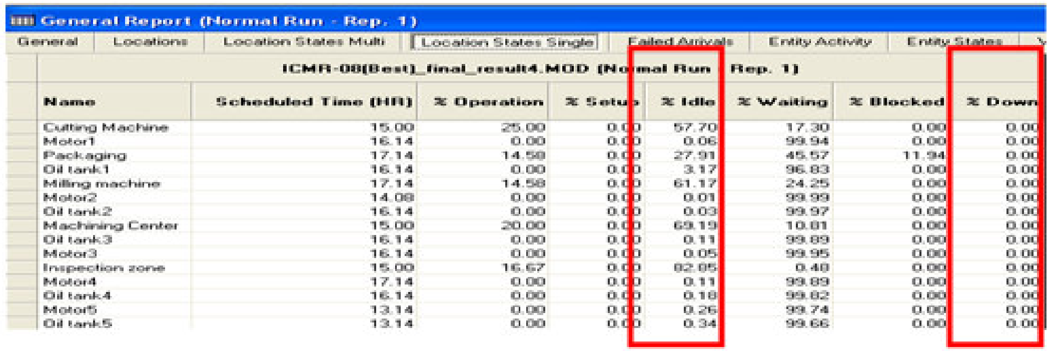
General Report (Normal Run - Rep. 1)

General | Locations | Location States Multi | Location States Single | Failed Arrivals | Entity Activity | Entity States

ICMR-08(16).MOD (Normal Run - Rep. 1)

Name	Scheduled Time (HR)	% Operation	% Setup	% Idle	% Waiting	% Blocked	% Down
Cutting Machine	17.04	16.14	0.00	56.86	27.00	0.00	0.00
Motor1	15.00	0.00	0.00	20.02	60.03	0.00	19.95
Packaging	15.00	15.00	0.00	84.59	0.41	0.00	0.00
Oil tank1	15.00	0.00	0.00	23.34	56.73	0.00	19.93
Milling machine	15.00	18.33	0.00	81.03	0.64	0.00	0.00
Motor2	15.00	0.00	0.00	18.19	63.63	0.00	18.18
Oil tank2	15.00	0.00	0.00	18.18	63.67	0.00	18.15
Machining Center	17.04	13.21	0.00	39.28	47.51	0.00	0.00
Oil tank3	17.04	0.00	0.00	0.10	70.55	0.00	29.35
Motor3	15.00	0.00	0.00	9.74	80.57	0.00	9.69
Inspection zone	15.00	15.00	0.00	84.57	0.43	0.00	0.00
Motor4	17.04	0.00	0.00	0.11	99.89	0.00	0.00
Oil tank4	17.04	0.00	0.00	0.17	70.48	0.00	29.35
Motor5	17.04	0.00	0.00	0.19	99.81	0.00	0.00
Oil tank5	17.04	0.00	0.00	0.27	70.38	0.00	29.35

Fig. 4. Location states single of the first system



General Report (Normal Run - Rep. 1)

General | Locations | Location States Multi | Location States Single | Failed Arrivals | Entity Activity | Entity States

ICMR-08(Best)_final_result4.MOD (Normal Run - Rep. 1)

Name	Scheduled Time (HR)	% Operation	% Setup	% Idle	% Waiting	% Blocked	% Down
Cutting Machine	15.00	25.00	0.00	57.70	17.30	0.00	0.00
Motor1	16.14	0.00	0.00	0.06	99.94	0.00	0.00
Packaging	17.14	14.58	0.00	27.91	45.57	11.94	0.00
Oil tank1	16.14	0.00	0.00	3.17	96.83	0.00	0.00
Milling machine	17.14	14.58	0.00	61.17	24.25	0.00	0.00
Motor2	14.08	0.00	0.00	0.01	99.99	0.00	0.00
Oil tank2	16.14	0.00	0.00	0.03	99.97	0.00	0.00
Machining Center	15.00	20.00	0.00	69.19	10.81	0.00	0.00
Oil tank3	16.14	0.00	0.00	0.11	99.89	0.00	0.00
Motor3	16.14	0.00	0.00	0.05	99.95	0.00	0.00
Inspection zone	15.00	16.67	0.00	82.85	0.48	0.00	0.00
Motor4	17.14	0.00	0.00	0.11	99.89	0.00	0.00
Oil tank4	16.14	0.00	0.00	0.18	99.82	0.00	0.00
Motor5	13.14	0.00	0.00	0.26	99.74	0.00	0.00
Oil tank5	13.14	0.00	0.00	0.34	99.66	0.00	0.00

Fig. 5. Location states single of the second system

Devices in the first system are down after and can not operate again until the end of operation shift. It can be described that unnecessary carbon emission occurred and thus the wasted energy. The statuses of device in the first and second system are shown in Figure 6.

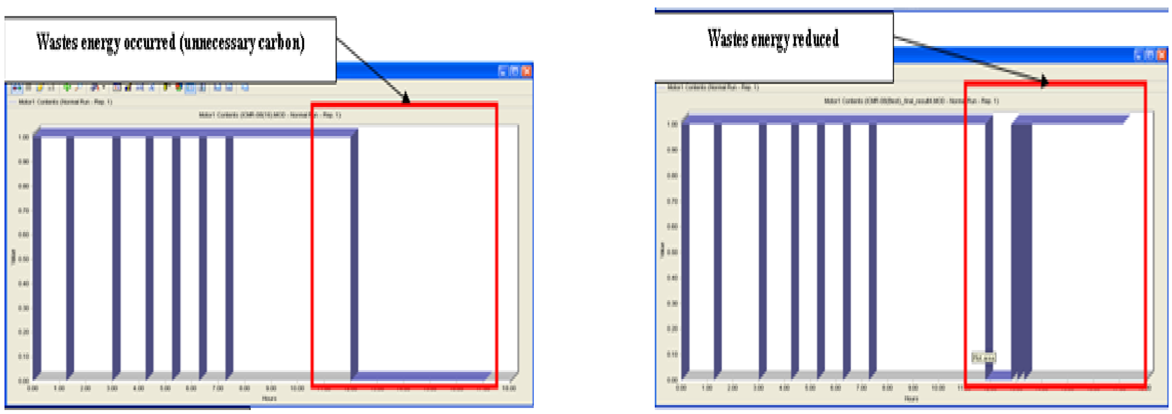


Fig. 6. The status of Motor1 in the first (left) system and second (right) system

6.4 Carbon Emissions

The amount of used energy is transformed into the unit of joules firstly then multiplied with emission factor and fraction of carbon oxidised to get carbon content in unit of Gg C according to the IPCC [13] approach. Energy consumption rate of motor and oil tank at down time & idle time are assumed to be at the rate of 0.067 kwh/min and 0.067 litre/ min respectively (each device's capacity = 1 and it is assumed that energy is consumed every 15 minutes at down & idle time: 1/15 = 0.067). The calculation of carbon emission from the first and second system is listed in Table 4.

Table 4. Carbon emissions from the first and second system

Device	Carbon Emissions (G gram Carbon * 10^{-3}) System 1	Carbon Emissions (G gram Carbon * 10^{-3}) System 2
Motor1	1723.986	2.77
Motor2	1565.982	0.396
Motor3	838.134	2.376
Motor4	5.74	5.742
Motor5	9.12	9.702
Oil1	26872.36	2115.822
Oil2	22566.06	19.998
Oil3	20785.64	74.448
Oil4	20827.22	119.988
Oil5	20909.99	165.528

7.0 Concluding Remarks

In this paper, the characterization and implementation for low carbon manufacturing (LCM) have been explored specifically for the manufacturing system from the upstream (demand of the product) through downstream (finished goods) of the process chain. In the simulated experiment, the results show the reduction of total used energy and carbon emissions when applied operation model at shop-floor level. The idle time and down time have been considered as main factors for the unnecessary wastes which can be reduced with energy constraints in mathematical model. However, the operation model can be improved in the future by taking account of more queuing system constraints. For the future work, energy consumption data from the bench-top machine developed at Brunel University will be used to further evaluate and validate the models and simulations and the analytical approach as a whole. Furthermore, the operation model will be applied to Devolved Manufacturing scenario for reducing CO_2 emissions at the extended manufacturing supply chain level.

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MODULAR LASER INTEGRATION INTO MACHINE TOOLS

A new outlook on increasing manufacturing flexibility, productivity and quality

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Abstract

In order to improve the flexibility, speed and quality of the manufacturing of parts and components with laser-treated surface areas, the Fraunhofer IPT has developed a new technology platform from which to integrate laser modules into machine tools. In the course of this paper, this new concept of modular laser integration is described, using the example of a lathe/milling machine that has been equipped with two different laser tools for hardening and for deposition welding. The hybrid machine tool is the first of its kind not to need component reclamping between the fully-automated turning, milling, drilling, laser hardening and laser deposition welding operations. Simultaneous 4-axis processes are possible with both the laser processes and the cutting processes. Some machining results are discussed. The paper concludes with a short outlook on the economic potential of the new laser integration concept.

1.0 Introduction

The manufacture of complex components with localized sections of optimized peripheral layers that are subject to partial or severe stress currently involves different manufacturing processes (turning, milling, drilling, hardening, cladding) being carried at various machining stations. Such complex, stressed components, e.g. in propeller, drive and crank shafts, spindles, flanges and blanking punches) are used in the air and space industry, in the automotive industry, for machine and plant construction and in the tool and die making industry. These components are currently turned and milled before being subjected to an annealing or cladding process. In order to meet high standards of shape and dimensional tolerance, the components are then subjected to further turning and milling processes after heat treatment. Each of these individual machining stages are currently carried out on different machine tools or work centers, which results in higher transportation time, storage time and rigging time [1].

The integration of laser system technology into conventional machine tools enables the combination of turning, milling and drilling processes with the innovative laser machining processes of laser hardening and laser cladding without having to reclamp the work piece. This additional functionality not only increases the degree of manufacturing flexibility, but also significantly reduces production flow times, which is particularly advantageous for small and medium-sized production runs or for the speedy manufacture of critical spare parts (Fig. 1.).

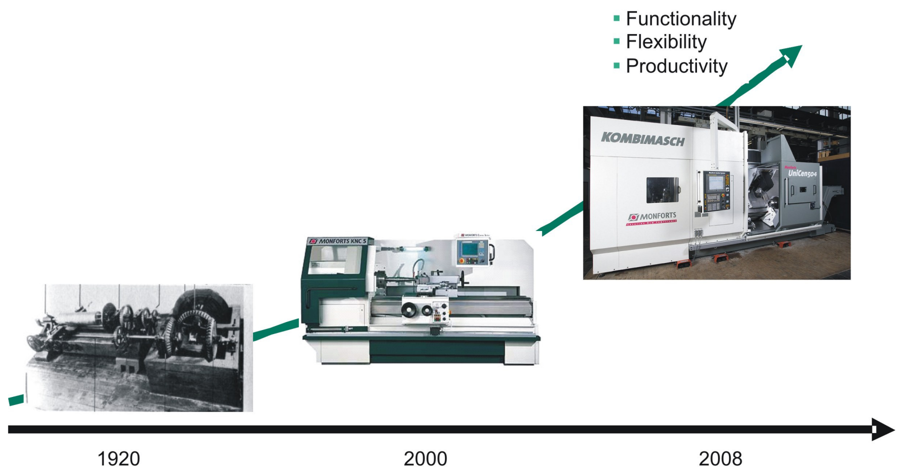

Fig. 1. Increased functionality, flexibility and productivity of machine tools by the modular integration of laser system technology

Until now, there are no machine tools on the market that can flexibly carry out both mechanical manufacturing processes such as milling and turning *and* laser surface treatment processes such as laser cladding und laser hardening without compromising on the functionality and flexibility of the conventional cutting processes [2]. This is caused by a lack of strategies that compensate for the negative interactions within the working space between the laser system technology and the cutting processes. Laser processing units that are mechanically fixed into the machine tool's working space can collide with the conventional cutting tools. During the laser process, the laser not only heats up the component but can cause thermal deformations of various machine elements or even of the entire machine structure which, in turn, has a negative effect on machining quality and in particular on the component's dimensional accuracy. The laser machining tools' sensitive optics also quickly become covered with coolant and material chips while the conventional cutting process is in progress, making the level of tool wear and the likelihood of a malfunction after only a short time and at relatively low loads unacceptably high [3]. The aim of the »KombiMasch« research project was therefore to reduce the amount of processing effort required for the industrially manufacture of rotationally symmetrical parts by combining conventional cutting and thermal surface processing technologies into a modular machine tool. Thus, a machine tool demonstrator has been built at the Fraunhofer IPT that enables the complete manufacturing of rotationally symmetrical parts by providing both conventional cutting and laser surface processing technologies in one machine tool. This demonstrator not only provides a flexible form of conventional machining before and after heat treatment, but also flexible laser surface processing technology based on modularly mountable laser processing units for both laser cladding and laser hardening within the same working space. This eliminates the need to reclamp and re-reference the work piece. The hybrid machine tool, with its integrated modular laser systems technology, can be used both for series production and for the production of individual parts via turning, milling and drilling processes that meet all dimensional accuracy requirements *and* via the laser processing technologies of laser hardening and laser cladding that can generate application-related surface properties in specific component surfaces. If post-processing operations are still necessary after the laser processes in order to correct an aspect of the geometry, the work piece does not need to be reclamped but can be turned or milled within the same hybrid machine tool. Other processing stages to protect the component during storage and transportation can therefore be eliminated, e.g. greasing, degreasing and packaging processes. As some of these operations are carried out by sub-contractors, the elimination of these additional operations helps to reduce environmental pollution.

The hybrid »KombiMasch« machine tool concept incorporates the following manufacturing technologies: milling, drilling and turning before heat treatment, laser hardening, laser cladding, milling and turning after heat treatment. The systems engineering developed at the Fraunhofer IPT covers the process technology investigations in industrial applications and an evaluation of the project results. Fundamental investigations into issues related to materials and applications as well as specific tests of the new laser cladding and laser hardening unit were carried out in relation to the manufacture of demonstrational parts. This led to the characterization of the process technology conditions needed in order to define the final specifications and to the execution of process investigations on the »KombiMasch« machine tool into combined manufacturing processes. The process data determined in the course of this research work was stored in a CAD/CAM system [4].

2.0 Systems Engineering

Fig. 2. Combination of conventional machining and laser process technology in one machine tool

In order to combine the different laser processes with cutting processes in only one machine, the Fraunhofer IPT has, for the first time, developed a technical platform for combined laser processing and conventional cutting processes. At the heart of this platform lie the modularly integrated laser processing units and the innovative optical and mechanical interfaces between laser processing units and laser source. The design of these modules makes it quick and easy to integrate the laser processing units into a conventional machine tool. The guidance and control of the laser processing units are accomplished by the axes and the control system of the machine tool. In order to demonstrate the potential of the newly developed modular laser integration technique, the Fraunhofer IPT built and successfully tested the first machine tool that combines turning, milling, drilling, laser cladding and laser hardening (Fig. 2.). Compared to other techniques used to integrate laser system technology into machine tools, the hybrid »KombiMasch« machine tool developed by the

Fraunhofer IPT is the first that does not involve component reclamping while at the same time offering a flexible and fully automated range of laser surface treatment processes. The manufacturing processes of turning, milling and drilling can also still be carried out as flexibly as in other conventional machines. Both the laser and cutting processes are capable of simultaneous 4-axis machining, making it possible to machine almost any component geometry. The turning/milling machine was developed as an inclined bed. The main spindle, opposing spindle, turret, tailstock, 4-axis milling spindle (B-axis spindle) and tool exchange magazine modules are designed to be added on as 'building blocks'. A list of the technical data for this machine tool is given in the following table.

Table I. Technical Data

Maximum turning length	900 mm
Maximum pitch	280 mm
Swing over bed	600 mm
Main and opposed spindle Motor spindle Speed range Maximum torque	 33 kW 25 - 4000 min^{-1} 630 Nm
B-axis spindle (travel) Motor spindle Speed range Maximum torque Holding torque	X: +440 mm, -10 mm Y: ±100 mm Z: +1000 mm B: ±95° (swivelling angle) 16 kW 25 - 12000 min^{-1} 76 Nm 5000 Nm
Turret	12 stations (VDI 40)
Weight of machine tool	16000 kg

3.0 Modular Laser Processing Units

Two modularly mountable laser processing units have been developed and built in order to enable the flexible use of the laser cladding and laser hardening processes integrated into the machine tool. For the first time, these modular laser tools can be automatically exchanged into the standard tool holder in the 4-axis milling spindle, just as the milling, turning and drilling tools are, without impairing the kinematic degrees of freedom of the 4-axis milling spindle and thus fulfilling the relevant kinematic und mechanical requirements. This significant advantage is combined with the distinctly multi-functional nature of the machine using just one 3 kilowatt high power diode laser beam source that feeds the laser radiation with the aid of a beam switch via optical fibers to the laser processing unit currently in use (either the laser cladding unit or the laser hardening unit). The stand-by position of the laser processing units is located outside of the working chamber of the machine tool. Therefore the integration of the laser processing units does not have any negative effect on the conventional machining processes. Furthermore, the stand-by position protects the laser's sensitive optical components from coolant or material chip contamination. The automated cladding process carried out by the modular laser cladding unit involves the processing of localized workpiece surface areas, generating functional sections in the peripheral layers. The application of such layers increases the functionality of the component surfaces. Special peripheral layers can be generated which are relevant to a specific application. Substrate materials or materials with particular characteristics can therefore be used cost-effectively. The additional material for the cladding process, in the form of welding wire, is fed into the laser focal point, which fuses the upper layers of the substrate material during the laser cladding process. By moving along the component surface, the laser generates a precisely defined welding bead close to the edge of the workpiece. Compared to conventional deposition welding, the laser cladding process is very stable and only distorts the workpiece to a minimal extent as the localized absorption of laser energy causes only minimal heat induction. The laser cladding unit consists of the optical laser guidance and forming components, the mechanical connection to the optical fiber to decouple the tensile forces, and the housing for the beam guidance unit, to which the wire feed unit and the process monitoring sensor are attached. The HSK63 interface that is attached to the housing around the laser cladding unit makes it possible to exchange the laser cladding unit in the B-axis spindle HSK tool holder, similar to the tool exchange in conventional milling and drilling tools. In order to ensure sufficient stiffness while keeping the weight of the laser cladding unit low (<20 kg), the beam tube consists of a fiber reinforced material designed and manufactured by the Fraunhofer IPT. The tensile strength of the individual fibers and the direction in which the layers of fibers are wrapped have been developed in such a way that the resulting stiffness of the fiber reinforced plastic (FRP) beam tube roughly corresponds to the stiffness of a steel tube of the same size (Fig. 3.).

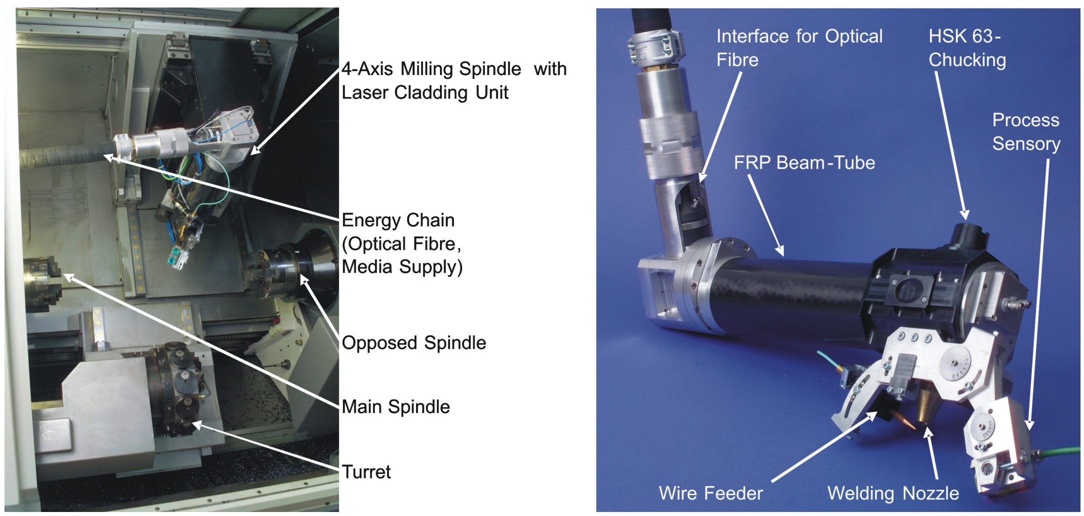

Fig. 3. Modular laser cladding unit

The laser cladding unit contains two tilted mirrors that guide the laser radiation coupled into the cladding unit by the optical fiber to the beam axis, coaxial to the B-axis spindle, before being focused by the focusing lens system. Both mirror systems have cross roller bearings to compensate for the rotational movement in the optical fiber connection that arises when the B-axis spindle rotates, thus preventing the optical fiber from buckling. All laser optics have integrated cooling channels that dissipate the absorbed laser energy and prevent heat from accumulating. The optical fiber is enclosed within a preloaded strain relief tube to lead the forces in the power chain through the tube to the mirror housing in the laser cladding unit instead of through the optical fiber itself (Fig. 4.).

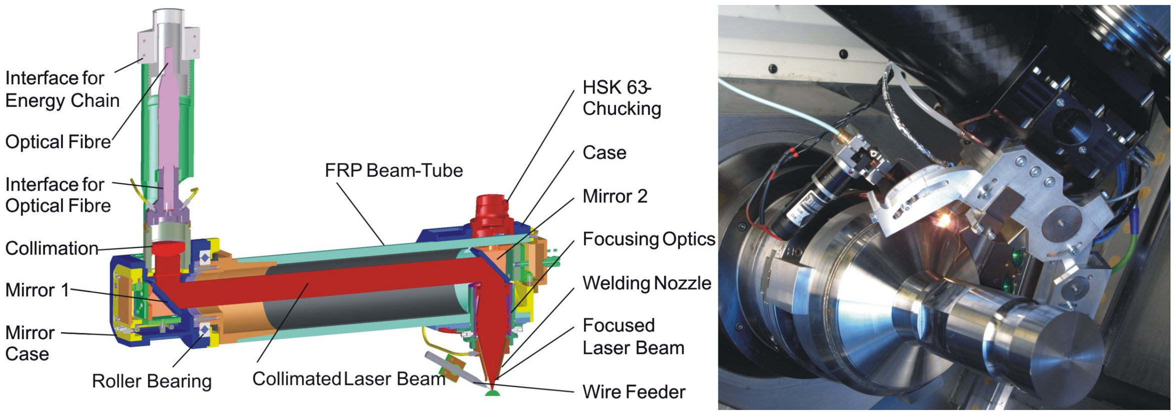

Fig. 4. Laser beam Guidance system of the modular laser cladding unit

As with the laser cladding unit, the laser hardening unit consists of a fiber connection with revolving bearings on the housing and can also be exchanged via the HSK63 interface into the B-axis spindle (Fig. 5.). The laser hardening unit contains a laser scanner with oscillating reflective scan optics (scanning mirrors) that creates the laser scanning field for flexible laser hardening. This standard module can generate any scanning field geometry within the 50 x 20 mm² scanning field. The maximum laser power that can be transmitted by the oscillating scanning mirrors is 3 kW. The Fraunhofer IPT developed the relevant mechanical and optical interfaces in order to integrate the standard scanner module into the machine tool and make it possible to exchange the laser scanner safely and reproducibly into the B-axis spindle as well as into the 'park' position. The laser scanner is enclosed within a scanner cage; the HSK63 interface is attached to this cage. For maintenance purposes, the laser scanner module can easily be removed from the scanner cage. The scanner cage is equipped with the same optical interface system with rotational bearings for the optical fiber connection as the laser cladding unit and guides the collimated laser radiation via a tilted mirror with rotational bearings to the laser scanner's oscillating optics. The scanner cage has also been equipped with a cross jet system that emits a stream of purging air perpendicular to the laser radiation to protect the F-Theta lens in the laser scanner from dust particles and dirt in the production environment.

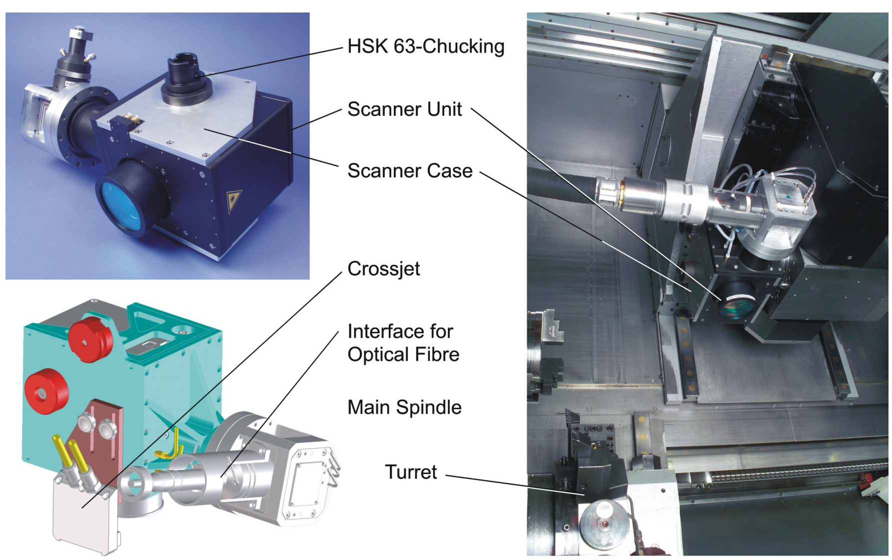

Fig. 5. Modular laser hardening unit

4.0 CAD/CAM Technology

Die The newly developed hybrid machine tool with integrated laser system technology is not only modular in terms of its mechanical design, but also in terms of the control interfaces. A profibus interface is responsible for the communication between the laser source, the laser beam tool and the machine tool. The machine tool's control unit takes over the main control function. Both the laser tools and the cutting tools are configured and administered via the machine controls. The tools paths are programmed and the tools (protective gas, laser power, wire feed) are switched or set using new NC functions that have been specially developed at the Fraunhofer IPT for carrying out laser cladding and hardening processes within the lathe. The development of the new NC functions are based on the results of extensive investigations into the process technology involved in wire-based laser cladding, laser hardening and cutting after heat treatment. Strategies were developed for wire-based laser cladding processes that produce high quality thick films (layer thickness > 3 mm) consisting of several layers being built up via an alternating series of cladding and cutting operations. This is the first time that laser hardening strategies have been developed with which to flexibly utilize laser scanner technology in machine tools. The hardening technique involves a rapid oscillation (> 1 m/s) in the laser beam (galvo scanning mirror) being superimposed over the feed motion of the laser tool (machine axes). This makes it possible to closely control the introduction of energy into the component and therefore to achieve a high level of machining quality. The machining process also becomes very flexible in terms of geometry. The NC functions have been transferred into different CAM machining strategies and integrated as a software module into a CAD/CAM programming system for turning/milling to make it easier for the operator to work with the new NC functions and to link the different cutting and laser operations to create high performance processes. The operator therefore has comprehensive NC programming for all the machining operations needed to perform all necessary processes on the component. NC cutting machine operators who are generally trained to use one specific process, as opposed to a whole range of cutting and laser processes, will therefore find it easier to work with the new machine.

5.0 Process Technology and Technological Potentials

The new machine concept, with its considerable potential in terms of automation and accelerated component manufacture, can now be applied to a wide range of components that are currently produced via a combination of turning, milling, drilling, cladding/ deposition welding (TIG, PTA) and/or hardening (e.g. induction). The stop valves and control valves, pistons and baskets used in power plant fittings are typical examples of the components that this machine can be used to produce. The conventional manufacture of these components starts with a mechanical processing followed by different thermal processing and a final finishing processing (hard machining). The overall process also includes various quality assurance tests, such as tear or hardness tests. These tests are needed because the components must fulfill important safety functions; sudden component failure would result in unacceptable damage. The components pass through a total of at least four different stations before they are finished (cutting before heat treatment, peripheral layer modification, cutting after heat treatment, quality inspection).

By substituting the laser cladding and laser hardening processes for the conventional cladding and hardening processes, the new hybrid machine tool can process the component parts from start to finish. The combination of laser processing and cutting in quick succession without the time-consuming reclamping processes makes this system both technologically and economically valuable. Using the laser to process the workpiece instead of conventionally welding and hardening it reduces component warping and, in turn, minimizes the amount of hard machining processes needed. The ability to introduce energy precisely and locally into the component also makes it possible to produce complex and delicate near net geometries. The use of laser technologies means that the surface treatment processes can be fully automated with the aid of conventional CAD/CAM/NC technology. Figure 6 shows the control valve from a high-pressure stop valve made using the KombiMasch at two different stages of the machining process (prepared for laser cladding and completely finished) as well as a longitudinal cross section through the finished component. The bond between the layers (1.4923/Stellit 6) meets all the manufacturer's requirements in terms of the amount of pores, cavities and cracks. The mixing required to form a metallurgical bond between the substrate and the cladding material takes place in a relatively small transition zone. A metallurgical perfect bond is generated between the layer and the substrate material (close-up, Fig. 6.). The profile of the hardened grain structure in the pan-head also fulfills the manufacturer's standards in terms of the properties needed for this specific application.

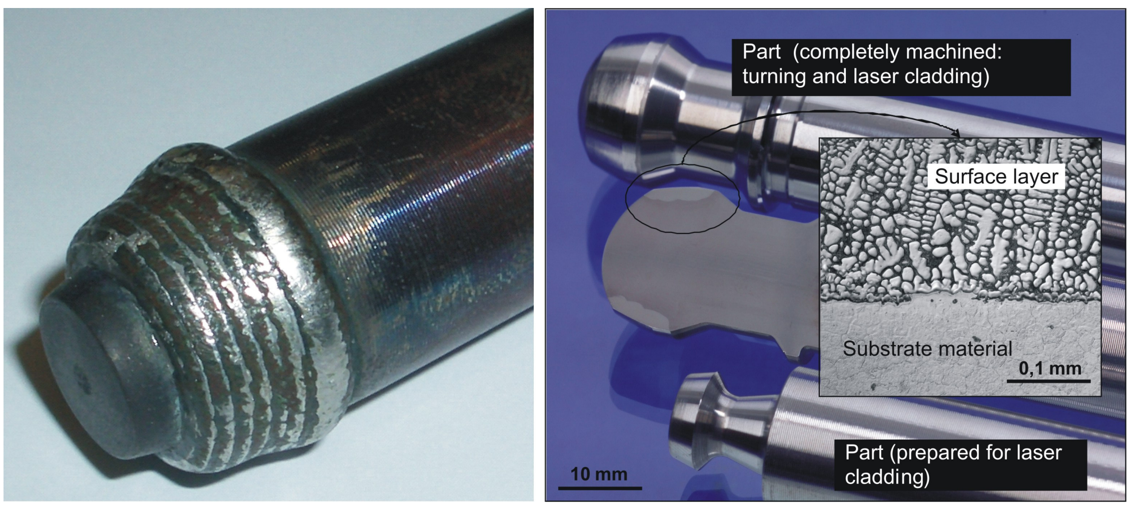

Fig. 6. Laser clad cone spindle (left), after machining (right)

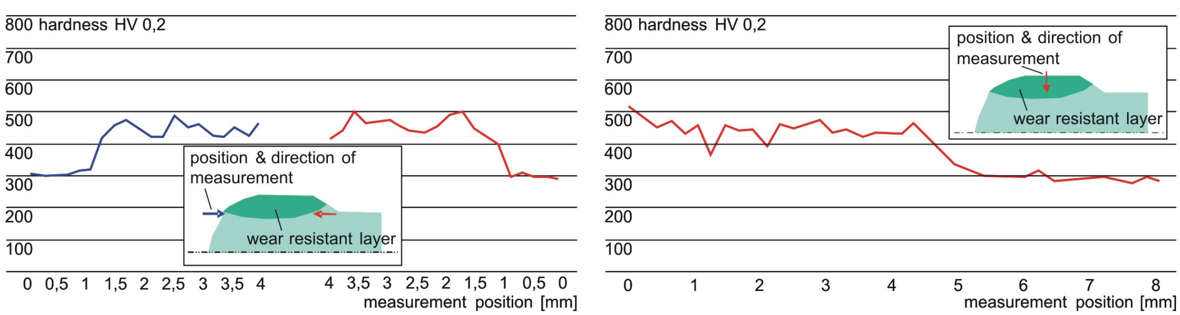

Fig. 7. Hardness of pan-head after laser cladding

The cladding is generated in a two-stage process. First, the laser heats up the pre-machined pan-head to 250 °C (the workpiece rotates while it is heated up). The cladding is then welded on, layer by layer. Before the next layer is welded on, the layer that was previously welded on is milled or lathed back to a defined height to remove any impurities and create the smooth surface topography (removal of ripples/undulations) needed for the wire-based laser cladding process. Compared to other cladding strategies, the ability of this automated machine to quickly change between laser tools and cutting tools means that any additional cutting is kept to an absolute minimum. After laser cladding, the component is subjected to the final machining stage in order to eliminate any warping. The pan-head is turned after heat treatment to give it its final geometry.

6.0 Economic Potentials

The first field tests in an industrial pilot application have shown that the newly developed machine generates added technological, economic and ecological value in the product value creation process (Fig. 8.). The use of this hybrid machine tool would lead to significant improvements in terms of throughput time and processing quality for a wide range of component parts that are currently produced in a series of conventional turning, milling and drilling, cladding and hardening operations with additional finishing (grinding, cutting after heat treatment). Typical examples of this type of parts are valves and control valves, pistons and shafts that are subject to high mechanical and/ or thermal load cycles. The sections of a component part that are subjected to particularly high loads (e.g. valve seats) are cladded or hardened with protective wear and corrosion resistant layers to prolong the service life of the entire component. The combination of conventional turning, milling and drilling operations with laser surface treatment in one hybrid machine tool makes it possible to perform all machining operations on the work piece without having to reclamp the work piece. The modular concept of the hybrid machine tool means that it can be customized to meet specific client requirements, safe in the knowledge that the laser processing units can not impair the conventional machining processes [5]. The »KombiMasch« machine tool offers the following technical and economical benefits:

- Shortening of production flow time as a result of the reductions in machining time, rigging time and storage time (Fig. 8.),
- Increase of machining flexibility of machine tools,
- Reduction of logistic efforts,
- Increase of product quality as a result of the integration of reliable and capable laser processing technologies,
- High amount of usability as a result of automated procedures.

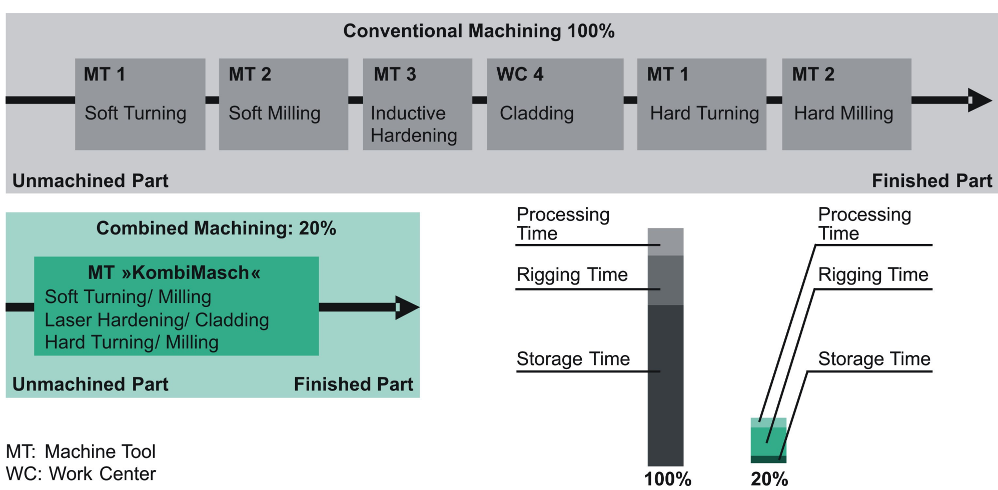

Fig. 8. Economic potentials

7.0 Conclusion

The combination of conventional turning, milling and drilling operations with laser surface treatment in one hybrid machine tool enables the complete machining of work pieces within a single clamping. For the first time two modularly mountable laser processing units for laser hardening and laser deposition welding based on a new combination of mechanical and optical interface to the machine tool have successfully been developed, built and tested. In comparison to former machine tools with integrated laser system technology, the »KombiMasch« system accomplishes the automated tool change of the laser processing units into the 4-axis milling spindle. By this, simultaneous 4-axis processes are possible with both the laser processes and the cutting processes. During mechanical processing, the two laser processing units are 'parked' outside of the machine's working area to protect the sensitive laser optics from the machine's vibrations, from material shavings or cooling lubricants. This layout also prevents the lasers from hindering the mechanical processes. The laser processing units, the laser source and the machine tool communicate via a profibus interface. The machine tool control is responsible for the central control function.

With the new machine tool components with laser treated surface areas have been manufactured in a fully-autometed process without any reclamping for the first time. The quality of the components in terms of form, shape and the characteristic of the laser welded and hardened rim zones is corresponding to the conventionally manufactured components. The rigging, machining and storage time have significantly been reduced.

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LASER PROCESS MONITORING: A CRITICAL REVIEW

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Abstract

Laser processes are nowadays well established sheet metal processing methods. Due to their high potential for industrial applications, the good product quality, resulting also in cost savings and enhanced productivity, laser processes are of high importance. The development of a reliable monitoring system evaluating quality on-line, provides a solution to this problem.

Thus, it is essential that advanced monitoring systems be developed in order for the requirements of laser processing to be fulfilled. The current work reviews the laser process monitoring systems that have been developed so far. Requirements and characteristics of laser processing that influence product quality are described. Sensorial information from several sensors is compared and analyzed. Methods of the most important monitoring of laser processes, applications and strategies are reviewed and evaluated in the current work.

Keywords: Laser processes, Monitoring, On-line quality evaluation

1.0 Introduction

Laser processes are thermal in which a focused laser beam of high energy intensity is used for heating and even melting the material in order to be machined. Due to their unique characteristics laser processes have met great response in industry ([1]):

- The effectiveness of laser machining depends upon the thermal properties and, to a certain extent, the optical rather than the mechanical properties of the material to be machined. Therefore, materials that are difficult to be machined, due to their high degree of hardeness or brittleness, can be processed easily with laser manufacturing techniques if their thermal properties are favorable.
- Since energy transfer between the laser and the material occurs through irradiation, no cutting forces are generated by the laser, leading to the absence of mechanically-induced material damage, tool wear and

machine vibration. Moreover, the material removal rate for laser machining is not limited by constraints such as maximum tool force, built-up edge formation or tool chatter.

- When combined with a multi-axis workpiece positioning system or robot, the laser beam can be used for drilling, cutting, grooving, welding, and heat treating processes on a single machine. This flexibility eliminates the transportation necessary for processing parts with a set of specialized machines. In addition, laser machining can result in higher precision and smaller kerf widths or hole diameters than other comparable mechanical techniques do.

Despite the very important advantages of laser processes, the result of this one could be influenced by a number of factors such as, defects in the microstructure of the material, contaminants on the workpiece surface, alteration on laser beam properties, etc. resulting in a non-acceptable product (Fig. 1). For that reason, the surveilance of the process is very important in order for the requested quality of the product to be assured, as well as for the efficiency of the process itself, especially if it is part of a mass production sequence.

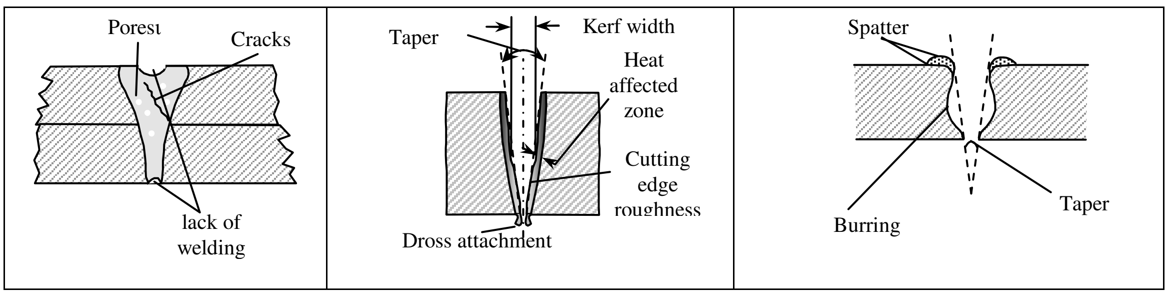


Fig. 1. possible defects in laser welding, laser cutting and laser drilling processes.

The accurate control of a laser process can be accomplished by ensuring that the process parameters are in a ceftified range of specifications. Furthermore, the ability to detect defects that occur during processing and the valid change of the process parameters values, play important role in assuring the pre-defined quality standards. Monitoring of a process, and consequently its control, can be categorized, based on the time accomplished, into three stages (Fig. 2):

- Pre-process
- In-process
- Post-process

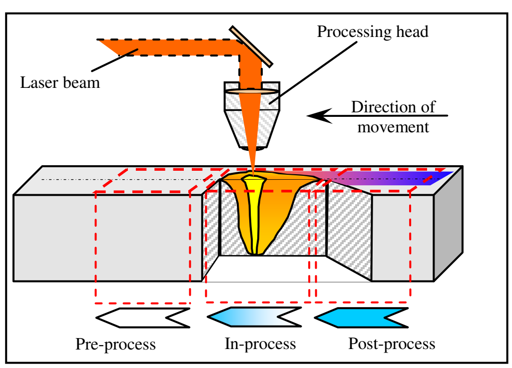


Fig. 2. Classification of monitoring stages based in the time accomplished [2].

The in-process monitoring, is very important due to the fact that it enables the control of the process without stopping it and uses destructive methods for the evaluation of the product quality, a fact that is of high importance to industrial applications.

2.0 Laser Welding, Cutting and Drilling Monitoring Techniques

In-line monitoring of the process is accomplished by the acquisition and evaluation of various indicators that can be detected during the process. Optical and acoustical emissions as well as temperature related data can be measured with the use of the appropriate sensors. These signals are a result of the laser-material interaction and thus, carry information of the process and can be used for monitoring purposes. Methods and systems that have been developed, for laser process monitoring, can be classified based on the signal type that is acquired:

- Monitoring using optical signals utilizing CMOS, CCD cameras and photodetectors.
- Monitoring using acoustical signals utilizing microphones and acoustic emission (AE) sensors
- Monitoring using temperature-based, electrical and other type of data.

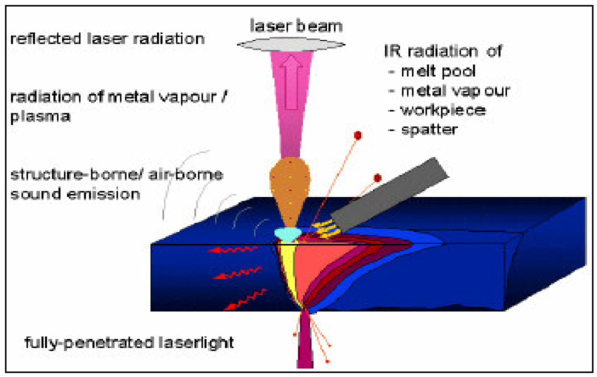


Fig. 3. Typical process emissions during laser material processing [2].

2.1 Process Monitoring using Optical Signals

An optical detector, particularly ultraviolet (UV), visible or infrared (IR) detectors, have been widely used for converting the flux density of the radiation, emitted by the welding process into an electrical signal. An optical filter is often placed in front of the detector to confine the spectral ranges of the whole sensor system. Typical setups using co-axial and off-axial arrangements are illustrated in (Fig. 4)

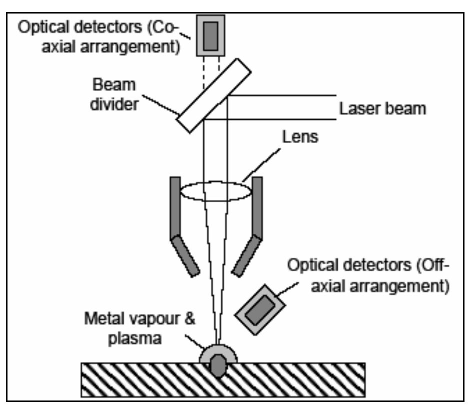
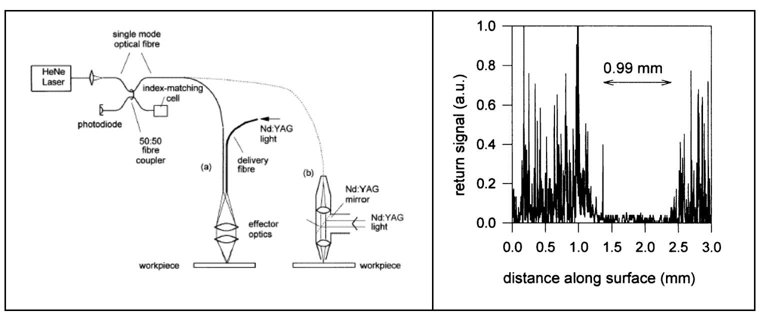


Fig. 4. Typical setups for optical detectors using co-axial and off-axial arrangements [3].

In ([4]), the measured signals were used for the development of prototypes, used for the detection of geometrical defects in laser welding area. In ([5], [8], [9]) the optical signals acquired from the interaction zone were analyzed in order to be correlated with those of the welding depth and its defects. Furthermore, in studies ([10], [11]), the acquired photodiode signals were used in order for the relationship among the plasma, the spatter and the bead shape to be clarified according to the welding variables. Through a correlation between these signals and the weld quality, there were a multiple regression analysis and a neural network developed for the estimation of the weld bead's penetration depth and width. In laser processing systems, using a fiber optical fiber for the delivery of the laser beam, the reflected energy is collected from the output lenses and from that re-launched back into the fibre. In ([24]), a method of monitoring the laser drilling and cutting processes, based on the energy reflected and re-launched back into the fiber, has been presented. It was observed that the amount of the radiation reflected could be used in order for the difference between successful and unsuccessful machining to be detected. In studies ([25], [26]), the monitoring of the surface plasma and measurement of the emitted light from the cutting front, respectively, were used for the determination of the cutting quality and the morphology of the cutting edge. It was observed that the wave frequency of the signal carried information concerning the striations formed in the cutting edge. In study ([27]), a technique, using a simple confocal sensor arrangement, based on a single-mode optical fibre for measuring the hole's diameter at high speed, was presented. Light from a low-power He-Ne laser source is launched into a single-mode fibre and guided to a 50:50, coupler, where its amplitude is divided. In order for the diameter to be measured, the focused spot from the He-Ne laser is traversed across the hole and a dropping out of the signal is observed. This is converted into a diameter measurement provided that the spot is traversing at a constant speed.



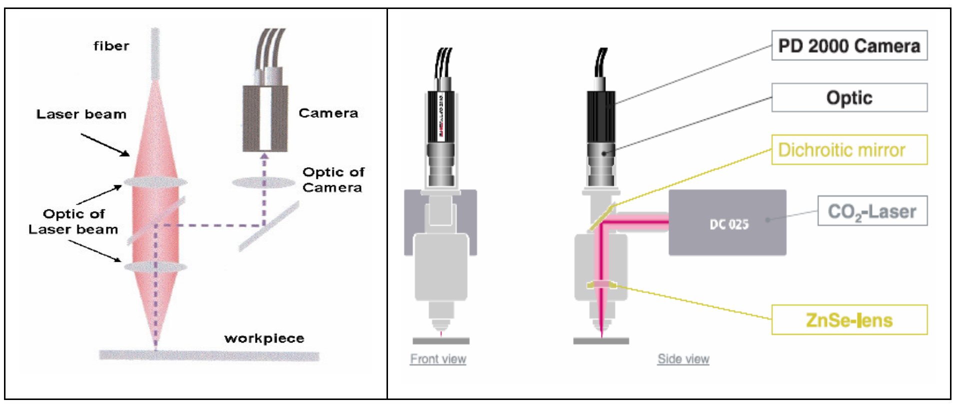
(a) (b)

Fig. 5. (a) The fibre-optic based measurement system and (b) measurement of hole formed by a fibre beam delivery system [27].

Apart from the photodiodes, various types of cameras have been used for capturing images from the processing zone. In [12], a monitoring procedure of the laser welding process was outlined, as an element of an integrated automotive panel production system. The system developed measures each welding bead on – line and in – process, in the following procedure. Immediately after the butt – welding, with the use of CO_2 laser, the welding bead is irradiated at a right angle to the bead direction and with a slit light of a semiconductor laser, in an oblique position above the bead. The light reflected from the bead is photographed by a TV camera, positioned directly above the bead and two – dimensional monochromatic image data, is obtained for the section of the welding bead. The slit light cutting line is extracted from this image data to convert it into waveform data. This data is processed in a computer to obtain five bead configurational data (swell, step, width, inclination and dent). Finally, this data is compared with specified reference ones in order for the welding quality to be assessed.

A real – time system was developed to process the image of the weld pool in [13] . In this study, a polar coordinate model was constructed to characterize the weld pool geometrically. The identification of the weld pool parameters was made with the use of a neural network. An accurate boundary of the weld pool was acquired with the use of a camera viewing the weld pool region at a 45o angle from the rear of the weld pool and a pulsed laser illumination. A fast image – processing algorithm was also developed to extract the boundary of the weld pool in real time.

Additionally, in ([14], [15]) there was a system presented for laser welding and laser cutting process monitoring with a CMOS camera, which observed the process, in a coaxial and centered to the laser beam position. The software of the camera evaluates online different failures and process parameters with the help of characteristic regions within the image of the camera and the recorded film is also used for analyzing the process and improving the process parameters. The systems have been used in industrial applications ([15], [16]).



(a) Laser welding (b) Laser cutting

Fig. 6. Monitoring system for (a) laser welding and (b) laser cutting ([14]- [16])

In ([21], [22]) a CCD camera was used for recording the magnitude of the irradiance emitted from the cut front and the shape of the erupted sparks in laser cutting and the images captured were used for the evaluation of the cutting quality and the on-line control of the process. A CCD camera was also used for monitoring the laser cutting process under study [23]. The imaging of the IR radiation, obtained with the CCD camera of the Coaxial Process Control, can be interpreted by comparing it with the thermal emission as calculated from the dynamical model and correlated with quality characteristics, such as the dross attachment and cutting edge's striations.

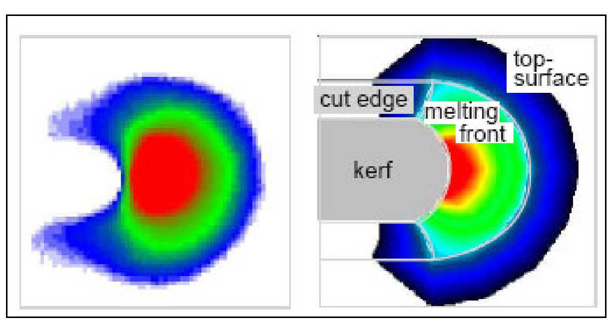


Fig. 7. (a) CCD image as recorded and (b) Simulation of the model [23].

2.2 Process Monitoring using Acoustic Signals

Process monitoring through acoustic signals involves a sensor that converts, in a measurable variable, the process sounds into electrical output. In -Process monitoring through acoustic emissions involves a microphone, placed nearby the processing zone to measure air-borne emissions or a piezoelectric transducer, mounted at an acoustic mirror, acoustic nozzle and workpiece for measuring structure born emissions.

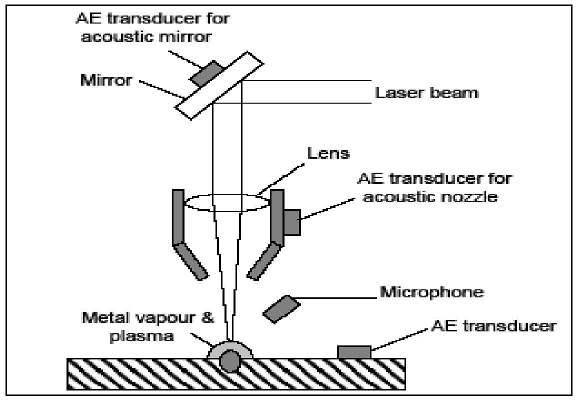


Fig. 8. Typical setup for acoustic emissions [3].

In [17], an attempt to determine a link between air-borne acoustic emission signals and weld characteristics was accomplished. Acoustic emissions when spectrally resolved into a power spectrum of 20 1 kHz sub-bands between 20 Hz and 20 kHz showed a distinctive frequency distribution under different welding conditions. It was shown that a comparison between the sum of a squared standard deviation over these 20 sub-bands with a standard result is capable of indicating weld quality. Furthermore, in studies ([18], [19]), optical and air-borne acoustic emissions during laser welding were acquired with the use of a photodiode and microphone. Results indicated that the keyhole and its surrounding liquid layer acted as a frequency selective amplifier for pressure fluctuations induced by changes in the interaction of the laser radiation with the walls of the keyhole ([18]). The optical emission was predicted to be increasing almost linearly with initial vapour flow rate and it was of the same magnitude as the measured emissions. The plume acoustic emission was predicted by considering the volume of ambient air displacement, required by the outflow of the vapour coming out from the laser weld keyhole. The analysis predicted that the plume acoustic emission should vary, as the time derivative of the vapour flow rate, and hence, as the time derivative of the optical signal ([19]).

One of the first studies of using air-borne acoustic emissions for monitoring the laser drilling process, was presented in [28] and results have shown that the acoustic signal is proportional to the thermal energy liberated during the combustion process and consequently, it depends on the amount of the combustible material ablated. An experimental investigation on laser drilling and laser grooving processes in ([29] - [31]), utilized the acoustic waves, generated during the impingement of the gas jet on the erosion front. Results indicated an inverse relationship between the depth of cut and the resonant frequency of grooving, cutting and drilling.

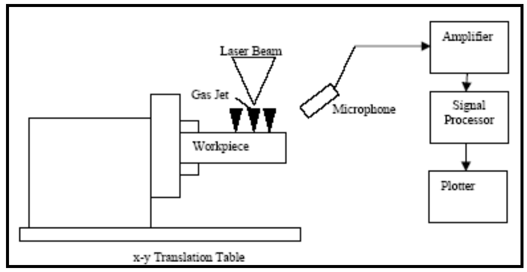


Fig. 9. Experimental setup for laser drilling and laser grooving monitoring using air-borne acoustic emissions ([30], [31]).

In study [32], an attempt was made to clarify the frequency characteristics of the laser processing sound by calculation, in which experimental data of the laser drilling with a single pulse laser beam was used, when a continuous pulse laser beam was assumed to be used for laser grooving, and for comparing the calculated frequency characteristics with the experimental characteristics. In this research, sound frequencies of up to only 20 kHz were monitored with a microphone. Furthermore, in [33], an attempt was presented to determine a link between the strength of processing sound and the groove cross-sectional area per pulse, when a processing condition and a work material is changed. Results indicated that the cross-section of material removed can be calculated by measuring the strength of the processing sound.

Finally, in [34], the influence of laser pulse shape on the laser drilling process and on the optoacoustic effect was studied for two laser applications: laser drilling in aluminium and laser drilling in hard dental tissues are presented. Results confirm that the laser pulse shape might have a significant influence on the interaction processes and can be used for increasing machining efficiencies whilst the optoacoustic signals are found to be depending on the laser pulse shape

2.3 Process Monitoring using Temperature and other Measurements

In study [6], temperature measurements, inside and near the weld pool during the laser welding process, were presented. The temperature fields inside the material are determined with thermocouples and on its surface are determined by the use of a charge coupled device (CCD) camera with infrared filters. The laser welding experiments were performed on austenitic stainless steel with the purpose of using the determined thermal fields as a database to calibrate a finite element simulation of the process. In [7], a sensor system is presented for monitoring the misalignment of the edges and undercuts during the laser welding. The principle that the sensor is based on is the measurement of the distribution of the heat radiation from the weld pool. This system consists of three sensors, one positioned to the left of the weld pool, one to the right and one as a reference sensor directly above the weld pool, which detects the heat radiation from the weld pool. From these data the power received can be calculated by each sensor, the misalignment as well as the undercut.

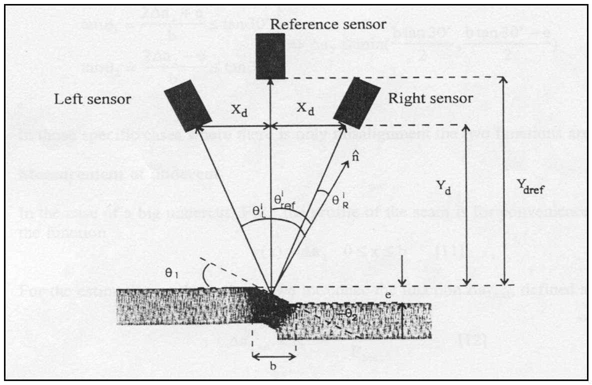


Fig. 10. Sensor arrangement for monitoring system in [7].

In study [35], a monitoring system for the laser welding process that utilizes a plasma charge sensor, was presented. The plasma behaviour has been observed during welding through measuring the space charge voltage induced on an electrically insulated welding nozzle, the plasma charge sensor (PCS). It was shown both theoretically and experimentally that the induced voltage is a measure of plasma temperature and thus, of the welding performance. In particular, the results have indicated, under laboratory conditions, that the PCS signal can measure the weld penetration and detect a wide range of weld defects.

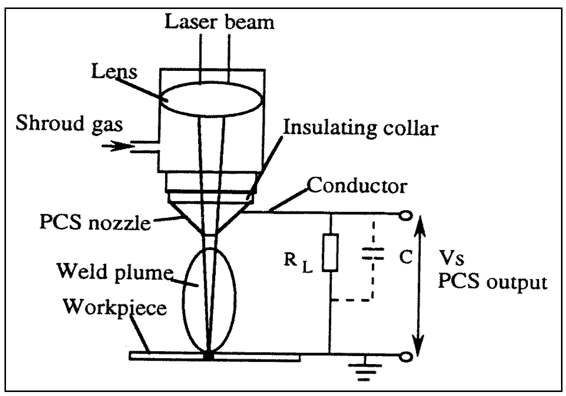
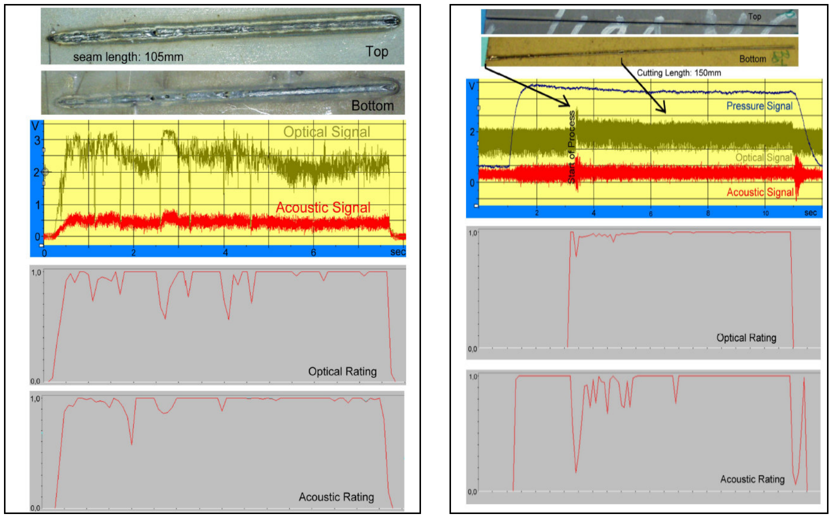


Fig. 11. Basic configuration of Plasma Charge Senor (PCS) [35].

2.4 Process Monitoring using Multiple Sensors

It has been demonstrated that combinations of different types of sensors, such as the photodiode and the electronic camera, or the photodiode and the microphone, or combinations of photodiode and filter arrangements being sensitive either to the IR, VIS or UV spectral region, sometimes aiming at different parts of the interaction zone, give an increased significance for the detection and classification of treatment faults, and at the same time, reduce the false alarm probability by, e.g., correlation-based signal assessment methods [36]. In [37], an approach with additional sensors and advanced evaluation methods has been investigated. The goal was to create flexible algorithms that can be used for the observation of laser welding as well as laser cutting. The signals from the optical and acoustic detector are processed by statistical methods immediately after they have been acquired. Short time mean values, standard deviations, derivatives and histograms are calculated from the data of both sources separately. After this first analysis, there is a statistical set of data for each method and sensor. In the second stage, the fuzzy part of the analysis was designed to process the statistical results. This concept allows for a fault classification and a highly reliable and easy to interpret evaluation. The outcome is reference free and is not based on measurement units.



a) Laser cutting b) Laser welding

Fig. 12. Cutting and welding example with corresponding signals and overall fuzzy ratings [37].

The relationship between airborne acoustic and optical emissions from the laser welding process is described in [38]. The emissions were measured with the use of a microphone and a photodiode during laser welding experiments. A thorough investigation of the signals recorded has revealed them to be highly related at a phase shift corresponding to the delay time for sound to propagate from the weld area to the microphone. A model was constructed which predicted the acoustic signal from light signal measurements. It was shown that the acoustic signals predicted, corresponded fairly well to the experimental acoustic data. The relationship between the signals has revealed that the sound pressure predictions were proportional to the time derivative of the light signal samples.

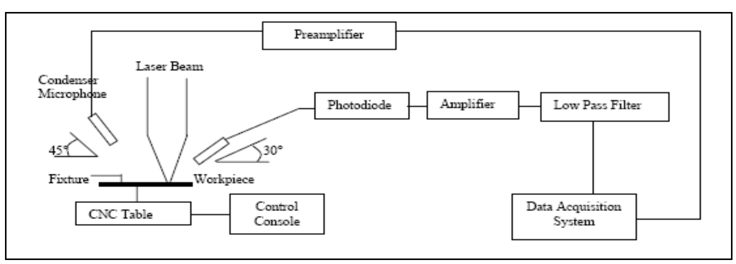


Fig. 13. Experimental setup for laser welding monitoring using acoustic and optical signals [38].

3.0 Conclusion

In the present work, a review of the surveillance techniques and methodologies for the most potentially laser processing techniques, including laser welding, laser cutting and laser drilling, has been presented. As it was shown, process information can be obtained by measuring and characterizing the various forms of energy that propagates from the laser material interaction site. Electromagnetic radiation and acoustic waves, air-borne or structure-borne, are two of the most significant signals that can be used for extracting information regarding process' evolution and characteristics and can be acquired using co-axial of even off-axial sensors' arrangement. Optical signals can be acquired using appropriate sensors, such as photodetectors or cameras, while acoustical signal using microphones or piezoelectric sensors.

To keep pace with the demands of the production industry, such as cost, quality and functionality, future systems of the laser process monitoring and control have to provide a further increasing level of speed, reliability and flexibility. Something that could be accomplished by real-time signal assessment systems, fed by extended reference and calibration data files, a-priori defined and/or self-generated for specific treatment situations, and by the on-line acquired signals of integrated multi-sensor fusion setups. Future monitoring systems need also to be more user-friendly, incorporating standardized user interfaces and increased functionality (self-testing, automated fault detection and correction actions, etc.), in order to be easily accommodated from industrial users.

Acknowledgement

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A NOVEL ARCHITECTURE FOR A RECONFIGURABLE MICRO MACHINING CELL

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Abstract

There is a growing demand for machine tools that are specifically designed for the manufacture of micro-scale components. Such machine tools are integrated into flexible micro-manufacturing systems. Design objectives for such tools include energy efficiency, small footprint and importantly flexibility, with the ability to easily reconfigure the manufacturing system in response to process requirements and product demands. Such systems find application in medical, photonics, automotive and electronic industries.

In this paper, a new architecture for a reconfigurable micro manufacturing system is presented. The proposed architecture comprises a micro manufacturing cell with the key design feature being a hexagonal-base on which three tool heads can be attached to three of its sides. Each such machine-tool head, or processing module, is able to perform a different manufacturing process. These tool heads are interchangeable, enabling the cell to be configured to process a wide range of components with different materials, dimensions, tolerances and specification. Additional components of the cell include manipulation robots and an automated buffer unit. Such cells can be integrated into a manufacturing system via a modular conveyor belt to transfer parts from one cell to another and into assembly. A key consideration of the architecture is a control system that is also modular and reconfigurable; such that when new processing modules are introduced the control system is aware of the change and adjusts accordingly. Further to this coordination, issues between modules and machining cells are also considered. Other design considerations include work-piece holding and manipulation.

This paper provides an overview of the architecture, the key design and implementation challenges as well as a high level operational performance assessment by means of a discrete event simulation model of the micro factory cell.

Keywords: micro manufacturing, reconfigurable manufacturing, flexible manufacturing system.

1.0 Introduction

The idea of producing a flexible Microfactory cell started to arise due to the needs of producing small machined parts using more efficient manufacturing systems and techniques. Therefore, it was necessary to come up with platforms that were suitable for producing micro-size parts. This idea, which developed during the 1990s, had several advantages, such as better use of resources including time, energy and space [1]. Besides this, micro-factories can be represented as fully automated units, which will result in higher precision and productivity levels, and less human involvement during any process. The concept of micro-factory has become essential in a number of industries that require a high level of precision and detail such as semiconductors, microprocessors medical parts (hearing aids) and electronics based industries. Due to the increasing dependence on consumer electronics and IT peripherals, these sectors are expected to continue to dominate micro-technology while other areas like automotives will see a significant decrease.

This concept considers the possibility of offering more than one process or function to be conducted using a micro-factory unit, and since manufacturing systems usually face changes in functions and production methods, it was necessary to develop the current concept of micro-factory to satisfy these changes and configurations by creating reconfigurable micro-factory platforms and modules that could be adjusted in order to perform more than one functionality and production capacity [2]. These recent developments in the micro-factory concept can provide a wider range of products that can be produced by only one platform, which is also a cost effective process because fewer resources will be consumed during each process. In this paper, an overview of the architecture will be presented, followed by a detailed description of the system parts. Then, an operational performance assessment will be addressed in order to validate the design properties.

2.0 Architecture Overview

A new concept of microfactory is presented in this paper, based on satisfying certain objectives, including designing a novel architecture of an easily-reconfigure machining cell that is capable of processing and handling a wide range of micro-component materials within a small footprint and with more energy efficiency. The purpose of designing such a system is to increase the productivity level by performing several machining processes simultaneously, reducing the set-up time of machining tools, and reducing the material handling process as well.

2.1 Proposed Architecture

The proposed architecture consists of three key components: a machining module, a material handling platform and the control system (Figure.1). These individual components will work in collaboration within the system to deliver the final product. With regards to the machining module, this was designed to have a hexagonal-shaped body and three tool-heads attached to each side. The body is based on a similar shape rotating base which has three workpiece holding fixtures fixed to all three of its sides. This module is responsible for holding raw materials and performing the required machining processes on them. The material handling platform consists of a number of units such as: the cylindrical robot-arm, a buffer unit, and a material transfer belt. This platform transfers micro-components to the machining modules as raw materials, and places them using the robot-arm, onto the holding fixtures, enabling the tool-heads to perform the required machining processes on them. Afterward, the same arm will pick up the workpiece, as finished goods, in order to place them on the transfer belt which will move these materials to the buffer unit. All these activities will be managed by a dedicated control system in order to obtain an improved work environment. This architecture has a footprint of 2300 mm (w), 1190 mm (h), which means that all the system's components will fit within this area.

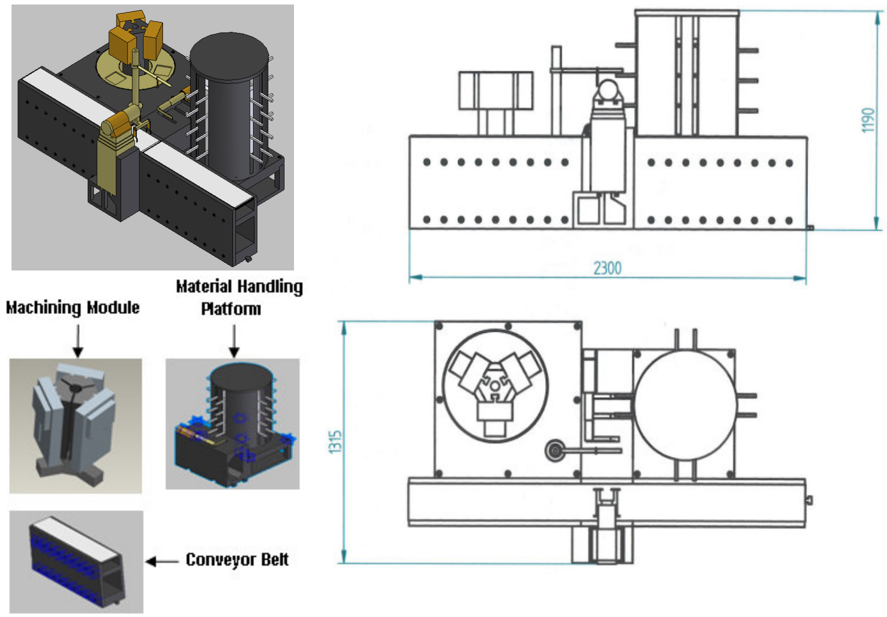

Fig.1. General view of the microfactory cell, showing main components and dimensions in millimetres (mm).

3.0 Key Design and Implementation Challenges

During the design stage of this system, several design and implementation issues have been taken into consideration including: the effect of operating three tool-heads simultaneously, maintaining the lowest level of vibration during each machining stage, and changing tool-heads smoothly. Each one of these issues has been resolved using designing, operating and controlling approaches.

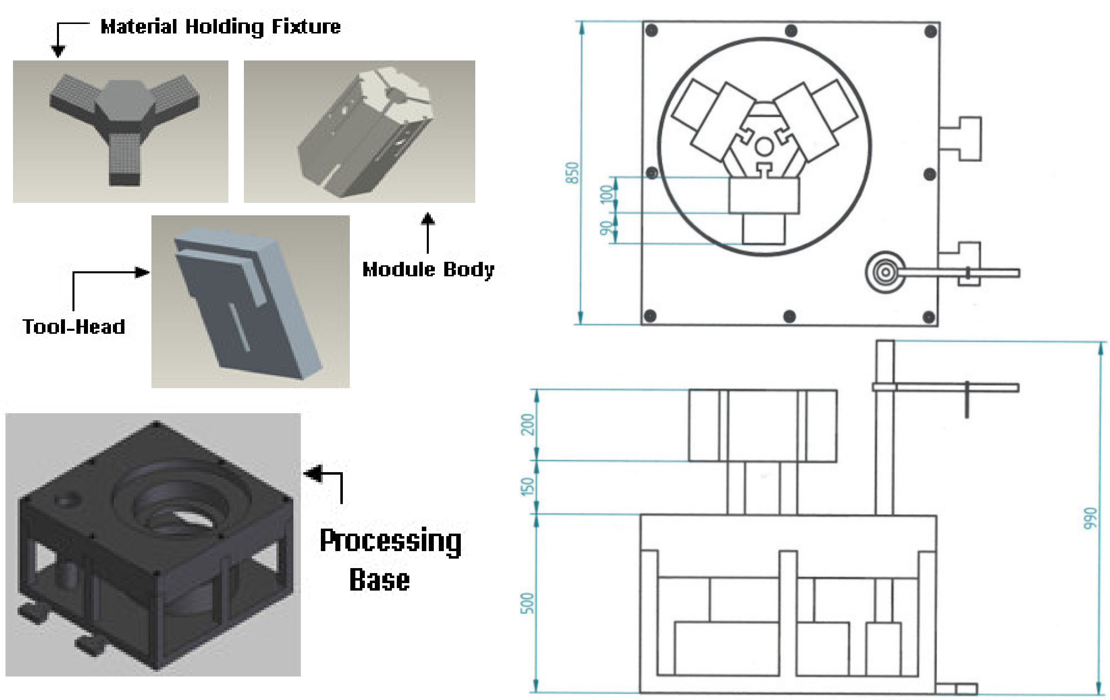

Fig.2. General and detailed views of the proposed machining module, including dimensions, in millimetres (mm).

3.1 Hexagonal Body

Fig.3. Top and general views of the module's hexagonal body.

Starting with the machining module, which represents the core of this system (Figure.2), the main body is designed to have a hexagonal shape (Figure.3). Moreover, the reason for choosing a hexagonal-shape is because it allows the fitting of three tool-heads on its outer sides. Also, it provides increased weight distribution and balance between the module's parts, since the module's body has a symmetric design, which means that all tool-heads will have the same design and properties, and the distance between each tool-head and the other will be precisely the same. Therefore, any physical contact between the tool-heads will be avoided. Moreover, this body contains vibration isolation gaps which separate the three tool heads from each other. The purpose of this feature is to increase the isolation level between tool-heads in order to improve the level of accuracy in the system.

3.2 The Module's Base

The previous hexagonal body is based on a similar hexagonal base with three fixtures attached to its sides. This base represents the moving part of the module which rotates in order to place each fixture under one of the tool-heads (Figure.4). Also, the hexagonal part of the base contains a damping system which is used to reduce the vibration of the module's body during each machining stage. The attached three fixtures have been designed based on a modular concept which increases the system's flexibility and reduces the required set-up time. The design of these fixtures allows jaws and clamps to move automatically to hold the workpiece. This technique is crucial in this cell due to the variety of the workpiece design, size and material.

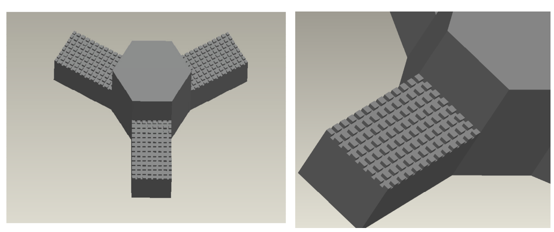

Fig.4. Views of the base unit and material holding fixtures

3.3 Tool-Heads

The three tool-heads in this module share an identical *BASE* structure including design, dimensions and material. However, the machining tools will vary due to the machining nature of each process. According to the module's re-configurability, this design should allow the operator to change each one of these tools with another new tool. The module's body has been designed to provide better physical and electrical contact with each tool, it contains two rectangular cavities that allow the tools base unit to slide and connect to the module's body. The circular connector between the two cavities is an air-suction unit, while the third part is a rectangular power connector. The mechanism of this assembly process is simple; first, the tool will slide into the body's two assembly paths that have a similar structure which matches the body's features. Then, as soon as the power connector in the module is connected to the power socket in the tool, the suction unit will work using a vacuum-mechanism to guarantee that both parts are well-connected and they can perform the designated process. The same procedures can be applied on the other two tools in order to have the final completed module.

3.4 Machining Processes

In order to present a wide range of produced parts, three different processes have been chosen to be performed in this Microfactory system: Micro EDM-Milling, Micro EDM-Drilling, and Laser Machining. The reason for choosing these processes can be justified; Electrical Discharge Machining can be miniaturized and fitted to Microsystems due to their simple mechanical setup and design [3], which can provide high efficiency and space saving opportunities. Moreover, Micro-EDMs have a number of advantages over other machining processes, such as cutting and drilling, because they are a non-contact machining technique using thermal energy like plasma, allowing it the capability to produce high precision products with much less tool breakage problems. The main concept of this technique is machining complex shapes using high speed rotation of a simple shaped electrode [4]. Laser technology has always been capable of providing top-class machining on small scale, due to the wide range of its application, such as engraving and surface finishing [5]. This technology can also be used with several types of material such as metals, ceramics, polymers and silicon.

4.0 Design Analysis of Machining Module

An initial dynamic FEA model has been developed to examine the dynamics of the machining module. Several inputs have been assumed at this stage of design: Motor speed (3000 rpm or 50 Hz), module's material (Granite body, Steel tool-heads, and cast iron base), and Base Damping (2%). At this stage, we assumed that the damping level of the base is equal to natural damping in order to examine the limits of this design. Based on this analysis, six natural frequencies have been observed: 121.6 Hz, 125.2 Hz, 128.3 Hz, 210 Hz, 212 Hz and 234.7 Hz (values higher than 234.7 Hz have been ignored due to their insignificance to the design). Figure 5 shows the reaction of the module during each one of the above natural frequencies.

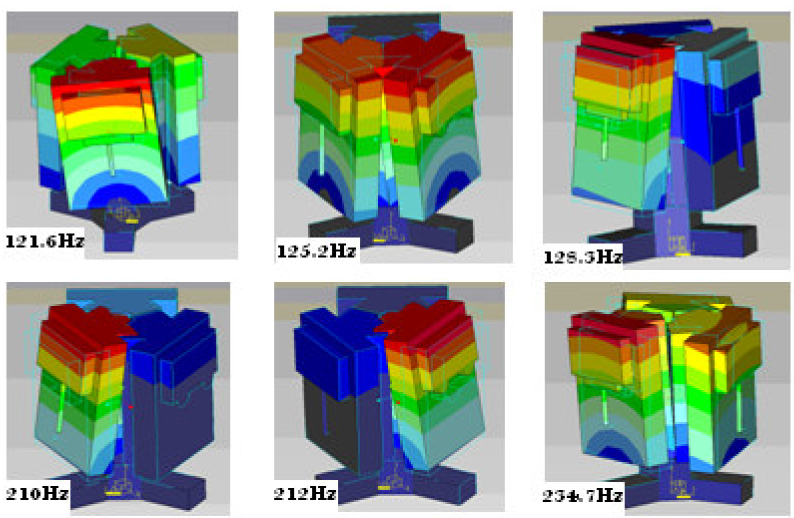

Fig.5. The module's reaction to six natural frequencies.

Moreover, based on these natural frequencies, both dynamic displacement and stress have been calculated. Additionally, according to these calculations (figure.6), two peaks have generated on frequencies (125.2 Hz) and (234.7 Hz). However, the module has an acceptable dynamic structure since both levels are low in considering the damping level of the hexagonal base. This is an important step in the design process due to the level of accuracy required during the machining stage.

5.0 Material Handling Platform

The other main part of the system, which is the platform, is in charge of material handling within this system. Furthermore, the control system will be considered as part of this platform due to its position in the system's layout.

5.1 Control Unit

The control unit will be mainly responsible for controlling the overall movement and function of the machine. This includes: activating the different parts on the cell that include the pumps and motors, controlling the mechanical parts in the system including fixtures, Grippers, and movement/operation of the tools. Connecting this unit to a database will be essential in monitoring the system's performance and use of the collected data to improve the system in the future.

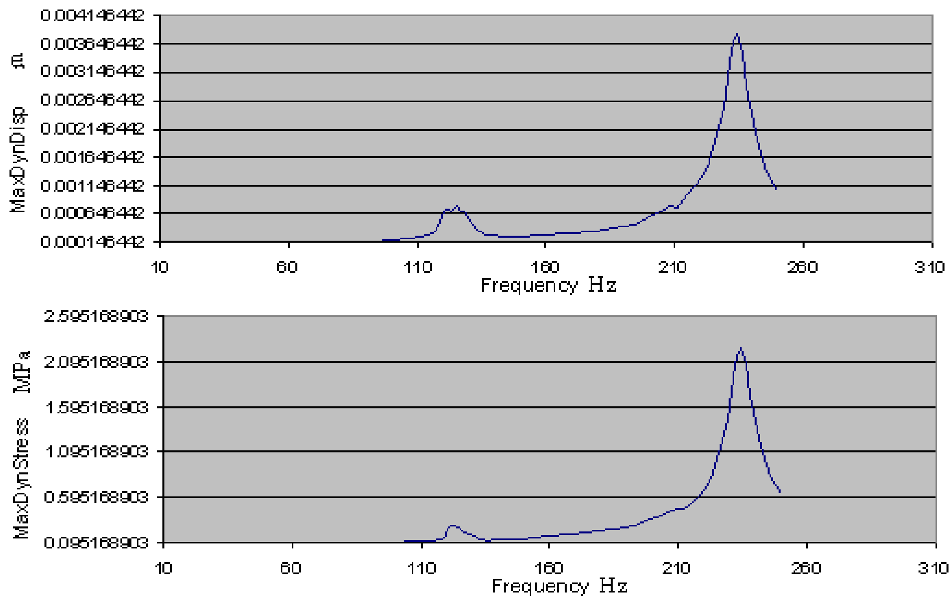

Fig.6. Dynamic displacement and stress Vs. Frequency.

5.2 Material Transfer Module

An automated mechanism is needed to be designed to transport material from one machine to another. From the mechanism's viewpoint, the material will be transported using a standard pallet. Thus, the simplest method would be the use of conveyor belts with appropriate width to accommodate the pallets. The module (Figure.7) would be built in standard sizes that could then be connected to each other in the desired layout.

5.3 Buffer Module

This module is aimed to temporarily store work-in-progress (WIP) by acting as a buffer between cells. The cell layout is supposed to be linked with a number of other similar cells that will provide the complete process line for mass manufacturing. It is expected that some machines will perform slower than others, or that there will be different components that will require different processes. This means that one cell would need to handle more than one pallet at a time in order to free the conveyor belt for other passing pallets. For this reason this module has been designed (Figure.8) to temporarily store WIP and retrieve it when the processing module is available, then transfer finished pallets back onto the conveyor belt.

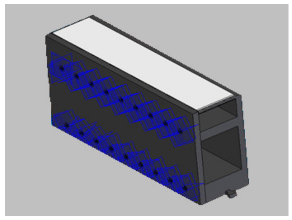

Fig.7. Conveyor Belt Module

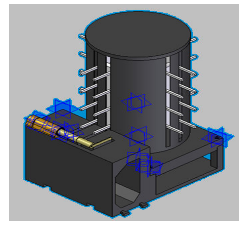

Fig.8. Complete Buffering Module

5.4 Cylindrical Robot-Arm

A cylindrical robot is employed, as shown in Figure.9, to pick and place components from the pallet to the holding fixtures, and vice versa. The robot chosen for this application is a simple 'cylindrical robot' which is usually a custom made item. The one shown in the figure below is merely a structure to show its position and the robot's main components.

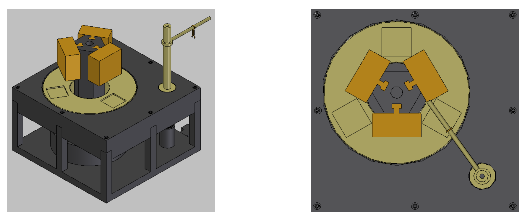

Fig.9. General and Top view of the Robotic-arm position

6.0 Operational Performance Assessment

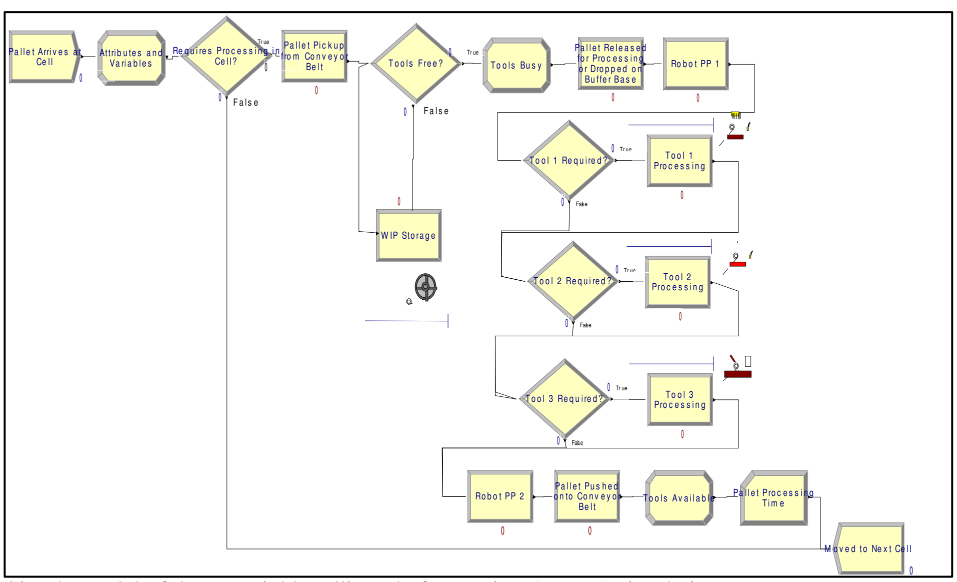

Fig.10. Simple model of the material handling platform using ARENA simulation.

Following the completion of the design it was important to perform an initial test in order to examine operational performance of the cell. A simulation model using *ARENA* [6] has been developed (Figure.10) to offer a simple demonstration of the machine's behaviour, since all timings are estimated values, as the actual machine is just a design that hasn't been manufactured yet (Table. I). However, the simulation provides some idea of what parameters the machine will run on and most importantly an estimated pallet processing time.

The aim of the simulation is mainly to understand the operational performance of the cell. This is measured in terms of queuing and utilization of resources. In figure 11, the work in progress (WIP) buffer is showing the highest utilization. Also, queues were only observed by the simulation model in the buffer and no other queues were observed in the system. This initial result confirms that there is no other build-up of queues anywhere else in the system, and enables simpler operational control of the cell as scheduling needs only to be concerned with controlling the queue in the WIP buffer. The second most utilized are the tools as they are also always in operation, but only handle one pallet at a time. The other processes show much less utilization since they are used much less relative to the WIP storage unit and tools. Results from the simulation also show that on average a pallet takes 6.5 minutes to exit the cell, recording a maximum time of 10.2 minutes and a minimum of 3.9 minutes. Results are in the expected range given the total lengths of time for processing, storage and transportation entered. Moreover, this run also shows that WIP storage is the only unit in the system that stores pallets.

TABLE I. Input Parameters

Resource	Input	Units
Pallet arrives at cell	Constant distribution {0.7}	Min per Pallet
Pallet pickup from belt	Triangular distribution {0.05,0.08,0.08}	Min per Pallet
WIP storage	Constant distribution {0.2}	Min per Pallet
Pallet released for processing	Constant distribution {0.3}	Min per Pallet
Component placed on fixtures by Robot-arm	Triangular distribution {0.3,0.4,0.5}	Min per Pallet
Total process time	Triangular distribution {2.5,3.1,3.7}	Min per Pallet
Tool 1(Micro EDM-Drilling)	Triangular distribution {0.3,0.5,0.7}	Min per component
Tool 2 (Micro EDM-Milling)	Triangular distribution {0.7,0.9,1.1}	Min per component
Tool 3 (Laser Machining)	Triangular distribution {1.5,1.7,1.9}	Min per component
Component picked up from fixtures by Robot-arm	Triangular distribution {0.3,0.4,0.5}	Min per Pallet
Pallet pushed onto belt by pushing unit	Constant distribution {0.5}	Min per Pallet

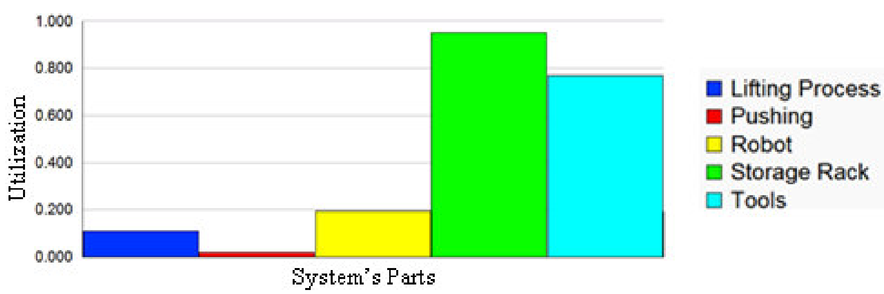

Fig.11. Resource utilization graph

7.0 Conclusion and Future Work

In this paper, we presented the initial design of a reconfigurable micromachining cell and discussed the design considerations of its key components. These include a hexagonal-base with modular fixtures, interchangeable toll-heads for performing a variety of processes, work-piece manipulation and work in progress storage components, and an adaptable control system. Flexibility, re-configurability and a small footprint have been the key design goals considered in this development. This entails that various complements of our cell to be assembled together in a variety of combinations and different layouts into a complete micro-factory, and reconfigure these cells by adding or replacing processes to accommodate production demands as these change.

Our approach in this development is iterative. In this paper, focus was on the presentation of the conceptual architecture design of our micro-manufacturing cell, including the results of our preliminary dynamic FEA analysis of the processing module and the operational performance of the whole cell with simulation. These results confirmed several of our design goals and allowed further progress of this development. The next step in our development is to elaborate this architecture more with detailed design specifications, including detailed FEA modelling of the cell. Then, we aim to build a prototype based on that specification. Further considerations that must still be addressed include the control system, which itself must also be dynamic and flexible entailing a "plug and play" approach, and the design of fixtures.

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IMPACT OF HEAT TRANSFER ON FEMTOSECOND LASER MICROMACHINING

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Abstract

Femtosecond laser cutting on glass is investigated using 150 fs pulses with a center wavelength of 800 nm. Experiments have revealed that heat transfer in the stuff resulted from laser irradiation has to been considered to improve the manufacturing quality of femtosecond laser cutting. In this research, multiple surfaces were manufactured by cutting grooves side by side on glass with a series of pulse energy levels, respectively. By analyzing the characteristics of different surfaces, it has been found that there exists a minimum spacing between two adjacent groove cuttings in the manufacturing of a surface. If the spacing is less than the minimum one, the sidewall between two groove cuttings will be melted by the heat coming from laser energy. The minimum spacing between two groove cuttings for preventing groove sidewalls from being melted is investigated as a function of pulse energy level and feed rate.

Keywords: Femtosecond laser micromachining, Groove cutting, Minimum spacing, Heat transfer.

1.0 Introduction

Laser-based machining of materials with femtosecond light pulses has attracted considerable attention in recent years. The development of ultrafast laser sources has simulated interest in the application of sub-nanosecond lasers for modification of semiconductors [1], [2]. With rapid technological advances in ultrafast laser technology, the tremendous potential of femtosecond laser (hereinafter, FS laser for short) pulses as a material processing tool has been demonstrated by many research works [3]-[8]. Nowadays, ultrafast laser technology is entering the industrial market and there is an increasing need for systematic analysis and characterization of a various materials machined by FS laser.

The research on application of FS laser micromachining falls into two categories. First, functional relationships between the ablation rate and laser parameters, typically including pulse energy, feed rate, spot size, pulse duration, and laser wavelength are established for different kinds of materials. Second, micromachining methods for different form 2D or 3D features, such as surface, hole, blind hole, counter bore, slot, step, and so on, are to be developed. The research in this paper is concerning the second aspect.

One of the advantages of FS laser pulse is that the thermal diffusion is limited. The energy of FS laser is deposited at a time scale much shorter than both the heat transfer and the electron-phonon coupling (typical heat diffusion time is in the order of nanosecond to microsecond time scale whereas the electron-phonon coupling time of most materials is in the picosecond to nanosecond) so that the light-matter interaction process is essentially frozen in time and the affected zone altered from solid to vapor phase and to plasma formation almost instantaneously. As a result, FS laser machining reduces collateral damages to the surroundings and the quality of the machined surface is significantly increases.

In our experiments, it has been found that stuff melting caused by thermal diffusion has considerable impact on the manufacturing quality of surface under some condition in FS laser machining. To the best of our knowledge, there is no research work concerning that phenomenon and its physical mechanism so far.

In this research, we found that there exists a minimum feasible spacing between two neighboring grooves when manufacturing a surface. The sidewalls of a groove will not melt until the spacing between two neighboring grooves is less than the minimum one when given other manufacturing parameters. The numerical relationship between the minimum spacing and laser energy, pulse frequency, and feedrate is investigated in this research.

2.0 Experimental Setup

A femtosecond laser micromachining system has been built in University of Calgary. Fig. 1 shows the architecture of the system. It includes two modules: laser system (Spectra Physics, Spitfire), micromachining workstation and its machining controllers (AeroTech). The micromachining workstation has to be installed on the heavy granite platform because of its very high resolution stage. The laser is a commercial 1~ 1000 Hz amplified Ti: sapphire laser system which produces polarized ~ 130 fs pulses with a peak wavelength at 800 nm. The mechanical shutter is controlled by a computer to select the number of laser pulses. The maximum power energy is 500 mw. The micromachining workstation includes a stage with computer-controlled *x* and *y* translation, and *x*, *y*, and *z* rotation ($\leq 5^o$) stage and a *z* translation axis on which four objectives are mounted: 5×, 10×, 50×, and 100×. The step resolution on *xy* translation of the stage is 10 nm. The far-field intensity distribution after the objective is a good approximation followed a Gaussian distribution. The Gauss laser irradiates from a lens that is settled on Z axis whose step resolution is less than 0.1 um. A vacuum chamber is installed on the stage. The controller is used for adjusting power energy and driving the stage and *z* axis manually or by CNC programming. The machining process is monitored on-line with a confocal CCD camera.

Glass samples were placed inside a chamber which is mounted on a stage, respectively. The machining experiments on glass were performed with the femtosecond laser system. The laser was focused on the sample by a 10× and 50× microscope objectives, respectively. The spot size ω_0 (10 µm, spatial radius at $1/e^2$ of peak intensity) on each sample was determined by measuring the diameters of single-pulse craters as a function of pulse energy, then by fitting the data to the appropriate equations as described previously. Due to the laser energy fluctuations and uncertainty in the spot size measurements, an uncertainty in the fluence measurement of approximately ±20% is caused. Unless otherwise specified, the laser polarization was chosen to be perpendicular to the translation direction. After machining, the sample was cleaved perpendicular to the grooves near the middle of the grooves. The sample was then analyzed using scanning electron microscopy (SEM).

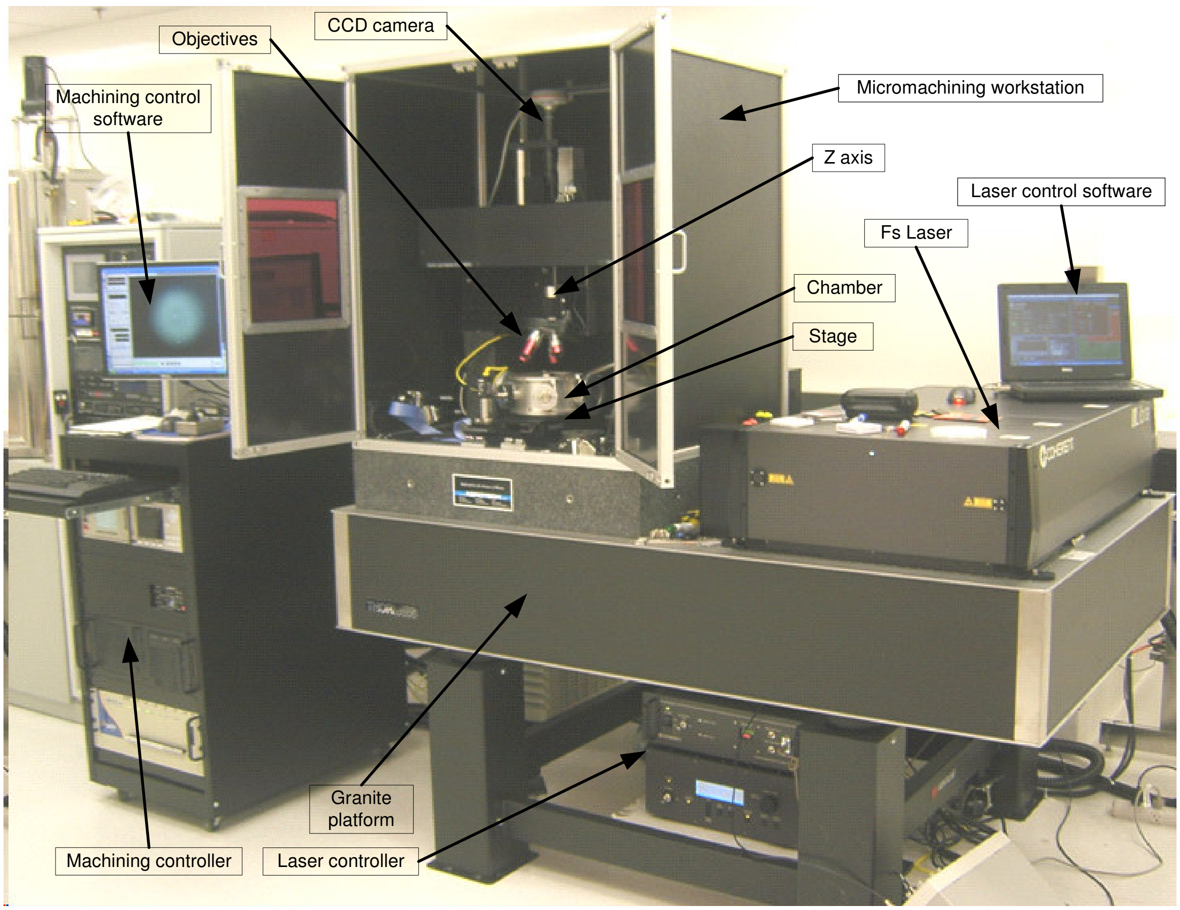


Fig.1. Femtosecond laser micromachining system

3.0 Pulse Energy

The single pulse has a Gaussian spatial and temporal profile (diffraction and Fourier transform limited) [9],

$$I(r,t) = I_0 \exp(-2r^2/\omega_0^2)\exp(-2t^2/\tau^2) \quad (1)$$

where I_0 denotes the peak intensity of the single pulse; ω_0 signifies the spatial radius at the ($1/e^2$) intensity contour; τ expresses temporal radius (150 fs in this research); *r* represents the radial coordinate of distance from the propagation axis; *t* is the time variable. The spatial distribution of the energy fluence is formulated as follows

$$\Phi(r) = \int_{-\infty}^{+\infty} I(r,t)dt = \sqrt{\frac{\pi}{2}}\tau I_0 \exp(-2r^2/\omega_0^2) = \Phi_0 \exp(-2r^2/\omega_0^2) \quad (2)$$

where $\Phi_0$is the peak fluence at the center of the single pulse beam.
By comparing formula (5) to Gaussian distribution, the following formula can be obtained

$$\omega_0 = 2\sigma \approx \frac{1}{6}d \quad (3)$$

where d represents the diameter of a laser spot, σ is the standard deviation of Gaussian distribution. In this research, the diameter of the laser spot is about 10 μm, so ω0 is about 1.67μm.
By integrating Equation (2) on the spherical domain of laser spot shown in Fig. 3, the relationships between the peak intensity, I0, and the pulse energy, denoted by E, is obtained as follows

$$E = \sqrt{\frac{\pi}{2}}\tau I_0 \omega_0^3 (\pi/2)^{3/2} = \Phi_0 \omega_0^3 (\pi/2)^{3/2} \quad (4)$$

4.0 Experimental Procedure

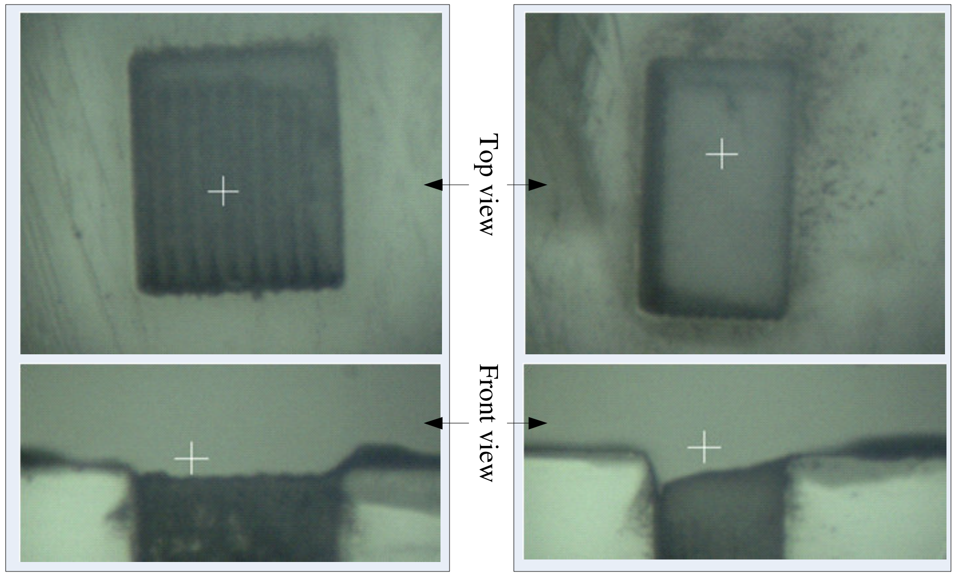
The surface is machined by cutting grooves side by side with the same feeding direction. The spacing between two adjacent grooves has significant impact on the micromachining quality. The following phenomenon was found under given power energy and feed speed: if the spacing between two adjacent grooves is less than a fix value, the sidewall between them is melted obviously and the molten material flows into the sibling groove so that the groove is partly filled in.

To reveal the relationships between the minimum spacing of two adjacent cuttings and the laser parameters in surface micromachining, different groups of grooves were cut with different power energy and feed rate to find out the corresponding minimum spacing. To analyze the experimental results, the relationship between power energy and the diameter of the craters created by laser pulses are also investigated.

5.0 Experimental Results and Discussion

5.1 Analysis of Mechanism

Fig. 2 shows the front view and top view of the sample which depicts the aforementioned phenomenon in groove cutting. The sample surfaces are cleaned by nitrogen gun to remove the debris resulted from the cutting. In Fig.2a, the sidewalls between grooves can be seen. The front view of the surface is in shape of scallops and the manufacturing quality is relative planar. In Fig. 2b, the surface is smoother than that shown in Fig. 2a, but it slopes along the cutting direction due to the melting of the sidewalls.



a. Set of grooves with sidewalls
b. Set of grooves with melted sidewalls

Fig. 2. Groove cuttings

The energy of the laser beam is distributed spatially in accord with Gaussian rule. There exists an ablation threshold of a laser beam for a given material. This is illustrated in Fig. 3. The ablation threshold was calculated in this research. When the laser beam illuminates on the sample surface, the ablation energy, which is distributed in the ablation sphere with the density higher than ablation threshold, denoted by Φ_{abl}, deposits into the sample and contributes to removing the material which results in a crater. The energy under the ablation threshold, which is the energy of laser beam except the ablation energy, is absorbed by the sample and diffuses by means of heat transfer.

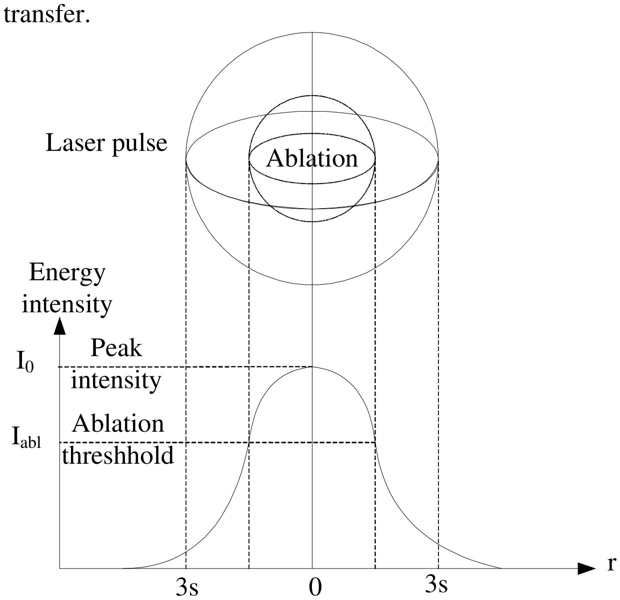


Fig. 3. Gaussian distribution of laser beam energy

Three cases may happen when cutting the two adjacent grooves, depending on their spacing, as illustrated in Fig. 4. In Fig. 4a, the spacing is big enough so that the impact of the first cutting on the second one can be neglected. When the spacing is getting smaller during the cutting, the heat energy resulted from the first cutting transfers to the location where the second cutting is performed and starts to impact on the second cutting so that the second groove is deeper and wider than the first one, as shown in Fig. 4b. When the spacing gets small enough during the cutting, besides the phenomenon shown in Fig. 4b, the sidewall between the two cuttings is melted and the melted material flows into the first groove. This is shown in Fig. 4c.

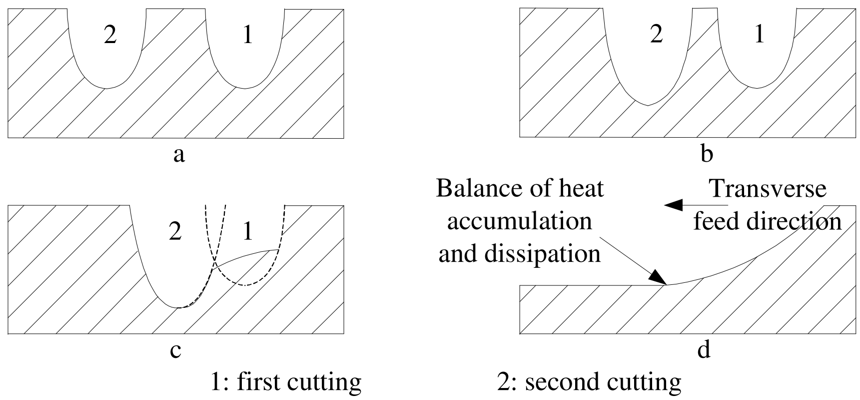


Fig. 4. Two groove cuttings with different spacing

When cutting multiple grooves with the spacing described in Fig. 4b or Fig. 4c, the accumulation and dissipation of the heat energy along the transversal direction (perpendicular to the cutting direction) will ultimately reach a balance at a groove cutting under given power energy and feed rate. As a result, the following cuttings bear the same depth. This is shown in Fig. 4d.

Three cases of two adjacent craters, which are similar to the three cases about two adjacent grooves along transverse direction, also happen along the longitude direction (cutting direction). They can be analyzed similarly to the above analysis for transverse direction. In this analysis, the spacing between two adjacent craters which are resulted from pulse shots plays the role like the spacing between two adjacent cuttings in transverse direction. This analysis process is omitted in this paper. After this analysis, we can see that the right view of a groove is like that described in Fig. 4d when the spacing is small enough.

By integrating the analyses along two directions, the shape of cutting surface with small transverse and longitude spacing is illustrated in Fig. 5. Accordingly, the effective way to improve the micromachining quality of surface is to reduce area 1 and area 2 shown in Fig. 5. Based on above analyses, area 1 (2) can be reduced by looking for the minimum spacing between two neighboring grooves (craters) along transverse (longitude) direction to avoid the impact of heat transfer. Obviously, the spacing between grooves should increase with the increase of pulse energy.

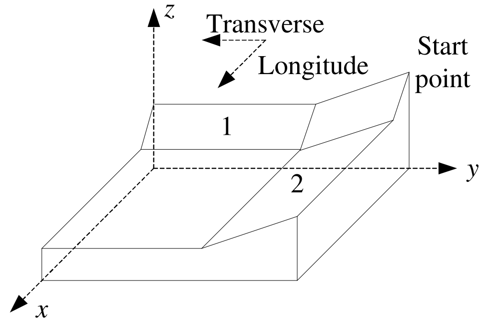


Fig. 5. Shape of cutting surface with small spacing

Actually, both the transverse minimum spacing and the longitude minimum spacing are related to the parameters of laser beam when the material is given. In the next section, the study is focused on the transverse minimum spacing.

5.2 Quantitative Analysis

In order to determine the relationship between parameters of laser pulse and the minimum spacing for avoiding melting the sidewalls of grooves, multiple groups of grooves were cut by a single pass of the translation stage at multiple pulse energy levels available in the power controller module of the system. The same feed rate was kept for each energy level within the corresponding set of grooves. Five feed rate levels are used, including 50µm/s, 100µm/s, 200µm/s, 400µm/s, and 800µm/s. Pulse energy is specified at 1.5µJ, 2.5µJ, 5µJ, 10µJ, 15µJ, and 20 µJ, respectively. Table 1 shows the minimum spacing between adjacent grooves under different pulse energy levels and feed rate levels (part of the experiment data).

Table 1 Minimum spacing (µm) versus pulse energy and feed rate

F (µm/s) \ P (µJ/s)	60	50	40	30	20	15	10	5	2.5	1.5
50	20.1	17.8	15.4	14.2	13.2	13.1	10.2	8.8	7.0	6.1
100	20.3	17.8	15.0	14.0	13.2	13.1	10.5	8.6	7.2	6.2
200	20.1	17.9	15.1	13.9	12.5	12.6	10.3	8.5	7.1	6.1
400	20.1	17.5	14.8	14.1	12.6	12.6	10.1	8.6	6.8	6.2
800	20.4	18.0	15.2	14.3	12.8	12.7	9.9	8.9	6.9	6.0

The frequency of the laser beam is 1*k*Hz

When a pulse energy level is fixed, the minimum spacing varies little with the feed speed. For example, the minimum spacing for the pulse energy level 10mw under different feed speed is around 10µm. The minimum spacing between grooves increases when the pulse energy level is increased.

For revealing the relationships between the minimum spacing and laser pulse energy, first, we made experiments to identify the relationships between the diameter of the craters on the sample and the laser pulse energy. Table 2 shows the part of the experimental data corresponding to the data in Table 1. As can be seen by comparing the data in Table 1 to those in Table 2, the value of the minimum spacing between two adjacent grooves is approximately equal to the value of crater diameter. Two extreme cases are illustrated in Fig. 6. In Fig. 6, the diameter of the laser spot is about 10µm.

Table 2 Crater diameter (µm) versus pulse energy

P (µJ/s)	60	50	40	30	20	15	10	5	2.5	1.5
Diameter	20.3	17.6	15.5	14.0	13.5	13.1	10.0	8.7	7.2	5.9

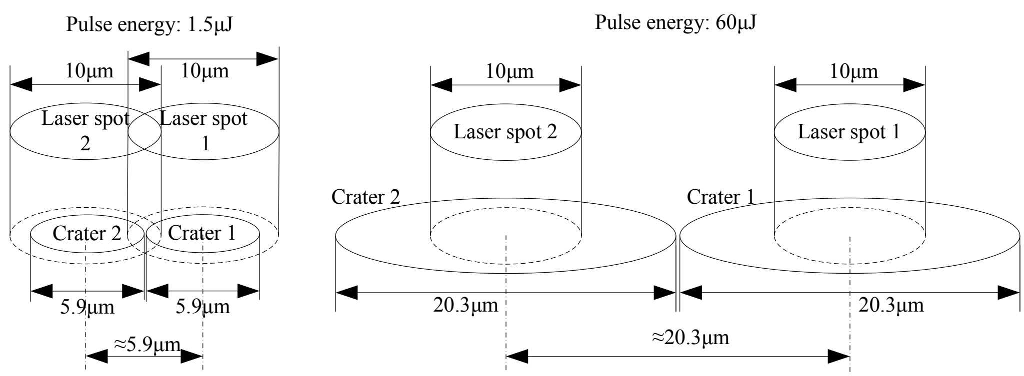


Fig. 6. Shape of cutting surfaces with small spacing

Fig. 7 shows the relationship between the natural logarithm of the peak intensity, ln(Φ_0), and the cube of crater diameter, d^3, (which is also equal to the minimum spacing between two adjacent grooves). The solid lines are semi-logarithmic fitting lines according to the experimental data. By extending the fitting line to a point, where the cube of crater diameter equals to 0, the value of ablation threshold is calculated: Φ_{abl}=0.143µJ/µm^3 (I_0=7.6×10^{11}J/cm^3). It can be seen that the crater diameter increases sharply when the peak energy fluence is more than Φ_0=0.469µJ/µm^3 (I_0=2.5×10^{12}J/cm^3). It means that much more energy of a laser pulse goes beyond the ablation threshold when the peak energy fluence is more than Φ_0=0.469µJ/µm^3 than that of a pulse with the peak fluence less than Φ_0=0.469µJ/µm^3.

6.0 Conclusion

The obvious melting phenomenon caused by heat transfer has been observed in the experiments of groove cutting by femtosecond laser. There exists a definite minimum spacing between two adjacent groove cuttings for avoiding the sidewall between two grooves from melting under a certain laser energy level. The experimental data revealed that the minimum spacing approximates to the crater diameter shot by laser pulses. The relationship between the minimum spacing and peak fluence of laser pulse were also analyzed. The result shows that the crater diameter increases sharply when the peak energy fluence is more than Φ0=0.469µJ/µm3 (I0=2.5×1012J/cm3) because much more energy of a laser pulse goes beyond the ablation threshold.

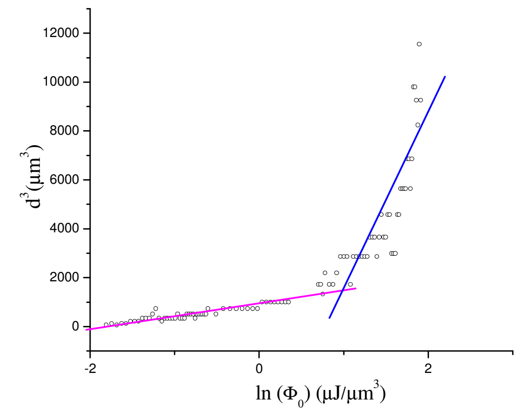


Fig. 7. Peak fluence of laser pulse vs. crater diameter

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EVALUATION OF CRITICAL PARAMETERS IN MICRO MACHINING OF HARDENED TOOL STEEL

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Abstract

Micro mechanical milling plays a significant role in fabrication of miniature features in a variety of materials with capability for producing three dimensional (3D) freeform surfaces. A major challenge for micro machining of hardened material is a high tool wear rate and unpredictable tool life. In addition, surface roughness and burr formation are factors to be closely controlled. In this paper, the statistical analysis of critical parameters for micro milling of hardened tool steel is presented. The parameters included spindle speed, depth of cut, ratio of undeformed chip thickness to cutting edge radius and lubrication/environment conditions. The significance of these parameters on surface finish, burr formation and tool wear are reported. The study shows that machining environment is the most significant factor in controlling surface finish and tool wear. While, selection of appropriate spindle speed and the ratio of undeformed chip thickness to cutting edge radius is more critical in limiting burr size. The work reported in this paper is important, because, industry needs to know key process variables (KPVs) that are critical in the control of micro machining performance. Additionally, the methodology enabled identification of optimum cutting values for these cutting parameters within the identified process window.

Keywords: micro milling, wear, tool steel.

1.0 Introduction

Mechanical micro machining is now recognised as a key technology for the manufacture of micro devices and features, especially 3D free form features. The technology can be feasible for a wide variety of materials compared to other micro fabrication technologies. The manufacture of micro dies from hardened steel materials is a particular case where micro milling finds application. However, in using sub-millimetre diameter milling tools, tool wear and fracture are the limiting factors. In addition, it is also recognised that the sharpness of the cutting tool in relation to the undeformed chip thickness affects the material removal process. Very small undeformed chip thickness compared to cutting edge radius can imply negative rake angles and promote material ploughing instead of the traditional shearing mechanism. The above case contributes to one aspect of the so called "size effect". Due to the size effect it is possible for the mechanism of material removal to be different between macro and microscale cutting [1]. Given the possible departure in cutting mechanism, the fragile size of the tool and the difficult to cut hardened workpiece material, it is essential to determine the key process variables for successful micro machining.

It is now recognised that at a certain level of undeformed chip thickness (minimum chip thickness), the limit for micro machining is established since this value indicates the chip formation process. Chea et al [2] proposed basic micro machining mechanisms based on the relative size of the undeformed chip thickness to the minimum chip thickness. If the chip load is less than the minimum chip thickness, chips will not be formed since the workpiece material will be compressed by the cutting tool and then recovers back after the tool passes. When the undeformed chip thickness is larger than the minimum chip thickness, then workpiece material will be removed in the form of chips through shearing mechanism. Thus, the ratio of undeformed chip thickness to cutting edge radius needs be known in order to predict the material removal mechanism. This ratio influences the effective rake angle, chip formation and chip thickness as well as the specific cutting energy [3].

One of the product attributes required for a micro device is a very good surface finish. In micro machining of aluminium and steel, surface finish was reported to be influenced by minimum chip thickness [1], cutting edge radius [4], workpiece material [5, 6] and feedrate [1]. When chip thickness is less that the cutting edge radius, the surface finish increases due to the ploughing effect [5, 7, 8]. Liu et al [1] further observed that in microscale machining, surface finish was affected by the trade-off between minimum chip thickness and traditional effect of feedrate. Larger cutting edge radius induce more ploughing effect and lead to poor surface finish [4, 8]. Statistical studies on the effect of tool diameter, spindle speed, depth of cut and feed rate on surface roughness in micro machining of brass [9] and aluminium [10] concluded that tool diameter was the most influential factor on surface roughness of micro milling. However, in most applications the tool diameter may be limited by the feature size or the need to remove material as fast as possible.

Other than surface finish, in micro milling, burr formation is another critical aspect for micro components since de-burring is more challenging and can damage micro features on the component. In slot milling, burrs occur along the side wall of the slot. These are known as the top burr. The mechanism of burr formation was proposed as the interaction between cutting edge radius and feed per tooth [3, 7, 8, 11]. This is due to the fact that a decrease in the ratio of undeformed chip thickness to the cutting edge radius results in a more negative rake angle. The material ahead the tool is pushed, bent and moved in the axial direction of the tool to form a burr [3, 11]. Additionally it is known that down milling leads to larger burr size as compared to up the milling mode [8, 12].

Tool wear is also a critical factor in micro machining of hard materials. Since tool wear can result in an increase of the cutting edge radius, the ratio of undeformed chip thickness to cutting edge radius decreases and this promotes burr formation [3, 8, 11, 12]. Thus, rapid wear progression can have a significant influence in formation of larger and undesirable burrs.

The motivation for this study was to investigate through analysis of variance, the dominant of key process variables with respect to influencing surface finish, burr size and tool wear when micro slotting hardened H13 tool steel (45 HRC). More specifically, the critical ratio of undeformed chip thickness to cutting edge radius, which in micro machining, defines the "size effect" has in the past been neglected in the statistical evaluation of key process variables. This factor is included in this study.

2.0 Experimental Details

2.1 Experimental Setup

A hardened H13 tool steel was selected as a workpiece material because it is widely used for die and mould applications. A mid range workpiece hardness of 45 HRc was selected. This is a fine grained tool steel. Hard homogeneous microstructure is ideal choice for micro machining as it minimises the effects of material elastic spring back after cutting and reduces the complexity of the different mechanism of removal that may be formed if different material phase were present. Ultra fine tungsten carbide micro tools were selected for the cutting tests. The ultra fine grain carbides provided the toughest shank for the milling process. The geometry was selected as two-flute micro with a flat end mill for easy of tool wear assessment.

A 500 µm tool diameter in the mid range (1 to 999 µm) of the micro tool size was selected. Slots with a volume of 0.18 mm^3 of material removed were machined on hardened tool steel. Before machining, new micro tools were inspected using a scanning electron microscope (SEM) to examine the acceptability of cutting edge geometry and measure the cutting edge radius. The ratio of the maximum undeformed chip thickness to cutting edge radius, r_r, was then calculated for each tool. This is the one factor in the investigation, and it relates to the size effect.

2.2 Orthogonal Array and Experimental Design

The parameters chosen for study were, spindle speed (rpm), depth of cut (µm), ratio of undeformed chip thickness to cutting edge radius, r_r, and the cutting environment. As discussed earlier the parameter r_r is more critical in micro machining combining the effect of chip load and tool edge radius. The cutting parameters of spindle speed and depth of cut needs to be set when machining. These are also traditionally considered in process optimisation. In addition the spindle speed mirrors the cutting speed effect. When H13 tool steel was machined in macroscale milling, Ghani et al [13] reported after Taguchi experiments that cutting speed is the most significant factor on surface finish. The cutting environment was selected as another factor due to the fact that friction and temperature could influence the surface finish and wear progression.

In this paper the, Taguchi method was implemented based on an orthogonal array. The Taguchi method helps to economise time and cost of experimentation. The orthogonal array has been reported to be the most flexible method for designing experiments [14]. Table I show the summary of factors and levels set for the $L_9(3^4)$ array used in this study. After the cutting test, surface finish at the bottom of micro slot and top burr width along the slot wall were measured using a Wyko optical profiler. Tool diameter reduction and tool wear were evaluated after taking measurements using a scanning electron microscope.

Table I: Four factors and three levels of the experiment

Factors		Level		
		1	2	3
Spindle Speed (rpm)	A	20000	30000	40000
Depth of Cut (µm)	B	15	20	25
The ratio of undeformed chip thickness to cutting edge radius	C	0.4	1	2
Environment	D	Dry	MQL	Flood

3.0 Results and Discussions

In the Taguchi method, the signal to noise ratio (s/n) is a measurable value that determines the variation in the quality of the output. The determination of the s/n ratio is based upon the aim of an investigation. In this study, the aim is to minimise surface roughness, burr size, diameter reduction and tool wear. Thus, the smaller the better was selected as the strategy to determine the factor effect. Table II shows the s/n ratio outputs of surface finish (Ra), burr size, diameter reduction and tool wear from each test run. Factor effect graphs can be then plotted and the optimum level for each factor can be found at the maximum value of s/n ratio. The analysis of variance (ANOVA) was used to assess the influence of the designed parameters on the machining process. The results show the significance (in percentage) of each factor in dominating the output objective function.

Table II: Signal to noise ratio results

Test Run	s/n ratio				
	Ra	Burr	Diameter reduction	Tool wear	
				Flank	Chipping
1	15.70	-34.14	-24.52	-25.63	-21.40
2	16.29	-39.27	-5.75	-23.12	-18.12
3	14.86	-28.99	-18.14	-24.86	-18.06
4	11.50	-29.05	-23.34	-27.48	-21.99
5	9.35	-27.55	-23.62	-29.06	-22.29
6	16.90	-28.60	-4.11	-21.03	-11.77
7	15.16	-27.92	-9.94	-25.15	-18.09
8	13.85	-28.11	-23.85	-27.06	-21.16
9	11.74	-30.26	-26.28	-30.33	-21.81

3.1 Surface Roughness

Fig. 1 shows the factor effects on surface finish. The optimum value levels for the best surface finish are found to be at N = 20000 rpm, a_p= 25µm, r_r = 0.4 and using MQL condition. It is also interesting to note that the best surface finish for the H13 workpiece material occurs in the ploughing mode (at undeformed chip thickness less than tool edge radius). This could be expected since elastic spring back for the hardened material is expected to be at a minimum. Table III shows the ANOVA for surface finish. The largest value of variance (F) represents the most influential factor on surface finish. Thus machining environment is the most dominant on surface finish with at 45.56 % and followed by spindle speed (27.75%), the ratio of undeformed chip thickness to cutting edge radius (21.18%) and depth of cut (5.5%) respectively. Thus in micro milling of hardened steel the use of minimum quantity lubrication gives the best surface finish compared to dry or machining under flood coolant. The dominant effect of the more lubricant oil mist on surface finish supports the need for more lubricant tool surfaces. Once this is set then the selection of appropriate spindle speed becomes the next critical process variable.

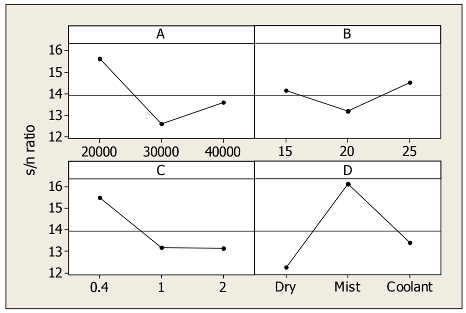


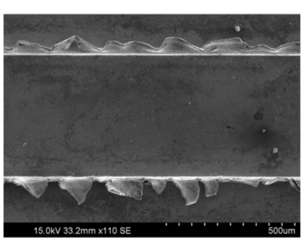
Fig. 1.Factor effect on surface finish

Table III; ANOVA for surface finish

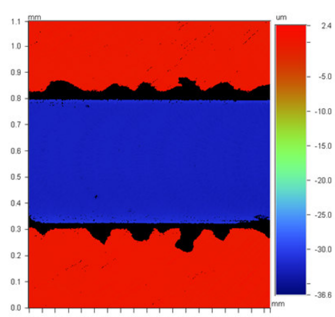
Source	Df	SS	MS	F	%
A	2	14.31	7.16	1.15	27.75
B	2	2.84	1.42	0.17	5.50
C	2	10.92	5.46	0.81	21.18
D	2	23.50	11.75	2.51	45.56
Error	0	0.00	-	-	-
Total	8	51.57	25.79	4.64	100.00

3.2 Burr Formation

The size of the burrs formed on the workpiece were evaluated and Fig. 2(a) and (b) show an example of a workpiece after dry cutting at N = 20000 rpm, a_p = 15µm, r_r= 0.4 as analyses by an SEM and Wyko optical profiler respectively. The burr width was measured from the Wyko images. The factor effect on burr formation, Fig. 3, displays that the optimum level in minimising burr width is at N = 30000 rpm, a_p = 25µm, r_r= 2 and using flood coolant condition. The ANOVA for burr formation is summarised in Table IV. Spindle speed is the most effective on burr formation (51.82%) and followed by the ratio of undeformed chip thickness to cutting edge radius (27.96%), machining environment (13.18%) and depth of cut (7.04%) respectively. The results show that the higher spindle speeds are better for reducing burr size. The higher the rpm, the higher the cutting speed and shear rate and these factors influence material shear and hence burr formation. In line with the expected theory the size effect as minored by the ratio of uncut thickness to cutting edge radius is statistically significant in controlling burr size. This is because the factor can set the threshold for minimum chip thickness and hence burr size.



(a)



(b)

Fig. 2. Burrs on workpiece after dry cutting at N= 20000 rpm, a_p= 15µm, r_r= 0.4 (a) SEM image and (b) Wyko image

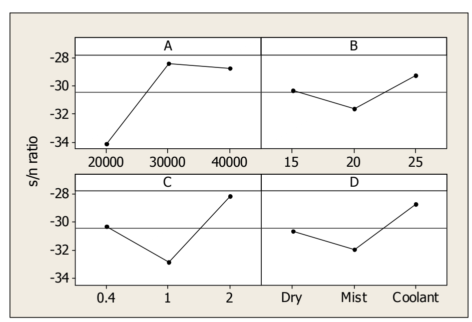


Fig. 3. Factor effect on burr formation

Table IV: ANOVA for burr formation

Source	Df	SS	MS	F	%
A	2	61.80	30.90	3.23	51.82
B	2	8.39	4.20	0.23	7.04
C	2	33.35	16.68	1.16	27.96
D	2	15.71	7.86	0.46	13.18
Error	0	0.00	-	-	-
Total	8	119.26	59.63	5.08	100.00

3.3 Diameter Reduction

The factor effect on tool diameter reduction is shown in Fig. 4 and the optimum level are N= 20000 rpm, a_p= 25µm, r_r= 2 and MQL condition. ANOVA of tool diameter reduction in Table V indicates that machining environment is a most significant factor in controlling reduction of tool diameter by tool wear at 93.20%. Again this could support the dominance of friction aspects in controlling wear performance of micro tools.

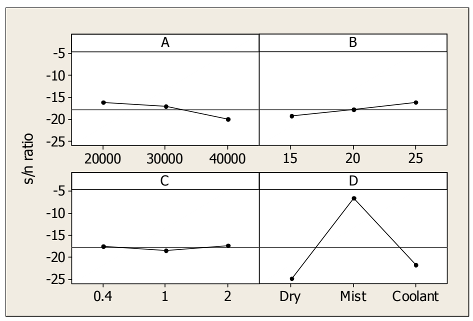


Fig. 4. Factor effect on tool diameter reduction

Table V: ANOVA for tool diameter reduction

Source	Df	SS	MS	F	%
A	2	24.88	12.44	0.13	4.06
B	2	14.32	7.16	0.07	2.34
C	2	2.49	1.24	0.01	0.41
D	2	570.97	285.49	41.09	93.20
Error	0	0.00	-	-	-
Total	8	612.66	306.33	41.30	100.00

3.4 Tool Wear

Fig. 5 shows an example image for tool flank wear and chipping. Edge chamfering was observed. Fig. 6 and 7 present the factor effect on flank wear and chipping respectively. The optimum level for minimisation of flank wear and chipping are different being 20000 rpm for flank wear and 30000 rpm for chipping. The results are expected since for flank wear a lower spindle and cutting speed helps reduce wear rates. While an increase in spindle speed may reduce cutting forces (and can result in lower chip loads) and hence promote less chipping. The optimum level for other parameters are the similar being a_p= 25 µm, r_r= 0.4 and MQL condition. ANOVA results for flank wear and chipping are shown in Table VI and VII respectively. The most influential factor on tool wear is the cutting environment with 63.5 % and 60.87 % for flank wear and chipping respectively. Again these results are in agreement with the drivers for tool diameter reduction as discussed in section 3.3.

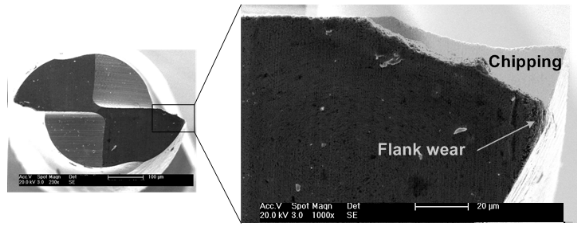


Fig. 5 Tool wear (at N= 30000 rpm, a_p= 20 µm, r_r= 2 and dry condition)

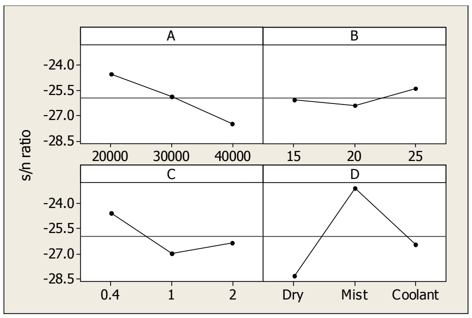


Fig. 6. Factor effect on flank wear

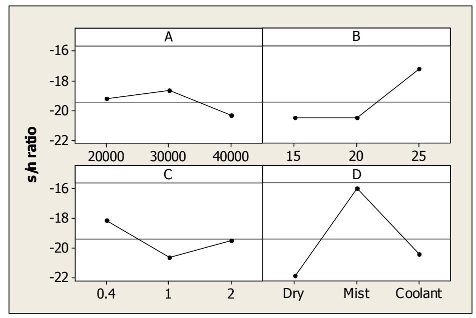


Fig. 7. Factor effect on chipping

Table VI: ANOVA for flank wear

Source	Df	SS	MS	F	%
A	2	13.372	6.686	0.750	20.08
B	2	1.576	0.788	0.070	2.37
C	2	9.362	4.681	0.490	14.06
D	2	42.295	21.148	5.220	63.50
Error	0	-	-	-	-
Total	8	67	33	7	100

Table VII: ANOVA for chipping

Source	Df	SS	MS	F	%
A	2	4.405	2.203	0.150	4.82
B	2	21.716	10.858	0.940	23.78
C	2	9.623	4.811	0.350	10.54
D	2	55.592	27.796	4.670	60.87
Error	0	-	-	-	-
Total	8	91	46	6	100

4.0 Conclusions

- The use of statistical analysis helps to identify key process variables in micro machining as well as establishing best process performance.
- The choice of machining environment is the most significant factor in improving surface finish and reducing tool wear (flank wear, edge chipping and tool diameter reduction).
- The optimum for all the investigations shows MQL to be better than dry milling or using flood coolant. The low friction coefficient vegetable oil mist used in the MQL helps in improving machining performance.
- The results show that when machining the hardened tool steel, surface finish was best when undeformed chip thickness is less than the cutting edge radius. This is the case for the hard and homogeneous material as material spring back is less prevalent compared to micro machining of ductile multiphase material.
- Since the machining environment and hence friction coefficient dominate surface finish and wear progression, the idea of using soft lubricant coatings over a hard coating could be implemented in order to obtain better surface finish and also to reduce tool wear.

- Burr formation can be controlled more significantly by selection of spindle speed and the ratio of undeformed chip thickness to cutting edge radius. In general increasing the spindle speed leads to lower burr size. The spindle speed and hence cutting speed has a bearing on the shear rate and chip temperature. These parameters influence the mechanism of material flow and extrusion that drive burr formation.
- The significant effect of the ratio of undeformed chip thickness to cutting edge radius on burr size can be accounted for by the size effect.

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GRINDING KNOWLEDGE SHARING THROUGH A KNOWLEDGE WAREHOUSE DEVELOPMENT

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Abstract

This paper reports upon a literature review of current development in knowledge management (KM) and grinding technology. As a result, it sets out a framework for a research into the development of a manufacturing knowledge warehouse that enables grinding knowledge to be shared in a manageable way. In practice the success of grinding is highly depending on the level of expertise and knowledge of the machinist and engineer. The existing techniques for selection of grinding conditions and control variables are empirical methods, historical data retrieval methods, model applications and artificial intelligence (AI). Different approaches have been implemented to select grinding conditions using Case-Based reasoning, Rule-Based reasoning, and hybrid approaches. In most cases, these methods are applied separately and mainly focusing on explicit knowledge processing.

It is noticed that knowledge has an interesting characteristic that the value of knowledge grows when it is shared. Knowledge sharing is a critical issue in any KM program. The community of practice (CoP) and the electronic network of practice (EnoP) are methods for more effective knowledge sharing. Although the shared artefact does not solve the problem of tacit knowledge sharing in a broad working environment, it can be of a real benefit and can play a variety of useful roles to support the sharing of tacit knowledge. To this end, this paper examines feasible structures for a knowledge warehouse development regarding both explicit and tacit knowledges. A case study within manufacturing environment, which covers grinding knowledge management, is presented in the paper.

Keywords: Knowledge management (KM), knowledge sharing, grinding, knowledge warehouse

1.0 Introduction

Many factors have contributed to the growth of knowledge management such as downsizing; outsourcing; revolution in information technology and deskilling [1], [2]. According to these factors, organizations and firms feel more pressure than ever to maintain a well-informed workforce, boost productivity and gain competitive advantage [3]. Downsizing and outsourcing mean a reduction in personnel. As people leave, organizations realize that they take valuable knowledge with them [4], [5]. These factors will have a great impact on the operations that depends on the skills of people such as grinding technology. The main objective of Knowledge Management (KM) is to mange knowledge process, whereas the knowledge itself cannot be managed; what can be managed is the knowledge gathering, storing and organizing, retrieving, and sharing. It was recommended that an organization should have an effective and efficient information system to facilitate knowledge management process [1], [6] - [12]. The knowledge management is often facilitated by information technology; information technology by itself is not KM. It can be argued that the knowledge management is more than the acquisition, analysis, storage and manipulation of data and information. It is an attempt to recognise the human assets within the minds of individuals and to leverage them as organisational assets that can be accessed and used by boarder set of individuals.

2.0 Knowledge Creation, Sharing and Their Techniques

Creating knowledge is not simply a matter of learning from others or acquiring knowledge from the outside [13]. Knowledge must be built on its own, frequently requiring intensive interaction between individuals and the organisation. The most powerful learning comes from direct experience and trial and error. For example, a child learns to eat, walk through trial and error.

According to Nonaka and Takeuchi [13], knowledge conversion is about the distinction between tacit knowledge and explicit knowledge and how tacit and explicit knowledge interact and interchange into each other. Tacit knowledge and explicit knowledge are not totally separated but mutually complementary entities. It is important to note that the interaction between tacit and explicit knowledge is performed by individuals but not the organisation. Etienne Wenger [14] describes the “negotiation of meaning” as how people experience the world and their engagement in it as meaningful. The negotiation of meaning involves the interaction of two processes, participation and reification, which form a duality. An important aspect of the participation/reification duality is balance between each of the constituent processes. Each needs to be in its proper proportion so that each remains in equilibrium with the other. Regarding knowledge duality theory, Wenger [14] consider that hard knowledge is the part of what people know that can be articulated, captured, and stored and soft knowledge is the part of what people know that can’t be articulated. According to the view of knowledge as duality then by implication, all knowledge is to some extent both hard and soft: it is simply that the balance between the two varieties.

The explicit knowledge such as working procedures and related data can be easily collected, stored, retrieved and shared [5],[6],[12]. Explicit knowledge in an organization is represented in the form of databases, documents, memos, reports, best practices, or process in the organization. The knowledge repository can be accessed at the convenience of employees and well suited even for busy employees.

The tacit knowledge is found in people’s-heads or experience and it is developed from direct experience of action. It could be shared through highly interactive conversion, story telling, and sharing experience [4], [10], [13], [14]. The most critical part of knowledge is the tacit knowledge, such as employee skill and experience, which is in their minds. Difficulty of managing tacit knowledge is an important challenge for KM program [4], [5], [17] – [20]. The challenge inherent with tacit knowledge is figuring out how to recognize, generate, share and manage it. While Information Technology in the form of e-mail, groupware, instant messaging, electronic database, video and audio recording, multimedia presentations, and related technologies can help facilitate the dissemination of tacit knowledge; identifying tacit knowledge in the first place is a major hurdle for most organizations [7], [20]. The reach of tacit knowledge and experience possessed by individuals can be greatly extended once it is captured and explicated so that others can easily find it and use it [11], [20]. The problem with current technology was that ignored the tacit aspects of knowledge [7], [11], [20].

Globalization affects most organizations that many organizations are now undergoing some forms of structural changes and looking for new technology of knowledge sharing to cope with the internationalization of business [1], [2], [5]. Knowledge sharing is a critical issue in any KM program. New knowledge could be created by the generation of novel concepts through knowledge sharing.

Coleman [21] described culture evolving from networked cultures, network applications, collaborative applications and groupware, knowledge management and to online communications cultures. Many leading companies start with the technology networks and infrastructures and build up to collaborative applications [21], [22]. By using a computer network or communication network, people from different geographical areas can communicate and share efforts across time and space and collaborate on their common targets. After network applications, many companies moved forward to use groupware to share their knowledge. Groupware is an umbrella term describing technologies that support person-to-person collaboration. Groupware includes e-mail, electronic meeting, desktop video conferencing as well as systems for workflow and business process reengineering [5], [20], [21], [23]. Recent advances in information and communication technologies have led to the emergence of online structures on which the primary purpose is knowledge exchange. These electronic networks enable individuals to interact around a specific practice, regardless of physical proximity or prior personal acquaintance, thus eliminate the need for face-to-face meeting. [24], [25]. The community of practice (CoP) and electronic network of practice (EnoP) are methods for more effective knowledge sharing. It makes some inroads in tackling the complexities and challenges in the new business environment and it can be integrated with both the physical and electronic environment. Although the EnoP and CoP do not solve the problem of tacit knowledge sharing in a distributed international environment, it can be of a real benefit and can play a variety of useful roles to support the sharing of tacit knowledge [10], [14], [20] [26].

Many companies are migrating from e-mail to collaborative culture that ensue will cause a huge increase of the generation of knowledge. This increase in knowledge generation will require corporate culture to evolve to the next step of managing this knowledge [22]. The table 1 shows common knowledge management technologies that have been adopted by knowledge intensive firms [27]:

Table 1. Knowledge management technology adopted [27]

Knowledge Management Technology Adoption	
E-mail	100%
Internet	100%
Videoconferencing	100%
Project management systems	91%
Groupware	91%
Knowledge-based systems	82%
Intranet	82%
Yellow Pages for knowledge	44%

3.0 Grinding Technology

Grinding is a material removal process that utilises a grinding wheel with a large number of randomly bonded grains [28]. Grinding is a widely used machining process in applications requiring high production rates and very good dimensional accuracy and surface finish. It is also one of the complex metal machining processes and one of the less understood [29]. Consequently, successful of grinding in practice is highly depending on the level of expertise of the machinist and engineer [30]. Grinding is also viewed as an unpredictable process because of the large number of the relationships between those variables of grinding and grinding process performance [31]. The variables are summarised in table 2 [29], [31].

Table 2: Grinding Variables

Variable	Definition
Specific Power	The coefficient of friction could be measured from F_t and F_n relationship. So tangential force and power can be used to measure specific power.
Specific Energy	Power/volume of metal removed
G-Ratio	Volume of metal removed /volume of wheel speed
Equivalent Diameter	the diameter of a wheel that would be used for surface grinding
Wheel dressing	For non rotating diamond dressing, either with a single point or multipoint diamond, the dressing lead and depth are two important factors
Wheel grade	Topography of a grinding wheel
Coolant effect	Grinding fluids
Sparkout	The end of most precision grinding cycle
Wheel wear Parameters	The sum of attritional (grain-flat-wear) and grain-fracture wears
Surface finish	The surface finish of a workpiece
Surface Integrity	The quality of the surface on the finished

The existing techniques for the selection of grinding variables are data retrieval method, empirical method, and artificial intelligence (AI). Although the data retrieval methods are simple and practicable, the data apply only to a particular machine situation [28], [32]. Empirical model methods tend to be limited value since a small change in a variable that is uncontrolled can have a large effect on the models [33], [34]. Rowe et al. [32] summarized the application of Artificial Intelligence that used in grinding technology: knowledge-based expert systems, fuzzy logic, neural networks, genetic algorithms and adaptive control for optimization [33]. AI includes rule-based, case based, neural networks, fuzzy logic, and hybrid methods [32].

Rowe [32] presented a conceptual framework for an intelligent grinding system. The intelligent grinding machine has the potential to include adaptive control optimization (ACO) and the features indicted below:

- To remember optimized conditions for future operation in learning database.
- To provide intelligent selection of grinding parameters from a learning database.

Li et al. [34], [35] developed an approach for selection of grinding process condition using the blackboard approach. The approach has shown the ability to integrate different intelligent technologies into one system. The knowledge agents consist of case-based reasoning, neural network reasoning and rule-based reasoning. Chen [36] proposed a tow-layer structure for the development of a grinding knowledge management system; it was focusing on the knowledge structures for manufacturing technology [36]. Morgan et al [37] developed an intelligent grinding assistant system. A decision-making system was integrated in the database to select the initial grinding parameters. Although different techniques have been investigated to select grinding conditions [20], [31] - [35] by many researchers and some initial experiments completed, none of them has been focused on the tacit knowledge, which is an important element for knowledge management.

4.0 Methodology of Knowledge Warehouse Development for Grinding

From the Literature review of KM, One of main KM objectives is to mange organisational knowledge to create new knowledge. The new knowledge is created by combining existing knowledge pieces or by generation of novel concepts through knowledge sharing. The problem with earlier technology was that ignored the tacit aspects of knowledge. The other role of IT in KM is to make the implicit visible.

According to the issue of the XPERTS investigation, knowledge management tools are not currently used within the European machinery-engineering domain. It should be noticed that in this sector, the industries are not really aware of the benefits of using such a tool [38]. The grinding process depends highly on skilled engineers or technicians that they can leave their jobs at anytime taking with them their knowledge and experience. The organisations need to find a way to keep their knowledge available when it is needed not only the explicit knowledge but even though the tacit knowledge. On the other hand, grinding is still an unpredictable process if there is not suitable knowledge available and it heavily relays on experience because of a large number of variables involved and inadequate understandings of the relationships between these variables and grinding process performance [29], [31], [32], [34], [35].

While groupware and intranet facilitate the knowledge exchange and the variation of tremendous amount of knowledge, it is very difficult to extract the exact knowledge efficiently from them [24] - [27]. The messages EnoP technology are not stored in a single repository that can be accessed by new comers or searched for historical information [21] - [27].

A flexible and easy to use web-knowledge based (warehouse) is proposed here, which could manage the explicit knowledge and facilitate transferring tacit knowledge into explicit knowledge. Upon this, the new knowledge base will support the decision making process for selecting grinding conditions. The new knowledge based system will encourage and facilitate the sharing of explicit and tacit knowledge by building problem solving and question-answer modules.

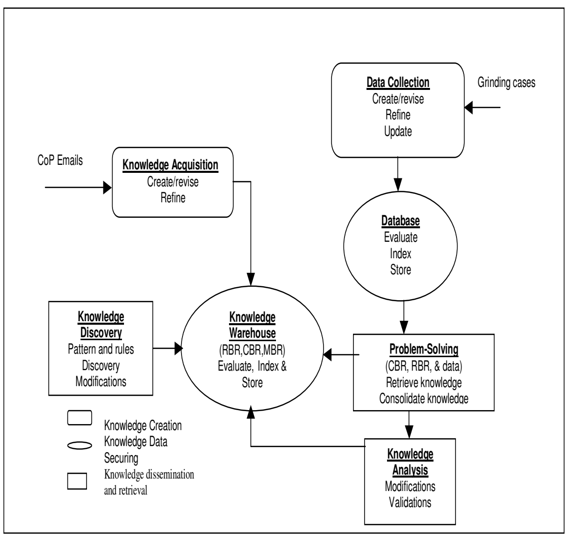


Fig. 1. Knowledge management in GKW

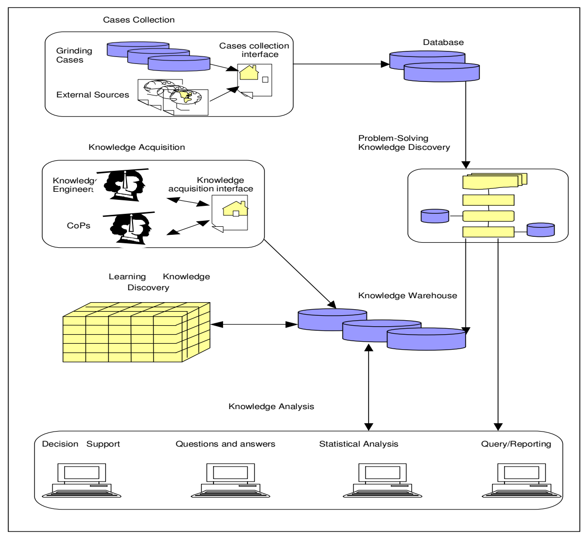


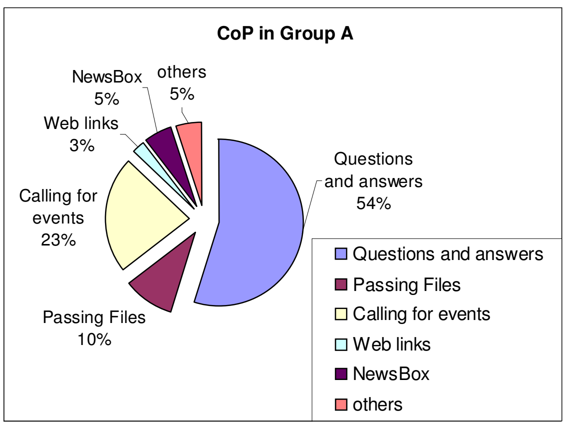
Fig. 2. GKW Module structure

A Grinding Knowledge Warehouse (GKW) is designed to facilitate and support knowledge management process for grinding technology. Figure 1 shows the knowledge management process in GKW. The GKW will include six modules as shown in Figure 2. The Grinding Knowledge Warehouse (GKW) includes five modules as shown in Figure 1. Data Input Module collects the data through the data collection interface and Community of Practices (CoP's) members. Database Module stores, retrieves, and shares data in various formats. These data will then transfer to Problem Solving Module and Learning Knowledge Discovery Module, which will provide the user guidance for selecting grinding conditions. Knowledge Acquisition Module facilitates knowledge conversion from tacit to explicit knowledge by directly acquiring the tacit knowledge from knowledge engineers or CoP members. Also, Knowledge Acquisition Module provides the interface for CoP members and knowledge engineers. The core of Problem Solving Module includes Case Based Reasoning and Rule Based Reasoning. Learning Knowledge Discovery Module extracts implicit, previously unknown and potential useful rules and patterns to modify and update existing rules and patterns. The GKW will be integrated into an internet based framework for a wide accessibility.

5.0 Comparison of Communications within Two Groups in Rolls-Royce

The structure of grinding knowledge has been analyzed and a framework of a grinding knowledge warehouse is constructed to facilitate knowledge management. In order to acquire an overview and awareness of the grinding knowledge sharing activities in Rolls Royce, several meetings and discussions were carried out. Community of practice is used as a sharing knowledge tool between the employees. Statistical analysis between two different communities was carried out to evaluate their performance.

From the CoP emails of group A and B between March 2005 until November 2006, it can be noticed that the CoP tool has been mainly used for questions and answers, passing documents, calling for conference or event, passing web links, sending NewsBox and others. Figure 3 represents the percentage of different category activities in each group. Depending on the work interests of the CoP members, the usage of the groupware is different. It has been found that 54% of the e-mails sent by the employees in group A are used to share their knowledge through sending questions and answers, while only 49% of the e-mails in Group B serves this purpose. Nevertheless, it confirmed that the highest percent was for question and answer category, which meant the CoP could be considered as a good tool for knowledge sharing.



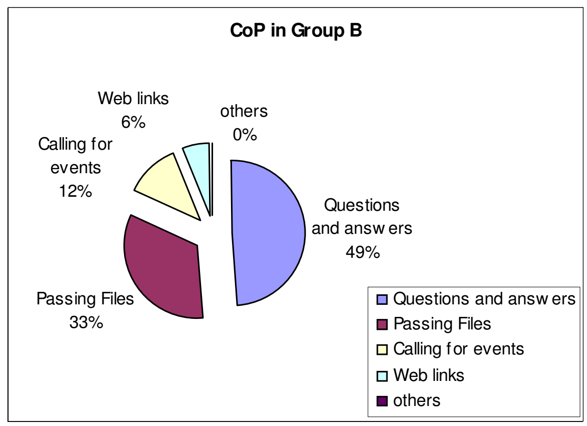


Fig. 3. Percentage of different activities within two communities of practice

The number of emails in group A is much more than the emails in group B, that means the CoP was used more frequently in group A than B as shown in Table 3. For group A, the number of asked questions is 40 questions. From these questions, 10 questions have not been answered. That means 75% of these questions have been answered. Thirty-six of these questions (90%) were about the manufacturing process. The total number of answers is forty-six answers. The answers were classified into three categories; answers contain knowledge, contacts, or others. It was found that 75% of these answers contain knowledge, 17% of answers does not. There are some 8% of answers are not relevant. It can be seen that e-mail is becoming a popular tool for knowledge dissemination. However the usage of such tool depends on difference working environment and the specialised fields.

Table 3. Number of emails communicated in group A and B

	Questions and answers	Passing Files	Calling for events	Web links	NewsBox	others	Total
Group A	86	15	36	4	7	7	155
Group B	16	11	4	2	0	0	33

6.0 Conclusive Remark

Many companies have used file servers, email and groupware as a collaborative tool [31], [35], [39], [40]. However, none of these tools are fundamentally designed to share knowledge. While intranet and groupware facilitate the creation of a tremendous amount of knowledge, it is very difficult to extract the exact knowledge efficiently from it [39]. By using the most advance research technology, finding the right knowledge is still very difficult.

On the other hand, from the statistical analysis of this research, it has been noticed that a knowledge warehouse could make knowledge more accessible for users, could retrieve knowledge more efficiently and quickly, and should facilitate extracting knowledge for CoP. The CoP has been used as a tool of collaborative among the Rolls-Royce workers. It been mainly used to send questions/answers, call for a meeting or seminar, and forward files or web links. From the meeting with the key representative of Rolls-Royce and the analysis of the emails, it has been convinced the importance of knowledge ware house development. The next stage will be how to extract the knowledge effectively from the CoP.

The new KW will encourage and facilitate the sharing of explicate and tacit knowledge. The grinding cases will be kept in the knowledge warehouse that will support the decision making process for selecting grinding conditions for new processes and optimization. As a result, it will save the time for CoP members by providing them with most relative answer to their questions. It also helps them sharing up-to-date knowledge. The further work will develop and integrate all the modules into a system which allow users to access the knowledge warehouse via the intranet.

Acknowledgement

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MODELLING AND SIMULATION OF THE DYNAMIC CUTTING PROCESS AND SURFACE TOPOGRAPHY GENERATION IN NANO/MICRO CUTTING

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Abstract

In nano/micro cutting process, the surface quality is heavily dependent on all the dynamic factors in machining including those from the material, tooling, cutting parameters, servo accuracy, mechanical structure deformation, and non-linear factors as well. The machined surfaces are generated based on the tool profile and the real tool path combining with the various external and internal disturbances. To bridge the gap between the machining conditions and the surface quality, the integrated simulation system presented involves the dynamic cutting process, control/drive system and surface generation module. It takes account all the intricate aspects of the cutting process, such as material heterogeneity, regenerative chatter, built-up edge (BUE), spindle run-out, environmental vibration, and tool interference, etc. The frequency ratio method is used to interpret the surface topography and texture formation. The proposed systematic modelling approach is verified by the cutting experiment.

Keywords: Dynamic cutting force, non-linear factors, surface topography, tool interference.

1.0 Introduction

Metal cutting, especially in nano/micro scale, is a complex process which comprises workpiece material, tooling geometry, cutting parameters, servo drive accuracy, static and dynamic deformations of structure in machining, etc. The machined surfaces are generated based on the tool profile and real tool path consider with various disturbances. It is of great benefit to build a systematic model and analyze the effects from the dynamic cutting process. Many linear/nonlinear factors in the whole system will contribute to the surface quality. The dynamic cutting force joints all the factors together, and produce the tool-workpiece relative displacement in the stiffness loop.

Take 3-Axis turning machine as a case in point, shown as Fig. 1, the stiffness loop in face cutting process involves: spindle axial runout, workpiece clamp error, workpiece material property, cutting tool geometry, tool holder stiffness, Z axis servo stiffness in axial direction, X axis slideway stiffness in side direction, and mounting stiffness. In this stiffness loop, all the elements are guaranteed by physical construction like bearings, mounting screws and other mechanical structures except the linear motor in axial direction. Since employ the direct driven linear motor, the stiffness in Z axial motion is directly provided by electrical servo motor. The tuning of Z axis linear motor, in the error sensitive direction, is one of the most critical ingredients of ultra-precision machine tool.

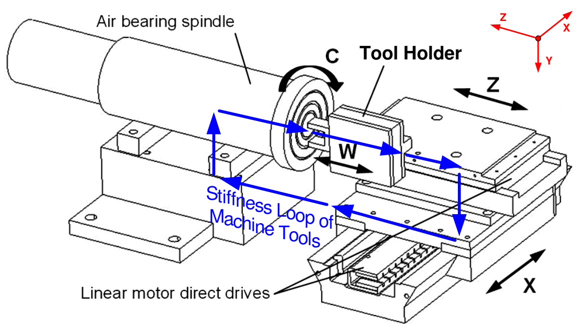


Fig. 1 Stiffness Loop of 3-Axis Turning Machine

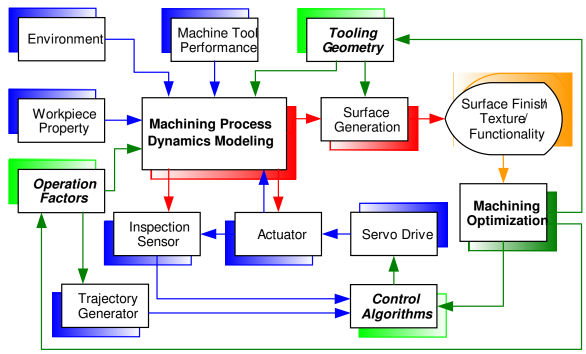


Fig. 2 Machining Process Integrated System

To get the connection of the tool path and the machined surface, several literatures focuses the surface topography generation process. Cheung and Lee [1]-[2] used the digitizing oscilloscope to record the relative displacement between the tool and the workpiece. After been analyzed by Fast Fourier Transform (FFT), the main frequency and amplitude of vibration reconstructed the tool deviation from ideal position. The tool profile superimposed onto the tool path to generate the surface topography. Lee and Cheung [3]-[4] built a dynamic cutting system to predict the surface topography in face turning. However the cutting force model only contained the linear factors and the whole cutting system was simplified into a second-order system. The servo control system, material hard grain effect, chatter [5], tool wear, spindle runout and environmental vibration were not taken into account. Luo et al. [6]-[7] introduced some non-linear factors to the cutting process and studied the effects of machining process variables and tooling characterizations on the surface texture, yet the tool interference effect in nano/micro scale cutting process had not been involved.

In short, for micro/nano cutting process, the machined surface performance is all about how successfully the tool-workpiece relative position meets its desired objective. The topography and texture of cutting surface will be generated by the dynamic feed response under the multifarious cutting factors.

In this paper, the dynamic cutting process system is established. The machined surface topography is predicted though the real tool path and tooling geometry. From analyzing the cutting force, the tool-workpiece relative displacement and the surface profile, the origins of surface error are located to the dynamic cutting factors. The preliminary cutting trials certify the validity of the dynamic cutting system modelling.

2.0 Systematic Modelling of the Dynamic Nano/micro Cutting

The generation of workpiece surface is a very complex material removal process as shown in Fig.2 including:

- servo control dynamics, which is joined by control algorithm, servo amplifiers, actuators and inspection sensors;

- machining process dynamics, which is highly affected by six main aspects: machine tool performance, cutting tool geometry, workpiece material properties, operation factors, servo motion and environment; and
- surface generation and surface texture, integrity and functionality analysis.

To get a better understanding of the complex process, a systematic model is developed in the MATLAB Simulink module as Fig. 3. The modelling approach bridges the gap between the determinative factors and the surface generation. Based on a thorough theoretical analysis of servo motions and cutting mechanics/dynamics, the integrated model produces a scientific methodology to simulate the precision surface generation in nano/micro turning processes.

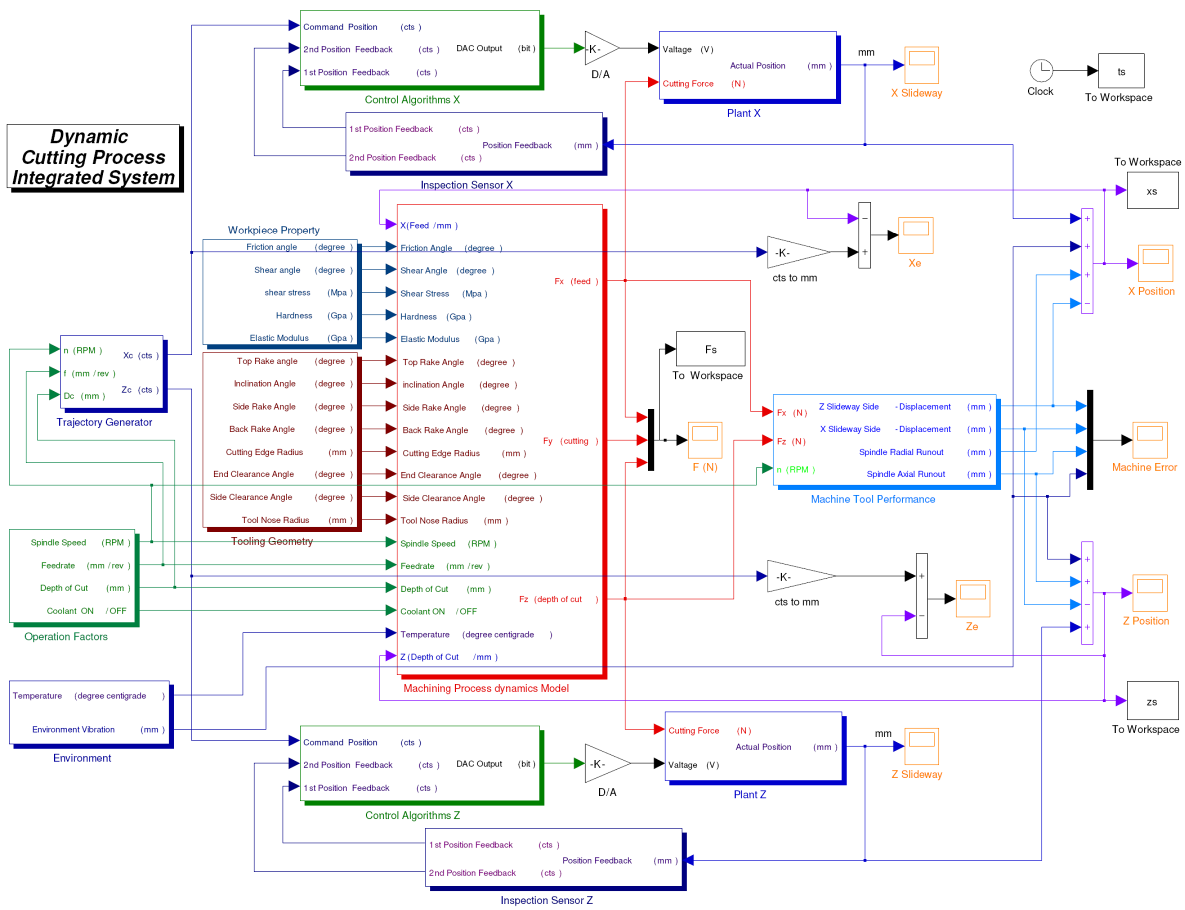


Fig. 3 Dynamic Machining Process Integrated Modelling

2.1 Modelling of Servo Control Dynamics

Most of the cutting dynamics simulations are simplified model the control and drive system as a second-order system. However, the advanced control algorithms are always applied on the ultra precision machine tools to achieve higher servo accuracy. Modelling the control system can also help to modify the controller construction and finally improve the surface quality. In this paper, the ultra precision turning machine employs the UMAC motion controller who provides a PID position/velocity servo control scheme with velocity and acceleration feedforward loops [8]. The discrete model uses Z-transforms whose sampling period is the real servo-interrupt cycle. The position quantification based on the encoder resolution is 4.88 nm.

The output from the UMAC controller is lead to servo amplifier to continue the current loop. The direct-drive linear motor model is built on the resistance and inductance of the motor windings, force constant and back EMF constant from the specifications. In this case, the static air bearing slideway is applied to reduce the friction and unexpected load in the motion direction. Therefore, the plant of the slide carriage is simplified represent as a pure mass module.

From servo control dynamics Model, the actual motion of each slideway is calculated for the next stage to generate the real tool path. In fact, there are some additional disturbances in the drive system: electrical noise in the current loop and cutting force disturbance superimposed on the sideways which is generated by dynamic cutting process model.

2.2 Dynamic Cutting Process

The quality of the machined surface is mainly determined by the relative motions between the cutting tool edge and the workpiece. In practice, the tool path deviates from the ideal tool path as a result of kinematic or dynamic factors from the dynamic cutting process, machine tool motion errors and environmental disturbances. For instance, the deformation of the slideway bearings under the action of dynamic cutting forces will deflect the cutting tool nose point; environmental vibrations will make the motion of the cutting tool away from the designed tool path.

Since the surface topography model basically follows the reflection of cutting tool edge profile, to calculate the real tool path becomes the critical part in the modelling approach. Table I lists the linear and nonlinear factors from the structural deformation and motion errors of the machine tool and cutting tool which will contribute the deviation of the tool path.

Table I: Linear and Nonlinear Factors in the Cutting Process

Source	Influence Factor	Mathematical Function	
BUE	Rake Angle	$\Delta\alpha = \alpha_A \ \mathrm{Rse}(\omega_\alpha t)$	(1)
Hard Grain	Shear Stress	$\Delta\tau_l = \tau_A \ \mathrm{Pul}(t)$	(2)
Coolant	Friction Angle	$\Delta u = r(t)$	(3)
Flank Wear	Tool Wear	$l_w = \frac{A}{H}\frac{F_r}{Vf}V_s + B\exp(\frac{-E}{RT_f})$ [9-10]	(4)
Regenerative Vibration	Feed and Depth of Cut Chatter	$\Delta c_t = Z(t) - Z(t-T)$ $\Delta c_w = X(t) - X(t-T)$	(5)
Spindle Runout	Displacement between Cutting Tool and Workpiece	$E_s = A_s \sin(\omega t + \phi)$	(6)
Slideway Stiffness		$e_s = F_s / k_s$	(7)
Environmental Vibration		$E_v = A_{ev} \sin(2\pi f_{ev} t)$	(8)

where $\Delta\alpha$ is the variation of the rake angle due to BUE, α_A and ω_α are the amplitude and frequency of the variation of the rake angle due to BUE, Rse is a function to generate an arbitrarily shaped period signal; $\Delta\tau_l$ is the increment of the shear stress due to the hard grain, τ_A is the amplitude of the increment of the shear stress due to the hard grain; Pul is the Pulse function to generate square wave; Δu is the change of the friction angle between the tool rake face and chip, r is the step function; l_w is the tool flank wear width, F_r is the resultant cutting force, H_t is the hardness of the cutting tool material, V is the cutting speed, V_s is the sliding speed, E is the process activation energy, R is the universal gas constant, T_f is the cutting temperature in the tool flank zone, A and B are the constants; Δc_t is the variation of cutting thickness, Δc_w is the variation of cutting width; E_s is the spindle synchronous error, A_s, ω and ϕ is the amplitude, spindle angular speed and phase shift of the spindle axial runout; e_s is the error of the slideway in X/Y/Z direction, k_s is the stiffness of the slideway in X/Y/Z direction, F_s is the cutting forced in X/Y/Z direction; E_v is the environmental vibration, f_{ev} and A_{ev} are the frequency and amplitude of the environmental vibration.

The demonstrated workpiece material is the Aluminum alloy, thus the dynamic cutting force model will follow the elastic-plastic mechanics model. Based on the elastic-plastic deformation principle, the forces acting on the rake face can be acquired by the coordinate transformation of the shear plane force based on the shear plane cutting model. The force acting on the cutting edge and flank face can be deduced based on the empirical formula of the contact stress and elastic recovery. Accumulating the forces action on the three zones, there will be the dynamic cutting forces in the three directions following the Cartesian coordinate system in Fig. 1 expressed as [11]:

$$\begin{cases} F_x(t) = (K_{fc}\sin\theta_r + 1 - \cos\theta_r)[d_c + z(t) - z(t-T)]\{[h + x(t) - x(t-T)] + \sqrt{R_0^2 - [R_0 - d_c - z(t) + z(t-T)]^2}\} \\ \quad + (K_{fe}\sin\theta_r + 1 - \cos\theta_r)R_0\theta_r + K_{ff1}\cdot(\cos\frac{\beta}{2} + \mu\sin\frac{\beta}{2}) + K_{ff2}\cdot(\cos\beta + \mu\sin\beta) \\ F_y(t) = K_{tc}\cdot[d_c + z(t) - z(t-T)]\{[h + x(t) - x(t-T)] + \sqrt{R_0^2 - [R_0 - d_c - z(t) + z(t-T)]^2}\} \\ \quad + K_{te}R_0\theta_r + K_{tf1}\cdot(\sin\frac{\beta}{2} - \mu\cos\frac{\beta}{2}) + K_{tf2}\cdot(\sin\beta - \mu\cos\beta) \\ F_z(t) = (K_{fc} - K_{rc})\sin\theta_r[d_c + z(t) - z(t-T)]\{[h + x(t) - x(t-T)] + \sqrt{R_0^2 - [R_0 - d_c - z(t) + z(t-T)]^2}\} + K_{te}R_0\theta_r\sin\theta_r \end{cases} \tag{9}$$

where h is the undeformed chip thickness, f is the feed rate, μ is the friction angle coefficient, R_0 is the tool nose radius and d_c is the depth of cut, β is the side clearance angle, θ_r is the intersection angle of two continuous tool paths, T is the spindle revolution period, K_{tc}, K_{rc}, K_{fc}, K_{te}, K_{re}, K_{fe}, K_{tf1}, K_{tf2}, K_{ff1} and K_{ff2} are the cutting constants at rake face, cutting edge and flank face in X, Y and Z directions, which can be acquired by the transformation from the orthogonal cutting experiments and an empirical tool force model.

As has been stated, the real tool path (X_{tp}, Z_{tp}) is created by all the above factors: servo motions influenced by dynamic cutting disturbance (X_{sm}, Z_{sm}), machine tool deformations (spindle radial runout E_{sr}, spindle axial runout E_{sa}, Z slideway side-stiffness K_{zx}, X slideway side-stiffness K_{xz}) and environmental vibrations (E_{evx}, E_{evz}) shown as:

$$\begin{cases} X_{tp} = X_{sm} + E_{evx} + E_{sr} - F_x / K_{zx} \\ Z_{tp} = Z_{sm} + E_{evz} + E_{sa} - F_z / K_{xz} \end{cases} \tag{10}$$

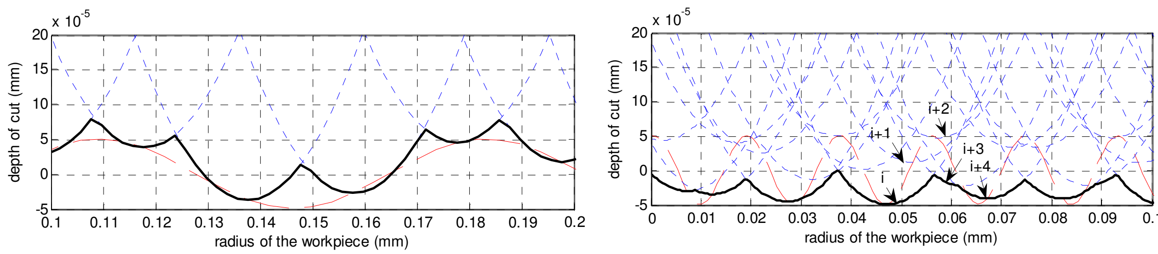
3.0 Simulation of Nano/micro Machined Surfaces

3.1 Prediction Algorithms for a Machined Surface

The last stage of machining system is to renders the surface topography. The cutting tool will follow the real tool path to reproduce the tool profile on the machined surface in the form of feed marks.

Cheung et al. [12] and Kim et al. [13] calculate the intersection of two adjacent tool profiles to get the boundary of each feed marks like Fig.8 (a). However, in the ultra-precision machining, whose feedrate is so small that the next several cuts will clean up the previous tool marks. As shown in Fig.4 (b), the (*i*+1) th and (*i*+2) th tool profiles which are over cut by the (*i*+3) th can not affect the workpiece surface generation. The machined surface is contoured by the *i* th, (*i*+3) th, (*i*+4) th, etc. tool profiles as a result of tool interference from vibrations. Frankly speaking, tool path vibration is not the entire reason to form the surface topography in this case. The tool interference is normal in the small feedrate cutting process, and it always help to flat the tool-workpiece vibration in this case.

All the 3D surface topography prediction procedures are described in Fig. 5 as a block flow diagram. The principal advantage of this approach is considering the multiple tool interference which is more coincident with the real practice.



(a) Intersections of two adjacent tool profiles (b) Intersections in consideration of all tool profiles

Fig. 4 2D Machined Surface Profile simulation

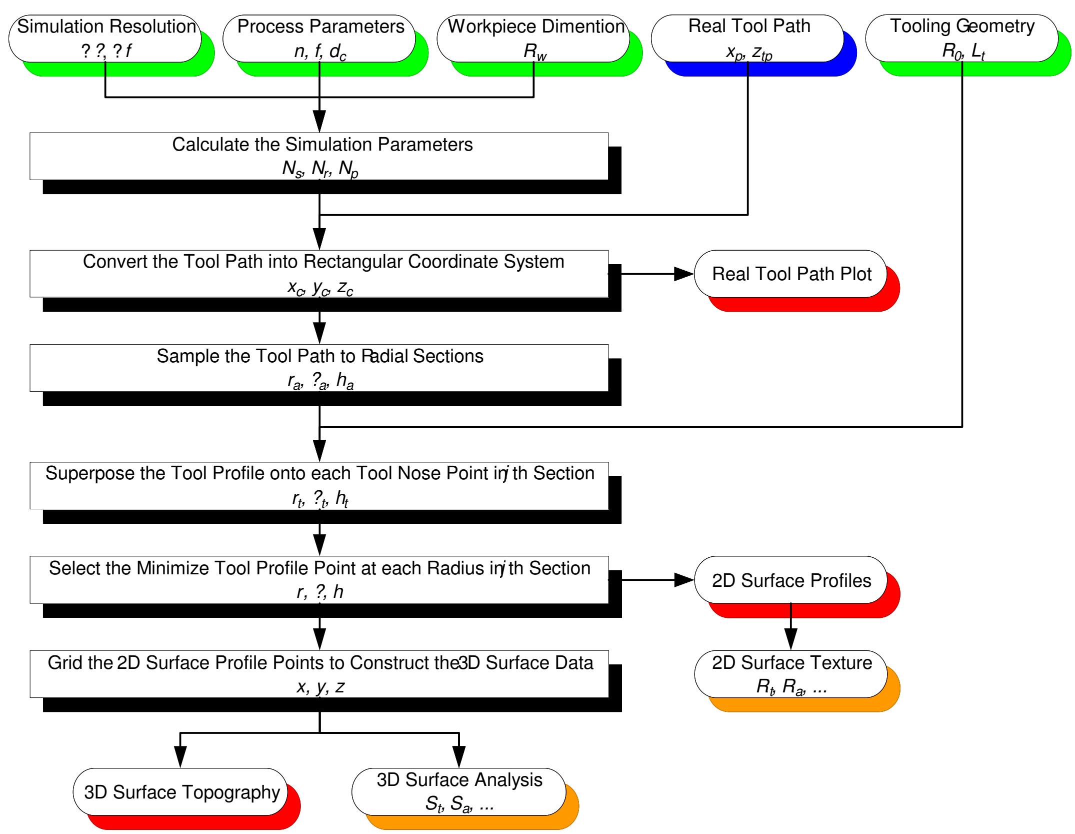


Fig. 5 The Flow Chart of 3D Surface Topography Simulation Model

3.2 Simulation on the Surface Generation

The relative displacement between the tool and the workpiece in Z direction is mainly decided by workpiece material, machine tool performance, tooling geometry and cutting parameters. The simulated surface under the dynamic cutting process, cut from edge to centre, is a 1.4 mm × 1.4 mm square located at the spindle central line as Fig. 6.

The impressive features on the surface are the rings and flutes which are much bigger than the tool feed mark size. To analysis the waviness structure regulation, it is better to work out the connection of the vibrations and the machined surface topography. Since the tool paths in one section are the discrete points by feed spacing per spindle revolution, the surface generation is like the process of cutting tool edge in feed direction sampling the vibratory tool path. The machined surface topography under vibration is directly decided by the relation between the vibration frequency f_v and the spindle rotational frequency f_s. Define the frequency ratio f_r as:

$$f_r = \frac{f_v}{f_s} = \frac{f_v}{n/60} = a + b \tag{11}$$

where a is the integer part of the ratio and b is the fractional part in the rage of -0.5 to 0.5. In this case namely, f_r is the frequency that the tool tip traverses the vibration within one spindle rotation period. The number of the flutes is identical to the integer part a, which means how many times the vibration is completely undergone per spindle revolution. The absolute value $|b|$, which can not cover the full vibration cycle, will make the phase offset in each spindle rotation. The orientation of the flutes is decided by the sign of b. Positive sign means counter-clockwise (CCW); negative sign is clockwise (CW). In other words, the radial section presents the fractional part of the frequency ratio b, while the integer part a will be reflected in the circumferential direction.

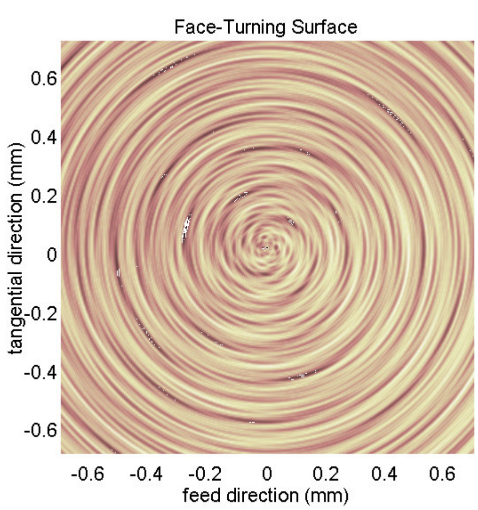
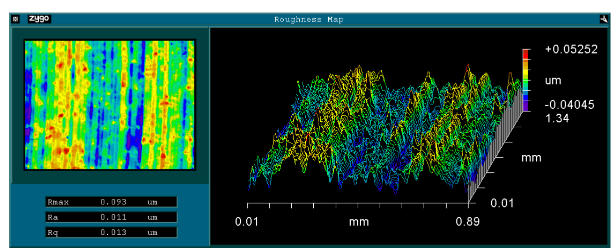
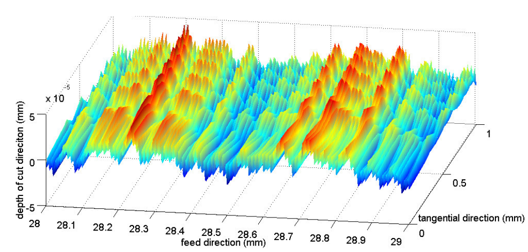


Fig. 6 Flat Turning Surface Simulation



(a) Measurement of the Actual Machined Surface



(b) Simulation of the Machined Surface

Fig.7 Identification of the Surface Prediction System

4.0 Experimental Verification

In order to evaluate the effectiveness of the dynamic cutting process model and the surface prediction method, the surface descript so far were verified through the experimental work. Fig.7 (a) shows the measurement result of an actual Al specimen machined at 1000 RPM spindle speed, 0.01 mm/rev feedrate, 0.01 mm depth of cut, and 0.508 mm tool nose radius using Zygo NV 5000 system. The measured surface locates on the 28-29 mm radius area where the tool marks are nearly the straight lines. The surface prediction is simulated as Fig.7 (b) whose form is accordant with the experiment result.

5.0 Conclusion

- Metal cutting process is combined with the material property, cutting chatter, tooling geometry, servo capability, mechanical performance, and environmental vibration, etc. The integrated simulation system can help to better understand the connection of the dynamic cutting process and the surface generation. The non-linear factors will simulate the real cutting condition, such as hard grain of material, BUE, regenerative vibration, tool wear and spindle runout. Building the drive and control system in the model gives the flexibility to evaluate and improve the control system performance.
- Surface prediction should take consider of tool interference effect. The tool interference commonly appears when the low feedrate or big rake radius cutting tool is adopted. The valleys on the machined surface may be not caused by the tool interference, but from the tool path vibration.
- The frequency ratio method can interpret the surface topography formation. In this case, a states the number of the flutes; $|b|$ is the phase offset in one section and the sign of b present the flutes direction.
- The computer simulation and preliminary experimental results have proved that the approach is able to identify any existence of tool vibrations in nano/micro cutting process and their effect on the surface generation. Currently, the authors are undertaking well-designed substantial cutting trials and simulations to further verify the approach developed potentially applied to free-form surfaces in multi-axis nano/micro machining, the results will be presented in other papers in the near future.

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ON THE DESIGN OF A MONITORING SYSTEM FOR DESKTOP MICRO-MILLING MACHINES

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Abstract

A critical issue in micro-milling is the unpredictability of tool life and the premature tool failure. Micro-end-milling is emerging as an important fabrication process. Its benefits include the ability to fabricate micro and meso-scale parts out of a greater range of materials and with more varied geometry than it is possible with lithography and etching. A variety of sensors can be used for capturing the necessary information on micro-machining process. These sensors may vary from encoders, load cells, accelerometers to acoustic emission sensors. Each sensor type has a main field of application, which depends both on the desired level of precision and the control parameter that must be measured. This paper presents the design philosophy, restrictions and considerations, of a combinational method for developing a process monitoring system that is capable of monitoring simultaneously the spindle's and tool's condition during micro-milling operations. The design of the monitoring system is based on vibration and acoustic emissions caused by the micro-milling process.

Keywords: Micro-Milling, Condition Monitoring, Vibration Emissions, Acoustic Emission

1.0 Introduction

The importance of maximizing the tool's working time and doing the utmost to keep them from breaking, is directly related to the cutting-process optimization in modern manufacturing [1]. One of the main goals is to find the appropriate balance among the tool-wear, surface quality and productivity regarding the tool's cost, its replacement cost, the cost of writing off the machine's idle time and so forth [2] .

In recent years, a trend for integrating several monitoring approaches, through sensor fusion, exists in developing the Tool Condition Monitoring Systems (TCM). Such solutions are very important for the development of new more effective systems for monitoring the micro-milling process. However, before investigating the modern TCM, the breakage mechanisms should be fully understood in order to be monitored effectively. Three breakage mechanisms may occur in the micro-milling operation [3]. The first one involves the chip clogging that could take place when chips are not removed fast from the machining area. Cutting forces and stresses on the tool are increased beyond its endurance limits. Consequently, a breakage is an unavoidable happening. Chip clogging is difficult or even impossible to be predicted. Secondly, a fatigue-related breakage may occur due to tool wear. The reason for this is that the cutting forces and stresses increase with the increase of the tool wear and stay high for an extended period. Thirdly, a tool breakage may occur if the tool deflection during the cutting is beyond the endurance limit of the tool. This may result because of the decreased sharpness of the cutting edges, their partial damage, or the deposition of material in the tiny grooves of the cutters. Unfortunately, in micro-milling machines, the breakage of the tool is not visually detectable, due to their small sizes, and the generated chips as well as the cooling mist in the machining area [3]. Thus, the only solution in micro milling is the use of TCM in order for the process effectiveness to be improved.

The tool condition monitoring systems (TCM) is a key issue for ensuring a better use of the machine-tool's capabilities. Sensorial information from several sensors (i.e. accelerometer, dynamometer, acoustic-emission AE sensor, strain force sensors, etc) is gathered during the process, analyzed and compared, by assessing the deviations, in representative variables, in the time and frequency domain [1]. The time and frequency domain analysis confirms the relevance of the sensor signals' signatures of the TCM systems in the HSM processes. The major factors affecting the TCM systems, the workpiece and the machine tool in an HSM process, are cutting force, tool wear, tool deflection and spindle vibration. In most engineering problems, feeding the process with inputs could lead to getting useful outputs. From the TCM system's viewpoint, there are some variables and parameters involved in the process. These can be considered as inputs to a TCM problem, and are; the spatial position of the cutting tool (Cartesian coordinate axes), the spindle speed (Vsp in rpm), the relative feed speed between tool and worktable (feed rate – f in mm/min), the cutting speed (Vc in m/min), the radial depth of cut (DoC in mm) as well as the cutting-tool diameter (d in mm). Regarding these variables (inputs), the experiments could be executed for various (in theory infinite) values and in different combinations, by collecting in this way, the sensorial signals and analyzing the tool wear condition.

The monitoring operation, as described by Artis in [4], is based on the comparative measuring methods. During the entire machining process, the curve of measured characteristics is compared with the stored characteristics of an identical machining operation having been carried out previously with a sharp tool. Whenever the characteristics of the current machining operation deviate from the comparison stored data by more than a specified tolerance range, the type and amount of deviation can be used in order for specific information on various errors to be obtained.

Micro-end milling enables the manufacturing of functional micro-components, in three dimensions, with a high material removal rate, with the use of tools under 50μm in diameter [5][6]. Furthermore, tool parameters such as the edge geometry, grain size and orientation that do not affect considerably the machined component at larger scales, are of great importance; whilst the unit removal size decreases because these parameters affect dramatically the accuracy, surface quality and integrity of the component [6]. These characteristics set a challenging environment for the development of a reliable tool condition monitoring system.

2.0 Monitoring System Requirements

Nowadays, in order for products with a high degree of economic efficiency, productivity and quality to be manufactured, the use of tool monitoring systems is indispensable for many production processes [7].

In order for the basic function of a TCM system to be guarantied, the following requirements for a monitoring system are being specified and are as follows:

- Few or no sensor systems on the machine (if possible)
- No cut-out required in the switch cabinet
- No space required in the switch cabinet
- No additional operator panel on the machine
- Quick installation
- Network capability
- Automatic set-up function, simplified operation
- Low-cost
- Modular and expandable
- Process visualization

The above requirements show that a high degree of integration is necessary in order for an efficient and flexible monitoring system to be built. However, this integration is not only limited to operation and visualization, but it is also necessary in order for further information and signals from the control system to be used. Moreover, the monitoring systems should recognize the defects and report them as a fault message or system state [8]. This result can be used as input for a diagnostic process in which the reasons for fault are found and located. In the field of manufacturing processes, the main tasks of these systems are:

- Function control and fault location of the machine components
- Process control for recognizing any process failure
- Recognition of machine inaccuracy, leading to the lack of quality
- Support to the operating and maintenance staff

3.0 Tool Condition Monitoring Methods

Current methods of tool condition monitoring can be classified into two main categories [6] [9]: i) the *direct* method, in which sensors gather data directly from the cutting edge of the tool and ii) the *indirect* method, in which sensors gather data that can be correlated with the tool condition.

Direct Tool Condition Monitoring Method

Optical microscopes are used for gathering detailed images and for inspecting the geometry of the cutting edges as well as the surface condition of the tool. Flank wear can be detected with the use of a CCD camera, whilst the crater wear requires the projection of a structured light pattern onto the tool, in order to acquire depth information from within the crater. In structured light sensing, with the use of laser interferometers, the distortion of parallel lines of the laser light gives a measure of the crater's depth. Due to the small size of the tools, used in micro machining, this method is rather difficult to be applied. Proximity sensors estimate the tool wear by measuring the change in the distance between the tool edge and the workpiece. This distance is affected by the tool's thermal distortions, the deflections or vibrations of the workpiece and the tool. Capacitive displacement sensors are capable of measuring a minimum distance of 0.2mm with a frequency up to 20 kHz [10]. Such sensors can also be used for measuring the unbalance, due to the loss of material from the tool cutting edges. The variation of the measured distance, up to certain limits, from a relatively fixed point to the cutting edge, can show the condition of the cutting tool. Direct tool condition monitoring strategies have been proposed and reviewed in literature. The main advantage of the methods proposed is that they do not introduce any restrictions on the cutting tool movements/operations.

Indirect Tool Condition Monitoring Method

A variety of sensors can be used for capturing the necessary information on the machining process. These sensors may vary from encoders, load cells, accelerometers to acoustic emission sensors.

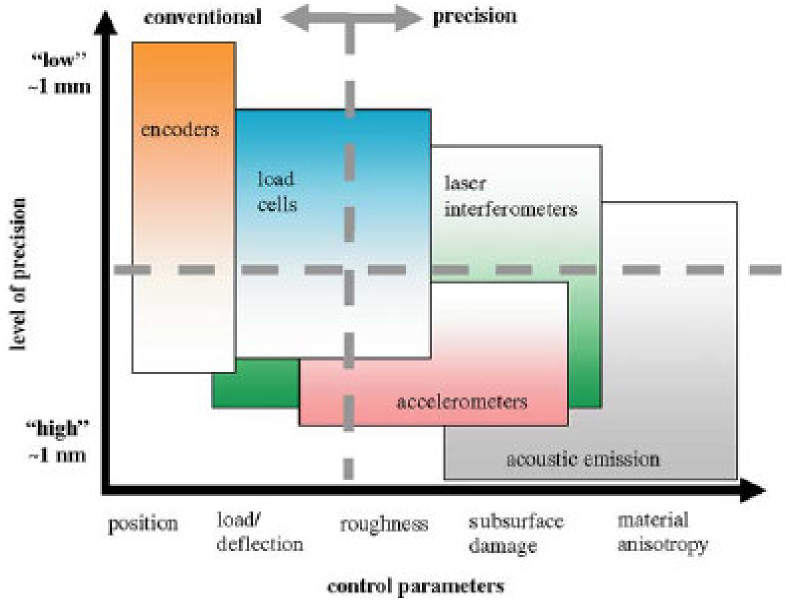

Fig. 1. Sensor application vs. level of precession and control parameters [11]

Each sensor type has a main field of application, which depends both on the desired level of precision and the control parameter that must be measured. However, due to the exponential growth of the sensor technology, these borders are flexible, since each sensor type may be utilized successfully in several applications. Load cells are mainly adequate to perform conventional machining, but they do not offer the necessary signal to noise ratio (S/N) and sensitivity that are required in precession machining [5][11]. Cutting forces and power consumption in micro end milling are extremely low, so the application of the load cells is reliable for the measured range of frequency, at several times higher than the rotational frequency of each tool's cutting edge. As shown in Fig. 1, acoustic emission (AE) sensors are rather adequate for high precision machining, due to the sensitivity ratio of high noise. Moreover, a major advantage of the AE sensors is their ability to deal with frequencies higher than the characteristic ones of the machining process, thus, limiting the introduction of noise into the generated signals[11][12]. The signals are classified into continuous and burst, having distinctly different characteristics. The continuous signal is associated with shear in the primary zone and wear on the tool face and flank, whilst burst signals result either from tool failure or from chip breakage [12]. The above advantages come to terms with the results of [13] that monitored a milling process successfully with the use of an AE sensor, placed on the work piece. Their monitoring set up was capable of holding an indication of the tool wear and surface quality and of measuring tool breakage. AE signals were proven as the best choice between signals from a microphone and an accelerometer. Vibrations in a machining process may be produced by cyclic variations on the dynamic components of the cutting forces [14]. An important point of a monitoring system is the measurement of vibrations of the cutting tool's rotational shaft. These measurements can be made with the use of accelerometers [15]. The sensors of this type can typically measure the acceleration in three dimensions (tri-axial), in a frequency greater than 10 kHz [16]. The most important point of an indirect tool condition monitoring system is the fusion [17][18][19] of different types of sensor signals and the conclusions concerning the tool condition. The mounting location of each sensor, related to the machining point, plays a major role to the desired characteristics of the indirect monitoring system.

4.0 TCM System Setup

The possible-preferred physical quantities and sensor types that can be used for detecting tool failure are: force and torque, vibration via acceleration, acoustic emission and ultrasound sensors and laser sensors. Due to the nature of the process (high speed machining) the maximum frequency is in the range of 9.5-10 kHz (90.000 rev/min) and of the cutting forces around 5Nt.

The measurement of the cutting forces has several drawbacks. Firstly, these forces are very low and are difficult to be measured accurately. Also the installation of the force-torque sensor has negative influence on the dynamics and stiffness of the machine. So there is a need for an ultra precise force sensor in order to meet the above force requirements.

Most promising techniques are the vibration and acoustic measurements (including acoustic emission). Acoustic emission (AE) measurements are high frequency acoustic signals that originate from the deformation of the work piece material. When the tool breaks the sensor it also measures the AE energy resulting from the fracture. In addition, accelerometers measure the vibrations generated by the process, and are capable of measuring the cutting operation even for the very small cutting forces. There is a need for capable vibration sensors to sense the changes in machining conditions. Piezoelectric vibration sensors measure the mechanical vibration of the machine structure resulting from the cutting process, typically up to 10 kHz. It can be used for detecting missing tools, broken tools, out-of-tolerance parts, machine collision and severe process faults. It is also possible to monitor any excessive vibration on the spindle. The vibration sensor is easy to be installed on new or existing machines. An ultrasound and vibration sensor is suitable for measuring vibration-induced oscillations up to an ultrasonic range (100 –: 80 000 Hz) in machine components.

A light barrier offers a reliable tool breakage and tool missing monitoring system if tools are too small to be monitored by force, true power, or if there is no suitable place available for an AE sensor to be mounted. In a reflective single-beam laser system, the tool conditions are monitored by constantly focusing a laser beam with a spot size of 50 μm on the cutter, and at the same time, directing the beam reflection towards a receiver. To avoid "hidden" areas, for example, when milling pockets or grooves, the laser beam is focused just above the tool working length. The light intensity of the reflected beam is measured with the use of the amplifier for indirectly detecting any tool breakages.

The proposed Tool and Spindle Condition monitoring system lies on the combination of Acoustic Emissions and the Acceleration sensor, installed on a 3-axis micro-milling experimental device as shown in Figure 2. The air-driven spindle has a maximum rotation speed of 100.000 rpm.

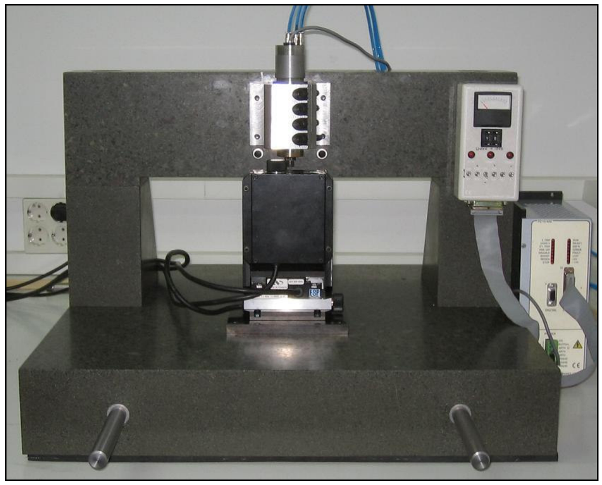

Fig. 2. Overview of Micro Milling experimental setup

It introduces the use of a sensor on the spindle mounting bracket and a second sensor on the clamping device or the X-Y-Z table. For indirect spindle condition monitoring an accelerometer may be used on the mounting bracket. This sensor can measure the vibration's velocity, due to the spindle's shaft unbalances. A recommended way of coupling such a sensor on the bracket is the stud mounting method.

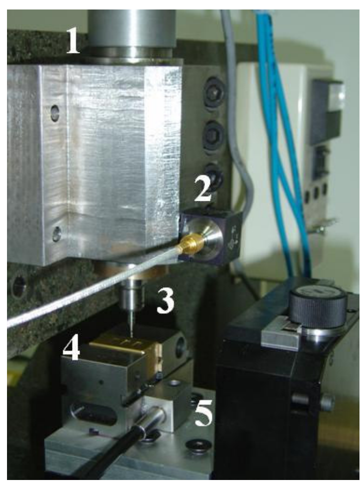

Fig .3. Close view of the machining area and monitoring sensors

Figure 3 shows the details of the micro-milling TCM monitoring setup. The micro-milling machine is equipped with an air driven high speed spindle (1) reaching 100.000 rpm. The acceleration sensor (2) mounted on the spindle bracket is a Kistler Annular Ceramic Shear Triaxial – 8762A50 accelerometer, with a sensitivity of 100mV/g and a frequency range from 0.0005 to 6 kHz. The micro-milling tool (3) may vary according to the machining needs; from conventional micro tools to synthetic or natural diamond milling tools. A calibre clamping device (4) ensures the proper placement of the work piece. Finally, the Acoustic Emission sensor (5), a Kistler 8152B2 AE one, with a frequency range of 100-900 kHz is placed as near to the milling point as possible, but without interfering with the process.. The overall connectivity diagrams of the sensor in the DAQ system are shown in the figures below.

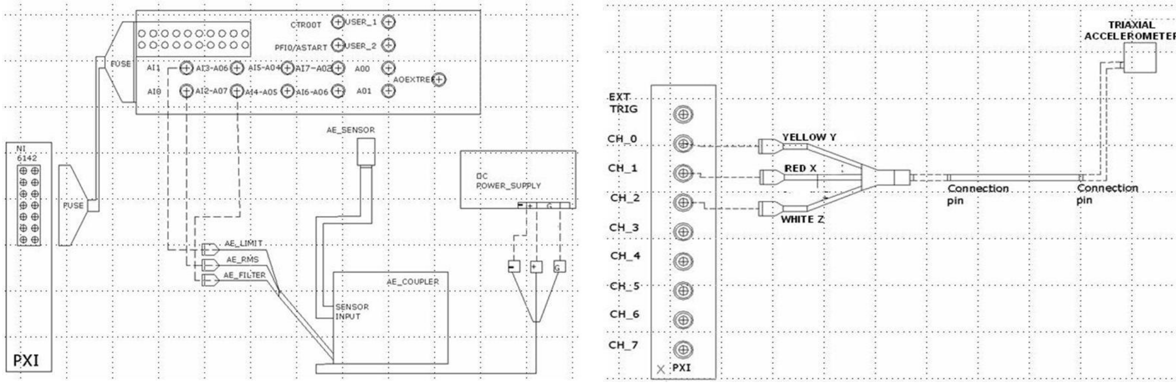

Fig. 4. Connectivity diagrams of the Acceleration (left) and Acoustic Emission (right) sensors

Data acquisition is accomplished by PXI (PCI eXtensions for Instrumentation) units, which are a rugged PC-based platform for measurement and automation systems. PXI combines PCI electrical-bus features with the rugged, modular, Eurocard packaging of CompactPCI, and then adds specialized synchronization buses and key software features. PXI is both a high-performance and low-cost deployment platform for measurement and automation systems that meet the requirements as mentioned in section 2 of this study.

5.0 Monitoring Strategy

Existing strategies of the process monitoring can be divided into signal based, model based, and classifying methods depending on the complexity of the manufacturing process [8]. Using signal- or boundary value-oriented methods, the measured signal values should be compared with pre-defined signal values or with a signal range. The basis of model-based monitoring techniques are process models that are either determined empirically or from physical relations. In using models for process control, it is important that the model be supplied with useful input variables describing the process that is to be examined. The target of the classifying monitoring systems is to find the link of a feature vector to a certain class of quality features. This vector is often determined by feature extraction of the process signals.

For the signal based technique, an analogue (electrical) signal from the sensor is usually (after basic signal conditioning, e.g. primary filtering) converted into a digital form. The time series obtained is then processed to extract signal features that are sensitive to the parameters of interest in the monitored process. The detection of process irregularities is achieved by the implementation of some sensing methodology, called a monitoring strategy [20]. In the past, it was sufficient to monitor an upper limit but meanwhile, many strategies and algorithms have since been developed in order to deal with the many different processes [21]. Most of the techniques that are incorporated into monitor strategies are based on static limits. A static limit can be a threshold for activating alarm signals, and it remains fixed during the processing of a workpiece. Furthermore, dynamic limits are introduced into monitoring strategies, which are driven from sensorial signals and tolerance ranges. The monitoring strategy adopted for this work is the so called dynamic limits strategy.

In this method, two dynamic limits follow the monitor signal continuously for every load level at a limited adopted speed. In the case of an extremely fast crossing of one or two dynamic limits, they are frozen (rendered static) and the total breakage, breakage, chipping, workpiece cavity, hard cut interruption, etc. are distinguished from one another via a visual comparison with the monitor signal. Slow but large load changes ,due to variations in cutting depth (hardness, oversize, out-of-roundness of workpiece), such as those occurring during the initial cuts, in particular, when machining cast and forged parts, are tolerated at a ratio up to 1:4. The signal is also automatically used for coping with the wide difference in force or signal values produced; for example, by large roughing tools as compared with small finishing ones. Signal adaptation automatically keeps them for analysis at an optimum level. The combination of feature conditioning, automatic signal adaptation and dynamic limits mean that monitoring functions are fully automated over a wide range of force or sensor signals in completely different machining situations, without manual adjustments or a teach-in phase. Tool breakages are practically detected at the instant of breakage (typically 5 ms), by means of typical changes in the sensor signal

6.0 Conclusions

A major issue in micro-milling is the unpredictable tool life and premature tool failure. The specific acoustic footprint and very small removal rates, during machining, as well as the use of small diameter cutters, makes the detection of tool breakage a very difficult task. Thus, it is essential to develop new tool monitoring systems to increase the process productivity, reduce machining costs and at the same time, improve the precision and quality of machined components. The existing tool condition monitoring systems have a relatively high cost to performance ratio, and they are efficient only in limited applications and operational conditions. There is a need for reliable, efficient and more economical systems, for the better monitoring of the machine and the tool condition, as well as for enhancing the quality of the parts produced. This paper presents the design philosophy, restrictions and considerations of a combinational method for developing a process monitoring system that is capable of monitoring simultaneously the spindle and tool's condition during the micro-milling operations.

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INVESTIGATION OF FEEDING DEVICES AND DEVELOPMENT OF DESIGN CONSIDERATIONS FOR A NEW FEEDER FOR MICRO-SHEET-FORMING

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Abstract

A recent review of micro-forming research and technological development suggested that the trend of the development is focused more on the manufacturing processes, machines and tooling, with efforts on the precision material handling being insufficient. Most of the developed machines were based on stand-alone concepts that do not support efficient integration to make them fully automated and integrated. Material feeding in most cases was not of sufficient precision and reliability for high throughput manufacturing applications. Precision feeding is necessary to ensure that micro-parts can be produced with sufficient accuracy, especially in multi-stage forming, while high-speed feeding is a necessity to meet production-rate requirements. Therefore, the design of a new high-precision and high-speed feeder for micro-forming is proposed. Several possible approaches are examined with a view to establishing feasible concepts. Based on the investigation, several concepts for thin sheet-metal feeding for micro-forming have been generated, these being argued and assessed with appropriate applied loads and force analysis. These form a basis for designing a new feeder.

Keywords: micro-forming, micro-handling, forming press, gripper feed, roll feed, micro-tooling

1.0 Introduction

Research into the forming of miniature/micro-products [1] has led to investigation into material-feeding methods and devices as a part of the development of a machine system to transfer laboratory-based forming processes to production [2]. Feeding the materials with higher rates and high accuracy in micro-sheet forming is one of the challenges to be met in micro-forming research and development for engineering applications.

Conventional press feeders have to meet three main criteria to be successful. Firstly, the feeder must be flexible in terms of set-up. Secondly, the delivery of material must be of sufficient precision to satisfy the requirements for forming. Thirdly, the feeders must also ensure feeding at the correct time. All of these are particularly difficult to meet when forming thin sheet metals, such as those where the thickness is less than 100 microns, where the feeding distance is greater than 10mm and where the feeding rate higher than 500 stroke per minute (SPM). These are the requirements for the development of a new machine system for micro-sheet-forming: Fig. 1 shows a 3D model of the machine developed at the University of Strathclyde.

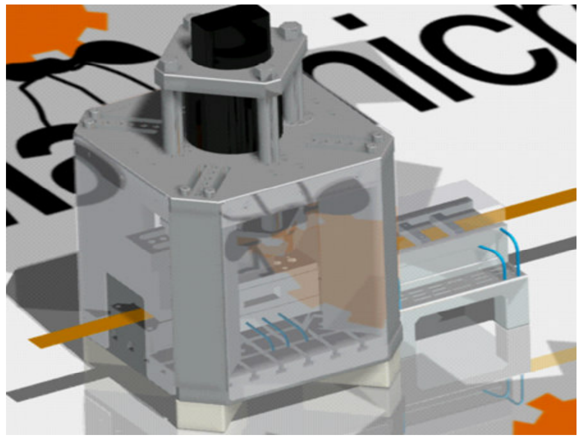

Fig. 1. 3D model of the micro-sheet-forming machine

Two methods of feeding sheet-metals in conventional stamping may be applied to micro-sheet-forming - roller feeding and gripper feeding [3-4]. The servo roll feeder uses an electric servomotor while a gripper feeder mainly uses pneumatic actuation. Although the latter may exhibit limited flexibility in the varying of its travel distance and feeding speed, this type of the feeder has the potential to compete with the servo roll feeder in respect of positional accuracy and precision. Greater accuracy is achievable due to the possibility of a gripper feeding mechanism not having a complicated mechanical transmission and hence, no backlash, wear, tear, etc. which can contribute towards inaccuracies in feeding. However, an error arising in translation from angular rotation to linear motion in roll feeding contributes towards inaccuracies: this does not occur with a linear gripper feeder. With the possible use of a servo system, the performance of a gripper feeder could be improved, regarding the flexibility in travel distance within the system length set-up, and in feedback and positional accuracy. The research reported in this paper is dedicated to a study of these issues, based on which considerations for a new feeder design are developed.

2.0 Linear-Displacement Devices for Sheet-Metal Feeding Applications

Three categories of devices have been used widely for high-precision feeding - electromechanical actuators [5-9], electrical actuators [10-12] and piezoelectric-actuators [13-14]. Table 1 shows a comparative study made on those devices. The proper selection of a high-precision system is essential in order to secure high-precision/accuracy for high yield feeding applications. Linear motors are seen to have superior characteristics among the others in terms of speed, acceleration, precision/accuracy, robustness, ease of maintenance, etc. as well as being used widely by researchers as an alternative to conventional rotary machinery [10-18].

Table 1: Types of linear displacement devices and their suitability for micro-press feeding applications

Device Type	Accuracy and precision	Acceleration rate (g)	Force (N)	Size	Reliability
Solenoid	Inflexible and uncontrollable over the stroke distance, and hence difficult for precision to be defined.	Impressive response time and acceleration over short distance.	Fairly high force, which is inversely proportional to stroke distance.	Small and compact, suitable for a constrained space application.	Reliable in terms of mean time between failures (MTBF).
Ball/lead screws, belts, gears, rack and pinions, etc.	Flexible with limited stroke distances and accurate up to 6-7µm. A greater inaccuracy develops with time, due to wear, tear, etc.	Acceleration rate is low due to mechanical transmission being involved.	High thrust force is available.	Fairly small, depending on the application.	Reliable as demonstrated by most of the devices.
Linear motors and stages	Stroke distance may be limited. Combined with air-bearing, the system could have very high positioning precision. No backlashes to contribute to inaccuracies.	Acceleration rate can be high: 5-10g is typical, and 40g available commercially.	High thrust force, ranging from tenths up to thousands of Newtons.	Fairly small. Force is proportional to the coil size.	Reliable as demonstrated in many cases.
Piezoelectric-actuator (linear motor)	Very accurate and precise. Has been used in photonics and high precision applications but with very limited travel distances.	Response time is better over short distances, reflecting high acceleration rate.	Low force ranging between 7-10N, limiting its application to low force feed & positioning tasks only.	Depends on the travel distance required.	Reliable for low speed positioning. For high speed positioning, heat may tend to build-up as well as wear and tear.

Linear motors are seen to have advantages over others in terms of achievable accuracy with impressive acceleration rates. Since there are no backlashes and plays, which will contribute towards positioning inaccuracies in the system, greater accuracy is expected to be achieved. Therefore, a linear motor is seen to be a good platform when considering feeding design for sheet metal to achieve high precision and high-rate feeding.

In the selection of an appropriate motor for the feeder for a micro-press among iron-cored and iron-less motors, several parameters need to be considered - force density and magnetic attraction, stiffness and settling time in terms of dynamic and static characteristics, accuracy, velocity, stability, etc. Both iron-cored and iron-less motors have their respective advantages in terms of the foregoing factors. The first parameter to be considered is the force density. As the name implies, due to the presence of iron laminations in the forcer of an iron-core motor, extra force may be generated by attraction force from the magnetic track on the forcer, in addition to the force generated by the electromotive force (emf). Magnetic attraction on the iron lamination in the forcer also contributes to a 'cogging' effect on the iron-core motor. 'Cogging' affects the smoothness and repeatability of an iron-cored motor to achieve outstanding precision, such as that which an iron-less motor might be able to achieve [12]. An iron-less linear motor was used to study the multi-degrees-of-freedom error motions of a precision linear aerostatic-bearings stage [19] and to determine the achievable precision. Such a motor was used because a greater precision is achievable due to no 'cogging'-effect existing, compared to an iron-cored linear motor. In another study [20], an iron-less linear motor was used to drive an air-bearings stage and to determine the precision of the motor. Greater precision and repeatability were found with an ironless-linear-motor-driven stage.

A high stiffness of the motor in terms of static and dynamic characteristics is required due to the short settling time and rapid motion involved. A short settling time associated with high dynamics or high positional stability requires stiff mechanical characteristics of the motor. The epoxy structure in an iron-less motor may have low inherent stiffness, but the rigidity of the motor may be enhanced by the copper coils inside the forcer which leads to better stiffness. However, the steel structure in an iron-cored motor makes it stiffer than an iron-less motor. Nevertheless, according to previous reports [14]-[20], control of the ambient temperature to within 1°C may be needed, which should greatly assist thermal reduction to protect the structure of the linear motor from excessive thermal deformation. Greater stiffness in both the motor structure and the mounting could eliminate structural deformation that could cause backlash and play during rapid operation. Therefore, a high-accuracy process is feasible and qualified. Table II tabulates a comparative study of the iron-less and iron-cored linear motors.

Table II: Comparative study on iron-less and iron-cored linear motors

Micro-sheet forming feed application	**Description**	
	Iron-less	**Iron-cored**
Continuous force of 150N	Very suitable. Most iron-less motors have a continuous force ranging from 0 – 450N. This indicates that an iron-less motor is only suitable for low load demand, for example, in a positioning application with a light-weight feeding mechanism.	Very suitable. An iron-cored motor usually has a two-times greater continuous force than an iron-less one, which indicates suitability for applications demanding greater force.
Peak force of 500N	Very suitable for feeding. The greatest peak force is rated at up to 1600Nm and normally lasts for a few seconds before the motor starts to overheat and burn.	Very suitable. Higher continuous force leads to higher peak force, compared to an ironless linear motor.
Smooth motion	Very suitable. No cogging effect and using an air bearing (gap between forcer and U-channel magnetic tracks) make non-contact smooth, ultra-precision linear motion possible.	Iron lamination inside the forcer causes the cogging effect. Non-smooth motion between the forcer and the magnetic way experienced. It is not recommended for high smooth-motion applications.
Precision down to a sub-micron order	Sub-micron accuracy/precision and repeatability is possible and recommended.	Sub-micron accuracy/precision and repeatability is feasible in slow speed and can be used as a cheaper alternative option.
Speed stability	Up to 0.1% error at 1kHz measurement - it is very stable in terms of speed.	Speed stability is equal to that of an iron-less motor and it is recommended as a cheaper alternative.
Thermal dissipation	Not recommended due to no heat-transfer medium: entirely reliant on air circulation to reduce the motor temperature. Controlled ambient temperature might reduce thermal build-up.	Recommended for high heat build-up applications due to this motor having water and air-cooling mediums.
Dimensional constraint	Recommended due to compact sizes, e.g. a 200mm x 200mm sized feeder has been developed.	Not recommended due to large and bulky structure. A small and compact feeder is not feasible with this type of motor.
Acceleration	Most of the motors have an acceleration rate of up to 40g (more than 115g theoretically).	Acceleration rates of up to 10g are feasible.
Speed	Speed ranges of from 0 – 10m/s.	High speed ranges similar to those of iron-less motors are achievable.
Stroke < 50mm	Recommended. A moving magnet or moving forcer can be proposed.	Suitable, provided that moving-magnet motion is proposed.
Clean room applications	Very suitable due to no particle generation (if no moving cable is deployed).	Suitable if no moving cable motion is deployed.

3.0 Feasibility Study of a New Gripper Feeder

The correct sizing of the linear motor during the design stage is crucial, as this will have an impact on the performance of the entire system and will contribute to the achievement of the designated production rate. Associated considerations include the designated load and push/pull force. Figure 2 shows the applicable forces that are taken into account for a linear-motor sizing analysis. Three types of force contributing to the total peak and continuous linear-motor forces are identified for this particular application.

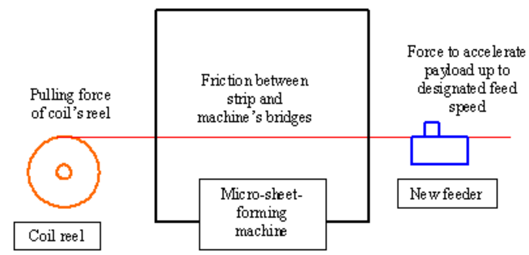

Fig. 2. Types of the related forces, friction between parts and payloads, that contribute to total peak and continuous force requirements.

3.1 Forces due to the Payload

As depicted in Fig. 3(a), for the case studied, about 0.3kg payload of the clamping mechanism and weight were required to be moved. As designed, the 0.3kg payload is: to advance 19mm in 0.120s; to dwell for 0.030s; to retract for 0.120s; and to dwell for 0.030s; the cycle being repeated thereafter for 3.33Hz operation. In this case, analysis and calculation of the required forces in order to determine the best linear motor and amplifiers are major requirements.

The first factor considered was the motion characteristics - the peak speed needed to accelerate the mass from the origin to the end point, the time duration which the travel takes, and the dwell period when the moves end. In general, for this type of motion, which is from point to point, the basic profile is trapezoidal movement. With this movement the time is divided equally into three parts. The first part is acceleration, the second part is constant velocity, and the third part is deceleration. Such motion characteristics should ensure a balance between the speed and acceleration to give the best motor combination. Based on trapezoidal motion, the time taken to accelerate is calculated as:

$$\frac{0.120s}{3} = 0.040s \qquad (1)$$

Then the peak speed required to make the movement was calculated and in this case, because the movement is symmetrical and divided into three parts, the equations below were used. The load cannot accelerate instantaneously from 0 to 0.475m/s and, as previous established; it will take 0.040s to reach this speed. Therefore accelerate rate then was calculated as shown in Fig. 3(b):

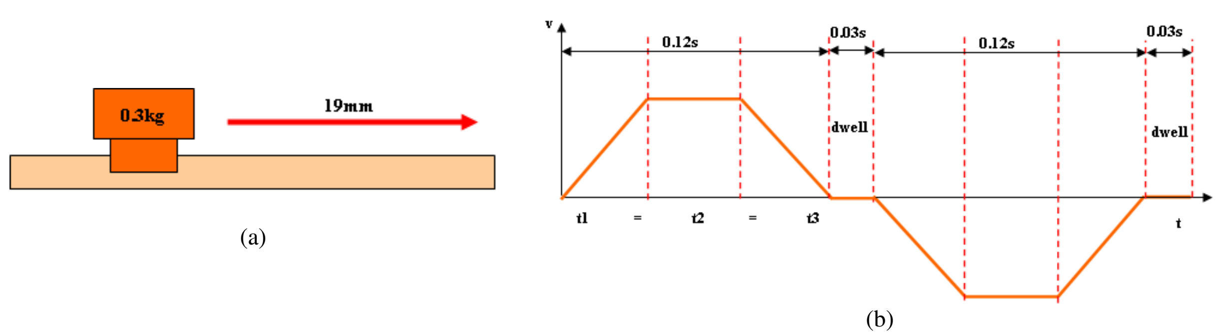

Fig. 3. (a) The load exerted on the forcer, and the direction and distance of movement;, and (b) the trapezoidal profile representing the acceleration of the forcer in one cycle.

$$v = \frac{3s}{2t} = \frac{3\times 0.019m}{2\times 0.04s} = 0.7125m/s \quad (2)$$

$$a = \frac{v-u}{t} = \frac{0.7125m/s - 0}{0.04s} = 17.81m/s^2 \approx 1.8g \quad (3)$$

The peak payload rating force, f_p, considers: the frictional force, f_f, (with the assumption of re-circulated ball bearings being used to carry the load in the system, having a coefficient of friction of about 0.002 up to 0.003); the force for acceleration, f_a, calculated using Newton's laws of motion; and the gravitational force for an inclined plane, f_g; as well as the external force, f_e,, caused by the cable management. Therefore, the payload rating force may be expressed as:

$$f_p = f_a + f_g + f_f + f_e \quad (4)$$

f_a represents the forces for the load, including the forcer mass, and is used to calculate the final coil-temperature rise, peak and the continuous current and minimum bus voltage. In the mechanical-transmission linear stage, the frictional value on the lead screw system should also be taken into account as it usually affects the system positional accuracy.

$$f_a = ma = 0.3\times 17.81 = 5.343N \quad (5)$$

$$f_g = \sin(\theta)mg = \sin(0)\times 0.1\times 9.81 = 0 \quad (6)$$

$$f_f = mg\mu = 0.3\times 9.81\times 0.003 = 0.009N \quad (7)$$

$$f_e = 0 \quad (8)$$

$$\therefore f_p = 5.343 + 0 + 0.009 + 0 = 5.352N \quad (9)$$

By adding a safety factor of 25%, the calculated force was increased to compensate for the degradation of the motor efficiency, the new force to move the payload was calculated to be 6.7N. Due to the minimum pulling force required being almost 7N, a piezoelectric actuator is not the best option for this application. As for a mechanical-transmission linear stage system, carrying a low/light load is not recommended due to the uneven distribution on load that might also contribute to positional inaccuracies, as has been reported in [9].

3.2 Friction Forces

Friction forces due to the contact between the sheet metal and the guide plates inside the machine (50µm thick strip, 50mm width and contact length 500mm) is analyzed as follows. The mass of material in contact was calculated as:

$$m = \rho V \quad (10)$$

$$V = 0.05\times 0.5\times 0.00005 = 1.25\times 10^{-6} m^3 \quad (11)$$

$$\rho = 7.82\times 10^3 kg/m^3 \quad (12)$$

$$\therefore m = 1.25\times 10^{-6}\times 7.82\times 10^3 = 9.775\times 10^{-3} kg \approx 10gram \quad (13)$$

The coefficient of friction between the strip (carbon steel) and the tool-steel surfaces is taken as 0.15 hence:

$$f_f = \mu ma \quad (14)$$
$$\mu = 0.15 \quad (15)$$
$$f_f = 0.15 \times 0.01 \times 9.81 = 0.02N \quad (16)$$

By adding a safety factor of 25%, the new frictional force value is found to be 0.03N. This value will be added to the calculation of the total peak force for the sizing of the linear motor.

3.3 Pulling Force for the Coil Reel

Another force which contributes to the total peak and continuous forces is the force for pulling the material from its reel, as illustrated in Fig. 4. This can be estimated as follows:.

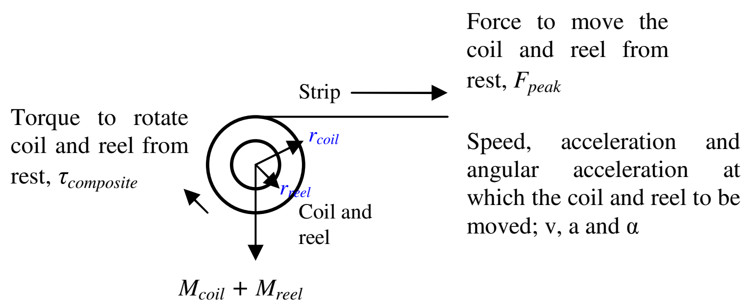

Fig. 4. Free-body diagram of the coil and reel producing a total of torque labeled as $\tau_{composite}$.

knowing that:

$s = 0.0190m$, $r = 0.0625m$, $t = 0.04s$, $u = 0$; and assuming the following:

$$\tau = fr = I\alpha \quad (17)$$
$$\alpha = \frac{a}{r} \quad (18)$$
$$I = mr^2 \quad (19)$$
$$a = \frac{v-u}{t}, v = \frac{3s}{2t}, u = 0 \quad (20)$$

From the trapezoidal motion:

$$v = \frac{3 \times 0.0190}{2 \times 0.04} = 0.7125 m/s \quad (21)$$
$$a = \frac{0.7125 - 0}{0.04} = 17.8125 m/s^2 \quad (22)$$
$$\alpha = \frac{17.8125}{0.0625} = 285 rad/s^2 \quad (23)$$

Supposing that the outer diameter of the coil (carbon steel) and the reel (made of Perspex) are 125mm and 110mm respectively, and by by assuming that both the coil and the reel are solid, moment of inertia of the composite material can be calculated, assuming the following::

$$\rho = \frac{m}{v}, \rho_{coil} = 7820 kg/m^3, \rho_{reel} = 1190 kg/m^3 \quad (24)$$

$$length_{coil} = 50m \quad v_{coil} = 50 \times 0.05 \times 0.00005 = 0.000125m^3 \quad r_{reel} = 0.055m \tag{25}$$

$$width_{coil} = 0.05m \quad m_{coil} = 0.000125 \times 7820 = 0.9775kg \quad h_{reel} = 0.012m \tag{26}$$

$$thickness_{coil} = 0.00005m$$

$$v_{reel} = \pi \times 0.055^2 \times 0.012 = 1.14 \times 10^{-4} m^3 ;\ m_{reel} = 1.14 \times 10^{-4} \times 1190 = 0.1357kg \tag{27 \& 28}$$

$$I_{coil} = \frac{m}{2}(r_{outer}^2 + r_{inner}^2) \qquad I_{coil} = \frac{0.9775}{2}(0.0625^2 + 0.0555^2) = 3.41 \times 10^{-3} kgm^2 \tag{29}$$

$$I_{reel} = \frac{mr_{reel}^2}{2} \qquad I_{reel} = \frac{0.1357 \times 0.055^2}{2} = 2.05 \times 10^{-4} kgm^2 \tag{30}$$

$$I_{composite} = I_{coil} + I_{reel} \tag{31}$$

$$I_{composite} = 3.41 \times 10^{-3} + 2.05 \times 10^{-4} = 3.62 \times 10^{-3} kgm^2 ;\ \tau_{composite} = 3.62 \times 10^{-3} kgm^2 \times 285 rad/s^2 = 1.032Nm \tag{32 \& 33}$$

$$f_{composite} = \frac{1.032}{0.0625} = 16.5N \tag{34}$$

Therefore, the total force required for rotating the combination of the coil and the reel is found to be at 16.5N. By adding a safety factor of 25% (to overcome internal frictional forces, etc), the total of the new force is calculated to be at 20.6N.

3.4 The Uncoil Braking Force

A study on the effect of the coil braking force towards strip tension during the stamping process was conducted previously [19]. However, effort was focused more on the quality in punching a hole quality instead of on feed accuracy. The relationship between the strip tension and the feed accuracy still needs to be studied in detail. As proposed previously [20], the strip tension should be kept at the same level as that of the torque needed when coiling the metal strip in the first place. An adjustable braking force was proposed to make the uncoil process flexible in terms of adjusting the torque to various values [19]. Supposing that the coiling process requires a similar level of torque as the uncoiling of the metal strip, given by the analysis in 3.3, the maximum force to uncoil is 20.6N. By taking f_{rms} of the rated force, therefore, the designated variable braking force for this application is as follows:

$$f_{brake} = \sqrt{\frac{20.6^2 \times 0.04}{0.15}} = 10.64N \tag{35}$$

Since 10.64N force acts during the whole cycle, this is therefore the value needed to be included in the peak force in the sizing of the linear motor.

3.5 Influences of Other Interfacial Forces

Micro-forces which may be neglected in the macro-world may no longer be neglected in the micro-world. The ratio of micro-forces to the weight of micro-parts is at about the same value, whereas in most common situations, the micro-forces are proportionally is greater than the weight of micro-parts, when the sizes of the latter are, 100µm^3 and smaller. Hence, such parts will stick and stay on the handling mechanism, overriding the effect of gravity and thus resulting in problems in the manipulation process. Three types of micro-forces which have a significant influence on micro-parts are known and have of late been studied extensively; adhesion forces, van der Waal's forces and electrostatic forces. Usually, the adhesive force between particle surfaces is due to the presence of van der Waal's forces and electrostatic forces [23-24]. However, these forces do not have a significant effect on material handling for this application, since the handled material is larger than 100µm^3.

3.6 Predicted Peak and Continuous Forces

Based on the analysis presented above, the peak force can be calculated as follows: (36)

$$F_{peak} = f_p + f_f + f_{composite} + f_{brake} = 6.7 + 0.03 + 20.63 + 10.64 = 38N$$

The rms force is the average force, f_{rms} from the motor and helps to determine the final temperature that the coil will reach. Based on the above trapezoidal-profile case, the calculation is as follows:

$$F_{rms} = \sqrt{\frac{F_{peak}^2 \times t}{t_{cycle}}} \qquad t = 0.04s \quad t_{cycle} = 0.15s \qquad \therefore F_{rms} = \sqrt{\frac{38^2 \times 0.04}{0.15}} = 19.6N \tag{37}$$

The new summations of the peak and continuous forces are 38N and 19.6N respectively. Both of these forces were considered when selecting a suitable linear motor. An Iron-less linear motor is chosen due to the demanded peak and continuous forces being relatively small. In addition, by using an iron-less linear motor, a compact system is feasible.

3.7 Coil Temperature, Peak and Continuous Current, and Minimum Bus Voltage

3.7.1 Final Coil Temperature Analysis

The final coil temperature represents the temperature at which the linear motor may be operated without adversely affecting its materials of construction. Therefore this final temperature can be as a guideline when deciding which servo controller is best suited to the designated linear motor. In order to determine the rise of coil temperature, the following equation was used. With the assumption of ambient temperature is 25°C, the rise can be calculated as below with the data supplied from one of the iron-less-linear-motor catalogues [25].

Back Electro-motive force (BEMF) = 24.5 V/m/s; Force constant = 21.3 N/amp; Motor constant = 26.3 N/√W; Coil resistant = 0.7 Ω; Thermal Resistant, R_T = 0.64 W/°C; from the analysis, f_p = 38.0N; f_{rms} = 19.6N.

With the assumed ambient temperature, coil temperature rise may be calculated as below:

$T = R_T \left(\frac{f_{rms}}{M_C} \right)^2 = 0.64 \left(\frac{19.6}{26.3} \right)^2 = 0.36°C$; Therefore, the final coil temperature = 25 + 0.36 = 25.36°C. (38)

3.7.2 Sizing the Amplifier

This analysis was conducted to determine the most appropriate size and type of servo controller to be used so that the linear motor can provide its best performance without suffering from current and voltage drain-out. Based on the given value of the motor's force constant and the calculated peak and continuous forces, the peak and continuous current and minimum bus voltage are calculated as follows:

Peak current= f_p/force-constant = 38/21.3 = 1.78A (39)

Continuous current= f_{rms}/force-constant = 19.6/21.3 = 0.92A (40)

Drive Voltage$_{min.}$ = (peak current x coil resistant) + (velocity x back EMF) = (1.78 x 0.7) + (0.7125 x 24.50) = 18.7V (41)

Therefore, the servomotor controller must be capable of supplying a peak current and a continuous current minimum of 1.78A and 0.92A respectively.

3.7.3 Thermal Expansion due to Temperature Increase

A thermal effect due to temperature changes in micro-manufacturing may not be negligible [26-27]. Apparently, a small increment in temperature may contribute significantly to the performance of the machine elements. The heat generated by the motor coil, if it is not well controlled, can cause thermal deflection of mechanical parts. Aluminum alloys are often found to be used as linear-stage material due to their good heat conductivity, in dissipating heat efficiently from the coils of the linear motor [25], [28-30]. The analysis below is conducted to understand how much deflection may be experienced by the parts of a gripper that is located on the top of the stage of the feeder. Supposing that aluminum alloys 6061-T6 have a conductivity of 24.3µm/m°C [31], the thermal expansion due to the heat generated by the motor during operation is [32]:

$$Exp_{thermal} = \Delta T \times 24.3\mu m = (25.36 - 25) \times 24.3 = 8.7\mu m \quad (42)$$

Supposing a 20mm travel distance, the total thermal expansion expected is:

$$Exp_{thermal-20mm} = \frac{8.7\mu m}{1m} \times 0.02m = 0.174\mu m \quad (43)$$

Therefore, the thermal expansion due to the heat generated by the coil of the motor for the gripper is expected to be a maximum of 0.174µm for 100% transferred heat. This small deformation due to 100% transferred heat can be negligible as the error is relatively low and not contributing significantly towards positional inaccuracy.

4.0 Conclusions and Further Considerations

Based on the studies described above, a linear actuation method that uses a linear motor is proposed as a strategy for developing a new feeder for micro-sheet-forming. Direct drive from a linear motor ensures that no mechanical transmission will be required, which latter could contribute to play and backlash that affect the accuracy of the feeding in micro-forming. For the case analysed (the strip materials and micro-stamping process specified), theoretically, 38.0N and 19.6N peak and continuous forces respectively are required to serve material feeding for this particular application. At least 2g of acceleration rate is needed to accelerate the payload, i.e. the gripper and strip moving for up to 200 parts per minute (ppm) in a high-precision operation. The level of precision to be achieved is significantly greater than that available in the use of a servo roll feeder, which, currently, offers only 50µm accuracy.

A solenoid has been chosen to serve the clamping application for the gripper design due to its impressive response time, holding force, ease of integration, etc. The logic output from the servomotor controller is used to control the solenoid, hence giving peace of mind on the integration side by eliminating the necessity of using another type of controller. A new feeder for micro-sheet-forming is now being constructed.

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COMPLEXITY IN ENGINEERING DESIGN AND MICRO DEVICES: A REVIEW OF LITERATURE

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Abstract

This paper summarizes the main findings of a survey of complexity literature for engineering design and reviews the use of this word in micro-devices literature. The general view on the definition of the word complexity is captured and complexity types are identified. The paper underlines the subjectivity and context-dependence of meaning of complexity, as it is currently used. The paper provides identification of the common characteristics of complexity definitions and the reasons why people attempt to develop or influence definitions of complexity. The paper concludes that a sufficient definition of complexity for micro-devices has not been provided and highlights how this issue is currently viewed in literature.

Keywords: complexity definition, type, micro-devices.

1.0 Introduction

Miniaturization has absorbed the attention of researchers from many decades. Increasing demand for new and smaller solutions with incorporation of multi-functionality has lead to the increasing "complexity" of these devices. The word "complexity" has been used to describe the large number of designed and manufactured micro- and nano- devices, the multidisciplinarity of the designs, the high technology equipment used for their production and assembly, as well as the lack of knowledge about micro-scale physics, chemistry and biology and hence of device function. Owing to this issue, the complexity literature has been investigated with the aim of identifying a sufficient definition of this word for the micro-devices domain. To fully understand how complexity is viewed five main topics were investigated: 1) universal definitions of complexity, 2) types of complexity, 3) reasons to define complexity, 4) sources of complexity and factors influencing it, and 5) complexity in micro-devices. All of them are presented in following sections of the paper.

2.0 Complexity Definition

Complexity is established as important field of study [1]. However, the word "complexity" is not only hard to define [2], [3] but in many areas, a precise definition is still not available. Factors that influence this difficulty are the context-dependence and subjectivity of complexity [4]-[6]. Researchers have made attempts to generate a universal definition of complexity, which have resulted in several journal publications, conferences, books and doctoral dissertations. Resulting from this body of work, "Complexity Theory" has been established as a separate domain of study with diverse applications. Despite this effort, the definition of complexity provided by researchers still varies in different fields (and sometimes even across the same field) showing a discrepancy in terms of meaning, usage and quantification.

In an attempt to define complexity, many researchers have started by identifying what it does not mean. They have indicated differences between complexity and complicatedness [6], [7], randomness [8] and other issues which influence complexity and can be confused with it, such as size, lack of knowledge, variety, and order/disorder [4]. Other authors have tried to establish its meaning by highlighting common characteristics, such as those given by Corning [5] who describes complex phenomenon as those that consist of many parts, with have high number of relationships/interactions, and in which the parts produce combined effects that are not easily predicted and may often be novel. Other features are pointed out by Simon [9] who stated that: complexity critically depends on system description, which can be simplified by correct representation, that a complex system is characterized by redundancy and that its hierarchy can be often described in economical terms (aggregation of redundant components and consideration of them as integrated units).

Complexity has been defined in many areas of study such as chaos theory, fuzzy logic, networks, philosophy, psychology, and statistics. [9]. Amongst these definitions are: algorithmic information context (AIC)[1] or "Kolmogorov's Complexity", length of the message, or "Crude Complexity", introduced by Gell-Mann, logical depth of a string in programming, created by Bennet, average amount of information stored at any time in order to make an optimal forecast, "Forecasting Complexity", established by Grassberger and many more. Each of these definitions is context specific. The majority of them suffer from a defect in construction, as they contain within the explanatory definition the word "complex". A trend is observable in the literature for the presentation of such circular definitions of complexity. These are then followed by the core part of the work, which is a focus on the measurement of this phenomenon and, having gained this quantitative tool, on methodologies to decrease complexity.

The area which provides more suitable definition for products, systems and any other materialistic creations is engineering design. Although, definitions particular to engineering design are focused mainly on the information which the system, device, and product contain, several diverse definitions are available. El-Haik & Yang [10] present complexity as "a quality of an object with many interwoven elements, aspects, details, or attributes that makes the whole object difficult to understand in a collective sense". Although, this definition is valid for every object it is not specific enough to allow for quantification as well as not present the whole meaning of complexity. Another, frequently cited, definition of complexity was introduced by Suh in connection with axiomatic design. He defined complexity very broadly with the aim of providing an absolute

[1] Simultaneously discovered by three independent scientists: Kolmogorov, Chaitin and Solomonoff

measure for it, this quantitative approach being visible in first words of definition. According to Suh, complexity is 'a measure of uncertainty in understanding what it is we want to know or in achieving a functional requirement (FR)' [6]. Both these definitions are focused around understanding a design from the points of view of difficulty and uncertainty. Hence, these definitions may cause problems where the design is "fully understood" or could be represented in simple manner, but would still be considered as "complex" by an observer. In the case of full understanding of design, the complexity would be measured as zero, which would indicate that there is no complexity in the device, despite the clear appearance of complexity to the observer.

Is it possible to design a device which is characterized by a complete lack of complexity? Some researchers claims that the answer to this question is 'no.' El-Haik & Yang [10] presented the idea of "irreducible complexity" which they considered a universal quality in all objects. However, they underlined that this level of complexity may significantly vary. This view was supported by Colwell [11] who based his opinion of the minimum amount of complexity required on systems performance – the impossibility of separate parts of the system performing the functions required from the device, or performing them inadequately, if they are not connected. He supported his view by citing Einstein's statement of the simplicity limitations in order to achieve required performance of a design outcome.

3.0 Sub-types of Complexity

The inconsistency in definitions of complexity causes differences in identification of their sub-types in the literature. Suh [6] identified four time-related sub-types of complexity: time-independent real complexity – 'a measure of uncertainty when the probability of achieving functional requirements is less then 1.0 because the system range is not identical to the design range', time-independent imaginary complexity – caused by lack of knowledge, time-dependent combinatorial complexity – caused by unpredictability of future events and time-dependent periodic complexity – existing in finite time period with predictable number of combinations of events. Adami [3] divided complexity into physical and structural. His domain of study was biological organisms; however he adapted the AIC definition of complexity, which was created for programming. Zamenopoulos and Alexiou [12] recognized sub-types of complexity as: functional and behavioural, whereas Tomiyama et al [13] noted both complexity by design and intrinsic complexity of multi-disciplinarity.

These sub-types of complexity were created based on particular characteristics identified by researchers and each author has provided their own sub-types referring to particular domain of research. However, some overlap of these sub-types of complexity, in terms of their meaning, can be identified This overlap is tabulated in Table 1. Since the development of a universal measure of complexity is "hard to imagine" [3], the creation of complexity subdivisions makes it possible, in the majority of cases, to group features which can be measured in order to provide a quantitative indication of complexity level.

Table 1: Sub-Types of Complexity

Type of Complexity indicated / Researcher(s) / Literature Source	Heylighen [2]	Adami [3]	Edmonds [4]	Thomson et al. [5]	Earl, Eckert & Clarkson [7]	McGuire [8]	Colwell [11]	Zamenopoulos & Alexiou [12]	Tomiyama et al. [13]	Funes [14]	Suh [15]	Kim [16]	Bose, Albonesi & Marculescu [17]	Gell-Mann [18]
Own definition	x		x	x				x			x			
Irreducible complexity							x							
Information complexity					x									
Kolmogorov		x	x			x		x		x				x
System complexity			x											
Observer complexity			x											
Löfgren’s Interpretation and Descriptive Complexity			x											
Kauffman’s number of conflicting constraints			x											
Physical		x												
Structural	x	x						x						
Functional	x							x						
Structural hierarchical	x													
Functional hierarchical	x													
Behavioural								x						
Crude complexity										x				
Logical depth			x							x				
Forecasting complexity										x				
Computational Complexity			x							x				x
Gell-Mann's Effective Complexity										x				
Complexity by design									x					
Intrinsic complexity of multi-disciplinarity									x					
Suh complexity											x	x		
Time-independent real											x	x		
Time-independent imaginative											x			
Time-dependent combinatorial											x			
Time-dependent periodic											x			

4.0 Why a Definition of Complexity is Required

Many authors have put considerable effort into defining complexity, but what was their purpose? What actions did they undertake once their definition of complexity was established? A number of authors have stated that the reason for their work is that complexity is harmful. However, others have pointed out that only specific types of complexity are damaging, whereas other types are useful and even required.

Suh [6] claimed that a 'vast sum of human and financial resources are wasted due to our inability to deal with engineering complexities.' Thomson et al. [5] pointed out that higher complexity than originally anticipated for the project, participates in cost and schedule overruns. Both authors accepted the unavoidability of complexity but blamed incorrect or inadequate management of complexity for badly influencing design. They criticized the general lack of knowledge about complexity, which lead to its misunderstanding. Their views have some commonality with the idea of "irreducible complexity", however they do not provide information about what level of complexity is acceptable.

As a reason to properly define complexity in a specific context, Suh [6] provided a view of the opportunity of its reduction and an increase in the system's reliability and robustness. In his complexity theory there are 3 harmful types of complexity: time-independent real and imaginary complexity, cause over-runs of projects in terms of time and cost, and time-dependent combinatorial complexity, leads system to a chaotic state and results in a system's failure. Suh underlined firstly, the necessity of reducing time-independent imaginary complexity, which could be achieved by writing down the design equation (showing relationship between the functional requirements and design parameters for particular product)[15], and, secondly, the need to change time-dependent combinatorial complexity to periodic complexity, what can provide long-term stability of the system.

Colwell [11] highlighted that the reduction of complexity is compromised by minimization of functionality and/or other tradeoffs. This value-adding complexity view is, in his opinion, only reasonable to a certain extent, beyond which the cost of increasing complexity is not necessary. He stated that each attempt to create complexity in design should be justified, and when this justification cannot reasonably be provided complexity should be reduced. Negative impacts of this additional amount of complexity, in his opinion, included: longer development schedules; design errata, follow-on design issues and cost and time overruns.

5.0 Sources of Complexity

Since, complexity is such an important aspect in any design, sources of it should be characterized. Identification of the reasons for a particular level of complexity, as well as those features which influence it, can help with its measurement and then, potentially, changes in its level, if required. Rodríguez-Toro, Jared and Swift [9] claimed that proper management of complexity sources can help in the reduction of 'design effort' which results in a shortening of development time and in cutting project costs.

According to Suh [6], complexity is caused by poor design, which can be result of, for example, a non-systematic approach to design, or a lack of knowledge (understanding) about the system under consideration. Earl, Eckert & Clarkson [7] stated that complexity has its origins in a combination of order and uncertainty, where the ordered background of existing designs, processes and requirements is combined with an uncertain change process and unpredictable outcome. However, both of these approaches are very broad, and hence can be very freely interpreted.

Thomson et al. [5] introduced more detailed identification of the factors which influence complexity in design, which can be considered as sources of complexity. They established, the concept of a "Design Complexity Map", which represents those attributes of a design affecting complexity. They identified six groups of factors: knowledge and sources, artefacts, design activity, external and internal aspects (e.g. technology, life phase systems), decision making and actors. Each of these groups contains at least two subgroups and each subgroup has number of positions underneath. Although, this map has been designated to represent complexity of the team environment during the design process, it is also valid for the design outcome itself. When applying this framework to a product, issues presented have to be divided into those that have direct impact on the complexity of design outcome, such as part artefacts, and show potential to be measured, and those with indirect impact such as actors participating in the design process. This framework shows potential to influence the complexity of the design outcome in the conceptual phase by both indicating which elements have to be taken into account and by providing an opportunity to measure complexity.

6.0 Complexity in Micro Devices

With regard to the high number of definitions provided for complexity and their sub-types, the assumption of the possibility of a special meaning of "complexity" for micro-scaled devices seems reasonable. Several attempts to define the complexity of micro-devices are available in the literature. However, it is notable that within the domain of micro-devices, devices are often stated to be either simple or complex without a definition of "complexity" or an explanation of where is the border between simple and "complex" lies.

Within this domain, there are three main methods by which definition of complexity is derived: by creation of a definition by the researcher, by adaptation of someone else's approach or by the identification of characteristics.

Zhou [19] represents an example of the first method. He defines complex micro-devices as 'devices composed of parts made from different materials fabricated by various technologies,' and claims that this complexity is continuously increasing due to new demands on the market. This definition, created for micro-assembly, is very broad and does not provide sufficient meaning of the word "complexity" for whole micro-devices domain.

The second approach, to adapt approach to complexity and its measurement from the macro scale, was undertaken by Kim [16], [20]. He applied the "axiomatic" approach to multi-scale systems design with a focus on micro and nano-scale. His work showed the possibility of a reduction its quantification. However, this is one of few attempts identified were a definition created for macro-scale was adapted in micro-scale domain. Kim states that usage of "functional periodicity" will allow the decrease of overall complexity by transformation of a system with time-dependent combinatorial complexity to a system with time-dependent periodic complexity, which was identified as less harmful. He also claims that by consideration of uncertainty associated with functions axiomatic design approach can help in understanding complexity in micro- and nano-assembly. Although he noted that 'information content well-characterizes the real complexity of tiny product manufacturing,' Kim neither states that the definition of complexity provided by Suh [6] is suitable for micro-devices nor created his own definition for this domain.

Finally, Albers and Marz [21] are an example of last method. They noted that every micro device is a multi-technology product. They stated that the design of these small devices, if they are aimed to be optimal and innovative, has to be realized as an integration of technology, process and product development, material sciences and simulation, embracing all these disciplines. They described the process of micro-technology design and manufacturing as very complex due to the unavailability of proper tools and the high degree of uncertainty of the functionality of products after manufacturing processes. This uncertainty, according to certain definitions of complexity confirms the high complexity of these devices, however it does not quantify its level nor solve the problem of identifying the sources of complexity.

Although, these attempts at definition of complexity for the micro-scale have been identified, the amount of available literature regarding this topic is small. However, several authors have described the necessity to decrease the level of complexity in micro-devices, especially regarding the negative influence of complexity on micro-architecture in terms of testability and manufacturing cost [17]. At the macro-scale, this harmful impact of complexity, beyond "irreducible complexity", as well as the concept that complexity increases rapidly as the system scale order grows [16], have convinced many researchers to attempt to measure and influence it. However, any impact, if achieved, has been measured relatively to the prior state, and new methods created have not been applied universally owing to the subjectivity of the judgments incorporated in their definition.

7.0 Conclusions

The literature presented above shows the increasing interest of scientists in "complexity." However, it also underlines the inconsistency in definitions of this word, its context dependence and subjectivity across different domains as well as inside an area of research. A large number of definitions have been outlined, most of them created *ad hoc* to undertake projects, and characterized by a focus on quantification of a particular issue. The development of complexity definitions, however vague and/or narrow, in the majority is aimed at decreasing the level of complexity owing to the consideration of complexity by majority of researchers as having a destructive effect.

The literature shows that some investigation of complexity has been undertaken in micro-devices domain. However, there is no sufficient definition of complexity identified particular to this domain. This leads to the suggestion that further studies should be undertaken to define and influence complexity for micro-devices.

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EFFECT OF PULSE ENERGY IN MICRO ELECTRIC DISCHARGE MACNINING OF MICRO HOLES

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Abstract

Micro Electric Discharge Machining (micro-EDM) is one of the most common micromachining techniques for manufacturing of micro holes and mini cavities. Micro-structures such as micro-holes, micro-channels, micro-gear and other complex shapes can be easily machined by using micro-EDM irrespective of material hardness. There are a lot of electrical and technological parameters which are effective in the machining characteristics and machined material surface integrity in micro-EDM. In this study, effects of energy parameters on the machining performance are investigated based on experimental results. Series of experiment were performed by keeping all parameters constant except pulse energy. Variations in micro-hole geometry, material removal rate, micro-hole depth and over-cut in micro-hole diameter were investigated. Experimental results have revealed that using high pulse energy setting and 400 µm diameter tool electrode during machining result in deeper micro-holes when compared to micro-holes machined under lower energy settings. However, machining with 100 µm diameter tool electrode, the result is reversed i.e. by using lower pulse energy, deeper holes were obtained. In addition, a defect formation is also observed inside the machined hole when tool electrode suppression rate and pulse energy is increased.

Keywords: Micro-EDM, micro-hole, micromachining.

1.0 Introduction

Miniaturization of parts and components play an important role in the development of today's and future technology in various fields. With the increasing demand for micro parts and structures in many industries, and also with rapid developments in micro-electro mechanical systems (MEMS), micro manufacturing techniques, especially micro electrical discharge machining, for producing these parts become increasingly important. Micro structures including micro holes, micro slots, micro shafts, and micro gears are mostly used micro products needed in industry. Especially micro holes are needed in optical devices, medical instruments and automobile engine parts [1]-[2].

Basically, electric discharge machining (EDM) is a thermal material removal process. The process is carried out in a dielectric liquid with a small gap between the workpiece and electrode. Electric discharge occurs when the dielectric is broken down by the application of voltage pulse. Some of the released energy during discharge is transferred to the electrodes and results in heating of highly localized regions of the electrodes. When temperature of heated region exceeds melting temperature of the electrodes, some of the melted and all of the evaporated material is then quenched and flushed away by dielectric liquid in the form small globular particles (debris material) and the remaining melt recast on the finished surface. Debris material is washed away from the sparking area by the continuously flushing dielectric fluid. Flowing pressure of the dielectric fluid should be adjusted to an appropriate value since high pressurized fluid result in vanishing the influence of electrical sparks, on the other hand, low pressure flow result in rising debris concentration in sparking area and cause secondary discharge, arc, and short circuit.

The application of EDM is not limited by the hardness or strength of material to be machined. EDM can be used to machine any conductive material and there is no direct contact between the electrode and the workpiece during machining that make possible to machine complex geometries using thin electrodes. Thermal properties such as melting point, boiling point, and electrical conductivity of workpiece materials influence the machining characteristics. The material removal rate of EDM process is primarily determined by the electrical conductivity and melting temperature of the workpiece material. A workpiece with higher electrical conductivity and lower melting temperature can be machined more efficiently.

2.0 Micro Electric Discharge Machining

Micro electric discharge machining (micro-EDM) is a derived form of EDM, which is generally used to manufacture micro and miniature parts and components by using the conventional electric discharge machining principles. Similar to EDM, material is removed by a series of rapidly recurring electric spark discharges between the tool and the workpiece electrodes in micro-EDM. Actually main differences of micro-EDM from conventional EDM are the type of pulse generator, the resolution of the X-, Y- and Z- axes movement, and the size of the tool used. In micro-EDM; pulse generator produces small pulses within pulse duration of a few micro seconds to nano seconds. Thus, micro-EDM utilizes low discharge energies ($\sim 10^{-9} - 10^{-5}$ joules) to remove small volumes ($\sim 0.05 - 500$ μm^3) of material [3]. The most important factor which makes micro-EDM very important in micromachining is its machining ability on any type of conductive and semi-conductive materials with high surface accuracy irrespective of material hardness. It is preferred especially for the machining of difficult-to-cut material due to its high efficiency and precision.

Small volumetric material removal rate of micro-EDM provides substantial opportunities for manufacturing of micro-dies and micro-structure such as micro holes, micro slot, and micro gears etc. The use of micro-EDM has many advantages in micro-parts, the main advantage is that it can machine complex shapes into any conductive material with very low forces. The forces are very small because the tool and the workpiece do not come into contact during the machining process. This property provides advantages to both the tool and the workpiece. For example, a very thin tool can be used because it will not be bent by the machining force hence, eliminating mechanical stress, chatter and vibration problems during machining. Other advantages of micro-EDM include low set-up cost, high aspect ratio, enhanced precision and large design freedom. Therefore, relying on the above advantages, micro-EDM is very effective to machine any kind of holes such as small diameter holes down to 10 µm and blind holes with aspect ratio of 20. In micro-EDM, tool electrode in different diametric sizes can be prepared by using Wire-Electric Discharge Grinding (WEDG) [4]. It is a prerequisite machining for drilling micro-holes and milling micro-cavities with micro-EDM technology. WEDG is used to prepare smaller size tool down to Ø10 µm by using electrical discharge machining principle with reverse polarity.

High aspect ratio micro-hole EDM was studied by Masuzawa et al. [5], Takahata et al. [6], and Lim et al. [7]. Improvement of micro-hole quality could be obtained by lower discharge energy [8]. Masuzawa [1] pointed out that the key point for lower discharge energy was the minimization of the stray capacitance between the electrode and workpiece. Effects of polarity, electrode shape, and rotational speed of electrode in micro-hole EDM drilling of carbide were investigated by Yan et al. [9] and the experimental results showed that positive polarity must be used in micro-hole EDM drilling to reduce tool wear and maintain micro-hole accuracy. The effects of two electrode materials, copper and tungsten carbide, on micro-hole EDM drilling were studied by Her et al. [10] and it was reported that the copper electrode could provide better surface roughness, lower electrode wear, but lower MRR than the tungsten carbide electrode. In this study, effects of energy parameter are investigated experimentally. A series of micro-hole machining were performed by keeping all parameters constant except pulse energy. Variations in micro-hole geometry, material removal rate, and micro-hole depth and over cut in micro-hole diameter were analyzed.

3.0 Materials and Data Acquisition

Plastic mold steel (70x10x2 mm) is used as a wokpiece material. Tungsten carbide (WC) electrodes with a standard diameter of 400 µm and 100 µm are used as a tool electrode. Dielectric liquid used for flushing is hydro carbide composed of mineral and synthetic oils.

An Agilent 54621D mixed signal oscilloscope with a value of 60MHz and 200 MSa/sec is used to display the shape of voltage and current pulse forms. Low inductance 0.2 ohm 1%R resistor is serially connected to discharge circuit to capture current pulse forms.

4.0 Experimental Results

A series of experiments was performed to estimate the undisclosed parameters defined in the micro-EDM machine. Those parameters only entered as a setting without a unit, which express the resultant pulse energy and current forms used during machining. Although discharge energy depends on pulse voltage and current, it is given in the machine settings as a type of pulse shapes that actually limits discharge energy. The current defined in the machine settings also carry the approximate meaning like in the energy. Machining conditions are summarized in Table 1.

Table 1: Machining conditions for varying energy parameter

Parameter type	Parameter value
Machining time (min.)	20
Frequency (kHz)	100
Width (µs)	4
Open Voltage (V)	80
Gap Voltage (V)	75
Gain	10
Temp. of dielectric liquid (ºC)	~20
Temp. of medium (room) (ºC)	~25

Energy type is classified into six different ranges by the machining tool manufacturer. Description of energy levels is given in Table 2.

Table 2: Description of Energy parameters (Sarix operating manual version 1.20)

Energy Parameter	Family Description
From 13 to 15	Very short pulses
From 100 to 114	Short pulses
From 200 to 215	Long braked pulses
From 250 to 265	Long, delayed, beaked pulses
From 300 to 315	Long, delayed pulses
From 350 to 365	Long pulses

The voltage and current in micro-hole machining is monitored and recorded. The monitoring technique can assist in the selection and optimization of micro-hole EDM process parameters. Shape of the pulse forms with different energy parameters are given in Figure 1. Selection of lower value of energy parameter results in the lower value of discharge time and discharge current. Peak current value approximately rises to 20 A for long pulses and gradually decreases for lower energy settings. It was observed that peak current decreases nearly to 5 A for very short pulses. Discharge time (pulse on time) is also longer about 2 µs in long pulse shape when comparing to short pulses of less than 200 ns. When the short pulses are considered, shapes of the pulses are not recorded properly due to insufficient sampling rate of the oscilloscope. An advanced data acquisition device should be used to record and to keep the very short pulse shape in more reliable range.

Three micro-holes were machined for each energy parameter to observe the repeatability of the process. Machined micro-hole diameter is always larger than the tool electrode diameter; the difference is varying depending on the machining conditions. Expansion in the micro-hole diameter is defined as *over-cut*, caused by side spark erosion. Variation in micro-hole diameters, electrode removal, standard deviation (STD) and over-cut are tabulated in Table 3. It was observed that, micro-hole expansion (over-cut) is slightly increasing with respect to energy parameter which is varying from very short pulses to long pulses. This difference in over-cut is due to the difference in spark intensity. Higher the energy value parameter leads to more intense spark and which erode more particles from the side surface of the micro-hole.

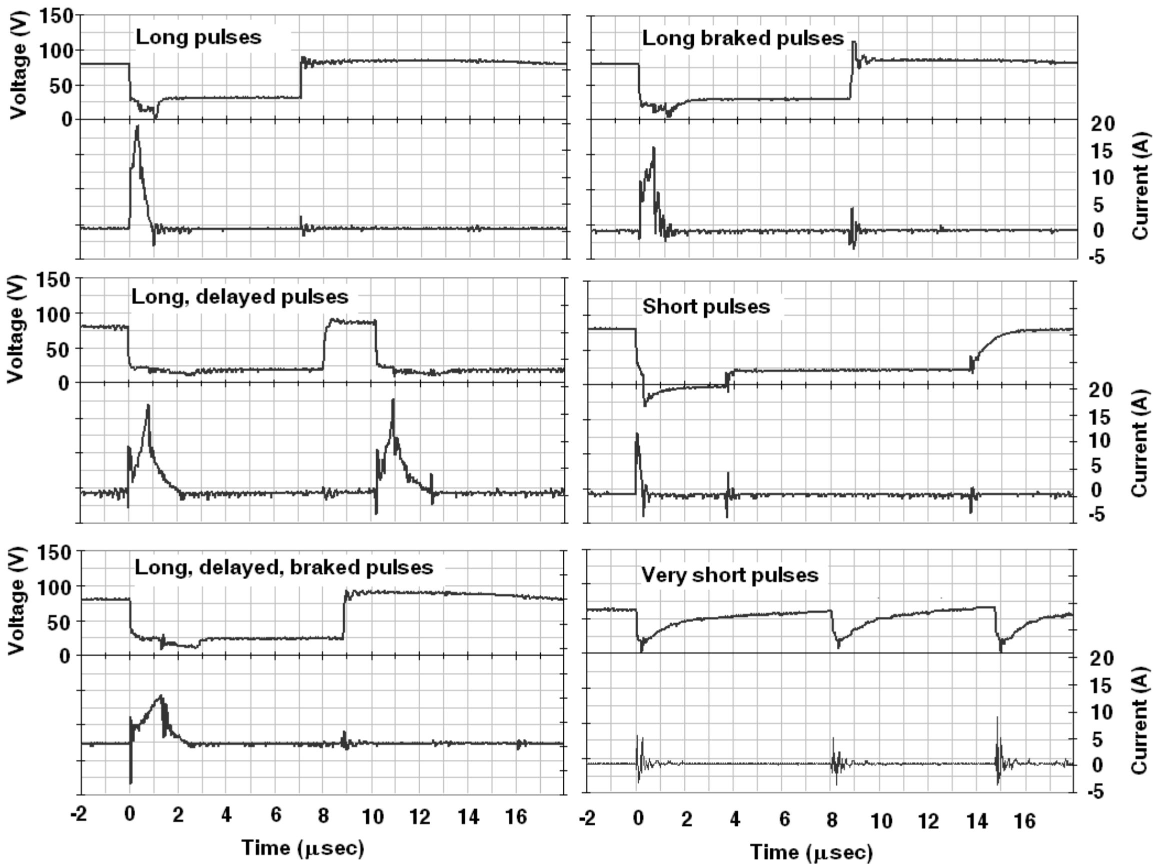


Fig. 1. Analyzed voltage and current pulse forms

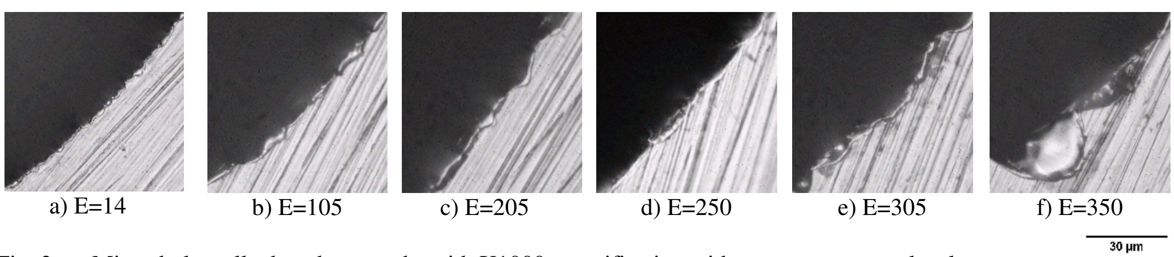
Magnified edge for each hole (Figure 2) is given to analyze the geometrical shape and edge surface roughness. Dimensional measurement for hole diameter and machined length of hole may sometimes not consistent with the diameter of other holes machined by the similar settings. Micro-hole diameter may be sometimes measured larger than the actual one. This inconsistency in the measurement is caused by the measurement devices and software used in the microscopic system, focusing problems arouse while magnified pictures are taken and image processing error are observed while measuring dimensions.

Cross-sectional views of the machined holes (Figure 3) are taken to analyze the geometrical shape and parallelism of the micro-hole wall side. A good shape can be obtained by using the entire machining conditions. One point in the cross-sectional view may draw attention about inconsistent cross-sectional dimension along the micro-hole radial axis that is induced by difficulty during sectioning process. Because of the very small size grinding and polishing process, it is difficult to control whether to reach the center of the machined hole, sometimes due to over grinding or insufficient grinding process; the approximate central cross-section is taken and analyzed. Actually, disregarding the dimensional measurement, the error during sectioning process is not substantially affecting the overall geometrical shape of the machined holes.

Table 3: Micro-hole diameter variation with energy type

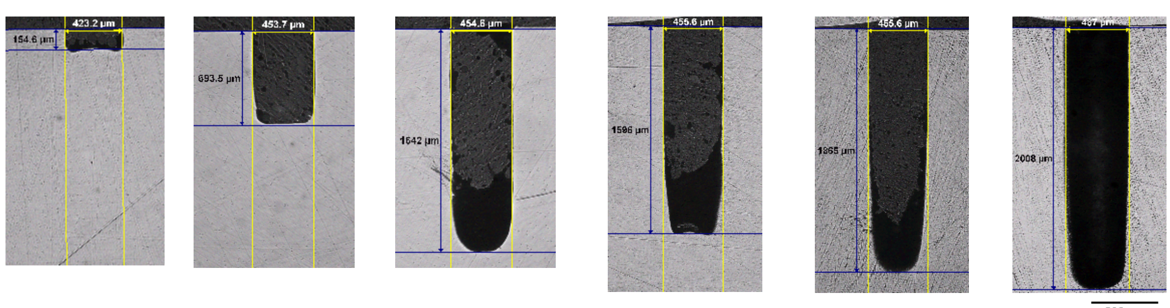
Energy	Target depth	Removed electrode length	Hole depth	Hole diameter	Mean diameter	STD for hole diameter	Average over-cut
14	180	31	150	447	435	10.91	17.58
	165	31	130	427			
	155	25	130	430			
105	843	161	682	438	437	10.07	18.3
	858	168	690	426			
	850	157	693	446			
114	897	237	660	435	433	2.65	16.1
	880	230	650	433			
	870	224	650	429			
205	2720	1150	1570	457	452	9.34	26
	2720	1140	1580	458			
	2820	1180	1640	441			
250	2910	1650	1260	461	448	12.33	23.5
	3060	1780	1280	443			
	3150	1790	1340	437			
305	3400	1660	1740	451	449	2.78	25
	3480	1720	1760	451			
	3460	1710	1750	446			
350	3400	1460	1940	457	457	6.71	28.5
	3380	1430	1950	464			
	3250	1400	1850	451			

- **Dimensions are in µm**



a) E=14 b) E=105 c) E=205 d) E=250 e) E=305 f) E=350

Fig. 2. Micro-hole wall edge photographs with X1000 magnification with respect to energy level



a) E=14 b) E=105 c) E=205 d) E=250 e) E=305 f) E=350

Fig. 3. Cross-sectional photographs of micro-holes machined with different energy level

The other most significant remark realized by means of this experimental work is the influence of the energy parameter while using smaller size electrode such as Ø100 µm. When Ø100 µm electrode is used to machine a micro-hole, very short pulses should be selected, otherwise, it become impossible to machine a correct drilled hole. Figure 4 explains the above statement explicitly, nearly aspect ratio of 17 is obtained by using very short pulses, whereas by using short pulses only a little cavity which is far from becoming micro-hole is obtained.

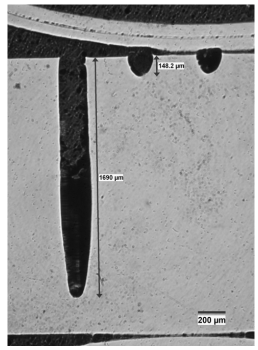


Fig. 4. Cross-sectional view of holes machined by Ø100 µm electrode with a machining time of 60 min. and energy parameter for a) 14, b)105 and c) 114

5.0 Conclusion

It is well known that machining accuracy of micro-EDM is limited by tool wear. The tool wear is characterized by corner and end wear which mean tool material removal in radial and axial directions, respectively. Thus, blind-micro-holes can get different forms and it is difficult to be measured without additional machining. Tool wear is found to be high especially at the corners of the tool electrode. This result can be easily attributed to the high discharge intensity on the corners. Gradual forward movement of the tool electrode results in a formation of a narrow edge clearance between tool electrode and the workpiece. Thus, dielectric liquid circulation became an important aspect since debris produced during machining alters dielectric liquid strength and therefore discharge conditions during machining. By means of the distorted flushing conditions, debris particles can not be flushed away appropriately from the sparking area. High concentration of debris particles in the sparking gap increases the chance of occurring secondary discharges, arcs and short circuits due to decreased dielectric strength which are undesirable discharge phenomena for obtaining precious EDMed feature.

From the pulse energy perspective, very short pulses used during machining result in small debris particles which provide proper flushing conditions from sharp tip edges. Thus, when smaller size electrode is used during machining, proper machining conditions can be established. On the other hand, higher pulse energy used during machining result in high energy intensity on the tip of electrode and the energy on the electrode body immediately tends to discharge to the workpiece and this phenomena occur consecutively many times without waiting for suitable conditions and which result in short circuit away from eroding workpiece.

Acknowledgement

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MICRO-DRILLING HOLES ON GLASS WAFER FOR FABRICATION OF MEMS

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Abstract

Edge chipping is a major problem in glass drilling. The fabrication of a new MEMS device requires micro-drilling a number of holes (800 µm diameter) on Pyrex (7740) glass wafer. The edge qualities of these holes are crucial to the function of this new MEMS device. However, current available ultrasonic drilling technique cannot meet the requirements on edge quality and positioning accuracy for drilling these holes on the glass wafer.

This paper presents the initial results in the development of a near chipping-free micro-drilling process for glass wafer. The drilling tests are performed on two machine tools using multilayered diamond drill, together with water as coolant. The cutting forces are measured by Kistler dynamometer and the drilled holes are inspected under a microscope. Finite Element simulation is carried out to optimize machining parameters to minimize edge chipping. The theoretical and experimental studies show that the contact pressure on diamond grit has significant effects on crack generation in the glass. Low contact pressure will result in short crack generation length. This will result in near chipping-free drilled surface. The high concentration of multilayered diamond drilling, use of water as coolant, high dynamic loop stiffness machine tool and optimized machining conditions are all contribute to low contact pressure on diamond grit and therefore a near chipping-free drilled holes on the glass wafer.

Keywords: Micro-milling, MEMS, edge chipping, glass drilling.

1.0 Introduction

The fabrication of a new MEMS device requires micro-drilling a number of holes (from 300 µm to 3 mm diameter) on Pyrex (7740) glass wafer. The edge qualities of these holes are crucial to the function of this new

MEMS device. Two glass wafers will be bonded together before the dicing operation. Therefore, it also requires 50 µm positioning accuracy when drilling those holes in order to meet the alignment requirement of the MEMS devices. However, glass is a very difficult material to be drilled as edge chipping is a major problem. Ultrasnoic drilling is an enable technique to minimize edge chipping but it is very difficult to achieve the required positioning accuracy. A cost-effective drilling process is needed to obtain near chipping-free edge quality and 50 µm positioning accuracy in this glass drilling process.

This paper shows some preliminary results in developing this near chipping-free glass drilling process. Finite Element simulation is carried out to optimize machining parameters to minimize edge chipping. The drilling tests are performed on two machine tools using multilayered diamond drill, together with water as coolant. The cutting forces are measured by Kistler dynamometer and the drilled holes are inspected under a microscope. It summarized with a solution for obtaining near chipping-free edge quality in glass drilling.

2.0 Theoretical Basis for Precision Machining of Glass

There have been tremendous efforts to precision machining brittle materials including glass by utilizing a so-called “brittle-to-ductile” transition phenomenon [1-7]. Lawn made a great contribution in finding “brittle-to-ductile” transition in brittle materials. His indentation test using a sharp point indenter on glass showed the progression of the plastic and fracture region. He found that the surface plastic deformation takes place at a certain loading. At some critical load and penetration depth a median crack developed which continues to grow with additional applied load/penetration. On the unloading process the mismatch stress causes lateral cracks to grow. These lateral crakes can propagate towards the surface which causes large levels of surface chipping to occur. Lawn has deduced functions to estimate the critical load of formation of median cracks and the corresponding critical crack length [1]. Hagan [2] has carried out similar indentation work and deduced the critical load to nucleate a micro-crack just beneath the elastic/plastic boundary and associated critical crack length. The equations are presented in the form of:

$$P^{*} = C_1\left[\frac{K_c^{\,4}}{H^3}\right] \tag{1}$$

$$C^{*} = C_2\left[\frac{K_c}{H}\right]^2 \tag{2}$$

where K_c and H are fracture toughness and hardness of glass. C_1 and C_2 are constants. For glass (Pyrex 7740), critical load P^* for a median crack and corresponding critical crack lengths are 0.023 N and 1.63 µm respectively. Obviously the value P^* is a single point load, and therefore is less than the cutting force when multiple diamond grits are involved in drilling processes.

Lawn also introduced an equation for the calculation of critical penetration depth for initiating a fracture, it can be described as:

$$d_c = \psi \left[\frac{E}{H} \right] \left[\frac{K_c}{H} \right]^2 \tag{3}$$

where ψ is a dimensionless constant dependant on indenter geometry, E is the Young's modulus. d_c is often called critical depth of cut in literature. From results of ductile modes grinding tests, Bifano has deducted that ψ equals to 0.15 in his model [3]. He also concluded that maximum chip thickness should be less than the critical penetration depth in order to achieve ductile regime grinding and minimum subsurface damage.

This glass drilling process will using multilayered diamond drills. The drill process is very similar to diamond grinding process using a cup wheel [4-7] although the feed direction is vertical to the machined surface in drilling process. So initially this research will be focus on process development to find out the optimized feed rate and grinding speed to achieve good edge quality with a material removal rate as high as possible.

3.0 Finite Element Study for Optimization of Machining Parameters

3.1 FEM Model

Finite element is used to model the material removal process by single diamond grit in order to find out the optimized machining parameters. The material behaviour of glass is modeled by Drucker-Prager damage model. Both plastic deformation and brittle fracture are considered in this model. The constitutive function for Drucker-Prager damage model is expressed as:

$$\sigma(\varepsilon^p, J_1, \dot{\varepsilon}, T) = G(\varepsilon^p, J_1) \cdot \Gamma(\dot{\varepsilon}) \cdot \Theta(T) \tag{4}$$

Where $F(\varepsilon^p, J_1)$ is the function for strain hardening and hydrostatic pressure. $\Gamma(\dot{\varepsilon})$ is strain rate sensitivity and $\Theta(T)$ is thermal softing function.

The damage function is described as:

$$D = \sum_i \frac{\Delta \varepsilon_i^p}{\varepsilon_{f_i}^p}, \tag{5}$$

where *D* is the dimensionless cummulative damage, $\Delta\varepsilon_i^p$ is the instantaneous increment of strain and ε_{fi}^p is the instantaneous strain to failure. This model is obtained from a curve fit to strain to failure verus temperature diagraph of glass [8]. The Drucker-Prager damage model will be compiled and loaded by the simulation software to calculate the glass material state throughout simulation.

Orthogonal model is used to model the drilling process by single diamond grit. Two sets of simulation experiments are devised. Simulaiton experiment 1 is designed to investigate the effect of dilling spindle rotational speed on normal cutting forces. Rotational speed of drilling spindle varying from 2000 rpm to 3500 rpm are used. They are equivalent rotational speeds of 5026 mm/min to 8796 mm/min for outer edge of a 0.8 mm diameter drills that is going to be used in the drilling test. In the simulation tests penetration depth is kept at 10 µm. In Simulation 2, penetration depths of 12.5 µm, 18 µm, 25 µm and 30 µm are used. In both simulation experiments, -45° rake angle diamond grit is ued. Its clerance angle is assumed to be at 10°.

A commercial finite element packge AdvantEdge is used for the numerical simulation of this orthogonal cutting process. Triangle element and adaptive remenshing technique are used to correct the problem of element distortion due to high deformations in simulation computation.

3.2 Simulation Results

3.2.1 Surface Generation

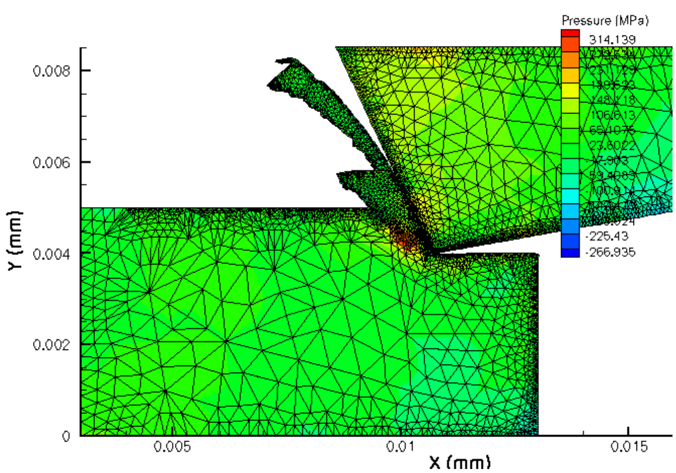


Fig. 1. Snapshot of FE simulation

Fig. 1 is a snapshot of simulated cutting process by a single diamond grit which locates at the outer edge of the drill. Both plastic deformation and brittle fracture can be observed in the formed chip. It indicates that the material removal is a combination of brittle fracture and plastic deformation. This observation conforms to the result of Scattergood's experimental observation through "interrupted cut method" in single point diamond turning. His test approves there exits a "brittle-ductile" transition plane, under which the plastic deformation takes place and ductile removal is achieved [9]. Although there are many diamond grits involved in material removal in the drilling process the simulation study can still be used to find out optimized machining parameters so as to minimize length of brittle fracture that extend down to the "brittle-ductile" transition plane.

3.2.2 Effects of Machining Parameters

The variations of normal cutting forces with cutting speed are shown in Fig.2. It can be seen that the normal cutting force are all bigger than the critical pressure predicted by Eq. (1). But when a spindle rotational speed of 2500 rpm is used the normal cutting forces is the smallest one within the test range. Therefore, the FEM simulation results indicate that 2500 rpm is a good spindle rotational speed to be used for a 0.8 mm diameter

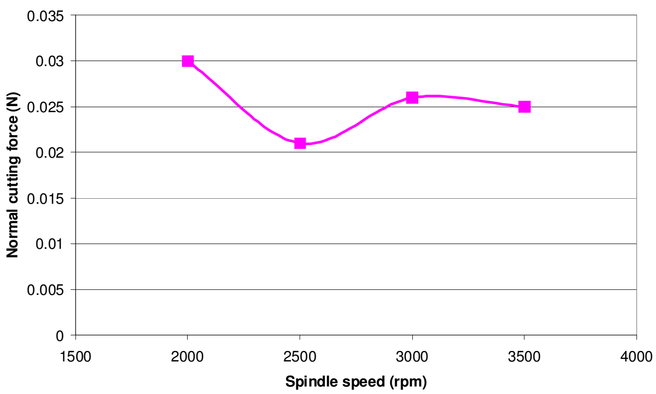


Fig. 2. Variation of normal cutting forces with spindle speed

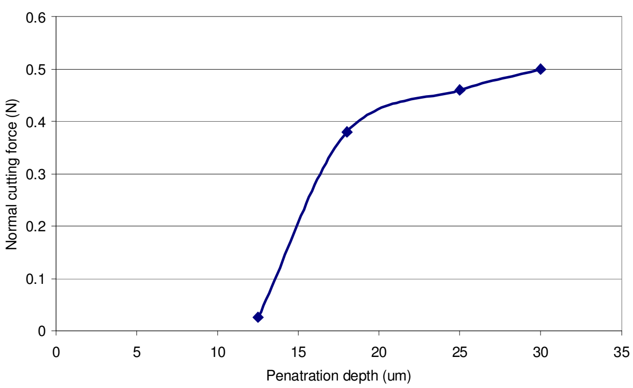
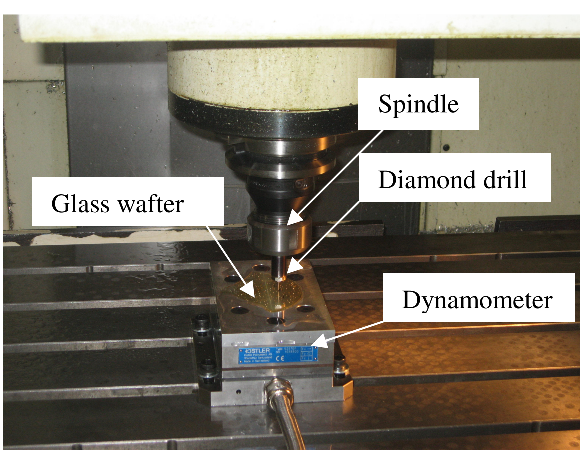


Fig. 3. Variation of normal cutting forces with penetration depth



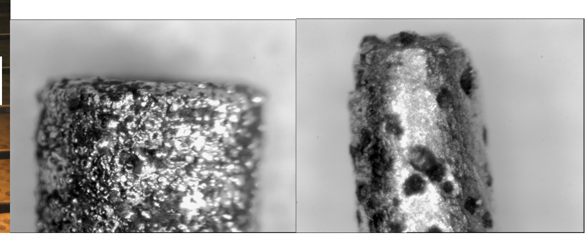


Fig. 4. Drilling test setup

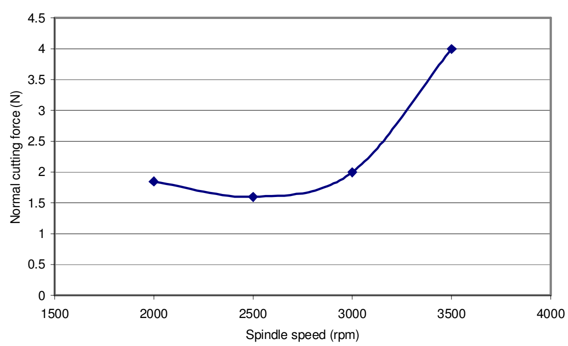
Fig. 5. (a) 3. 0 mm drill (b) 0.8 mm drill

drill. Fig. 3 shows the variation of normal cutting force dose not possess linear relationship with penetration depth. When a penetration depth of 12.5 µm is used it will obtain the smallest normal cutting forces in the test range. Therefore, diamond drill with grit size of 25µm is chosen in the following drilling test.

4.0 Glass Drilling Test

4.1 Experimental Condition

Two set of drilling tests are devised. Test 1 is carried out on a conventional CNC machining centre Takang VMC-1202. The test setup is shown in Fig. 4. A piece of glass is attached on the fixture by wax. Kistler Dynamometer 9257BA is used to measure drilling forces. 0.8 mm and 3.0 mm diameter drills are used in test 1. Spindle speeds of 2000 rpm, 2500 rpm, 3000 rpm and 3500 rpm are used when feed rate is kept at 0.25 mm/min. When spindle speed is kept at 2500 rpm, feed rates of 0.125, 0.18, 0.25 and 0.3 mm/min are used. A state-of-the art micromachining centre Kern Evo is used in Test 2 to study the effects of spindle stiffness on edge quality in glass drilling. Another 3.0 mm diameter drill which has the same specification as the one used in test 1 is adopted. In test 2 spindle speed of 2500 rpm and feed rate of 0.25 mm/min are used. Water is used as coolant. The images of the two kinds of diamond drills are shown in Fig. 5. They are electroplated drills with three layers of diamonds. Diamond grit size is 25 µm. The drilled holes are measured by OLYMPUS



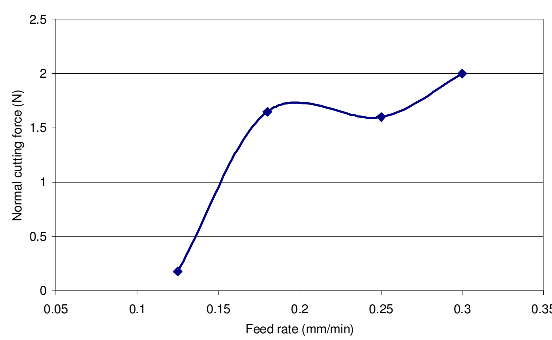


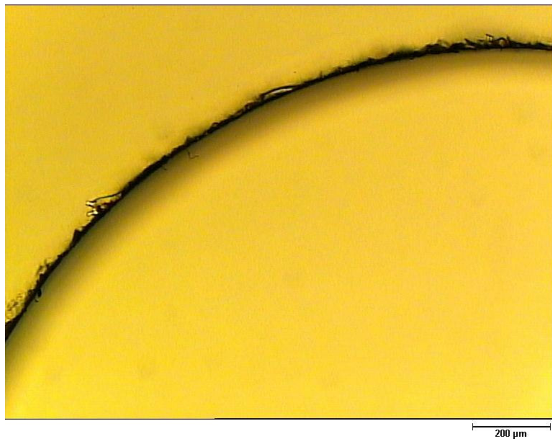
Fig. 6 Variation of normal cutting forces with spindle speed. Fig. 6 Variation of normal cutting forces with feed rate.

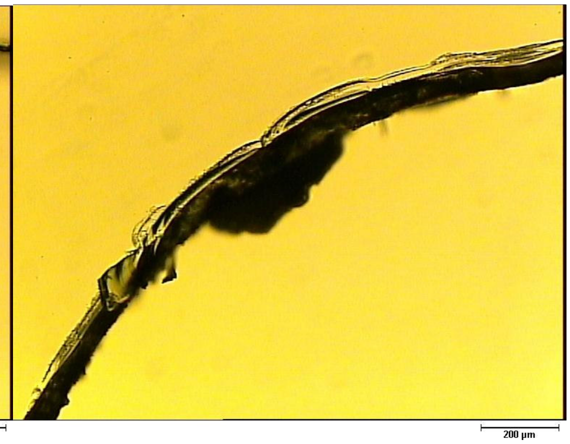
T041 Microscope.

4.2 Experimental Results and Discussions

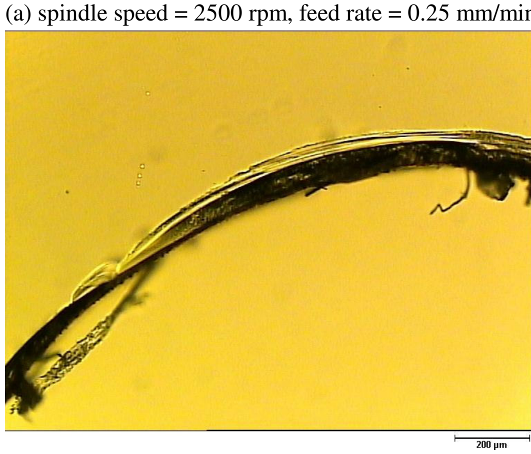
Fig. 6 and Fig. 7 shows the variations of normal cutting forces against spindle rotational speed and feed rate, which indicates the spindle speed of 2500 rpm and feed rate of 0.25 mm/min are optimized machining parameters to drill glass. This has been further confirmed by the images of holes drilled under different machining conditions which are shown in Fig. 8.

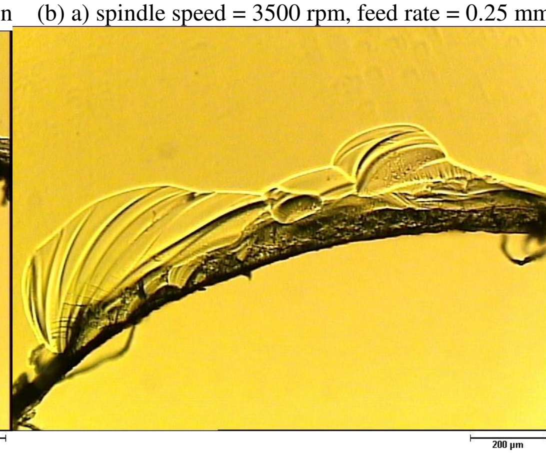
Fig. 9 shows the image of a glass wafer with six holes on it. The measured alignment accuracy by using Renishaw's CMM is 10 µm, which can meet the requirement. Fig. 10 shows that the hole drilled on Kern machine is obviously has less edge chipping than that machined on Takang machine. It is because both axial and radial stiffness of the HSK spindle on the Kern machine is bigger than spindle of Takang machine. The





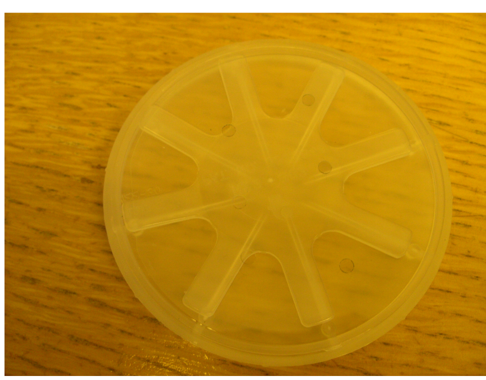
(a) spindle speed = 2500 rpm, feed rate = 0.25 mm/min (b) a) spindle speed = 3500 rpm, feed rate = 0.25 mm/min





(c) spindle speed = 2500 rpm, feed rate = 0.125 mm/min (d) a) spindle speed = 2500 rpm, feed rate = 0.3 mm/min

Fig. 8 Comparison of edge chipping under different machining conditions.



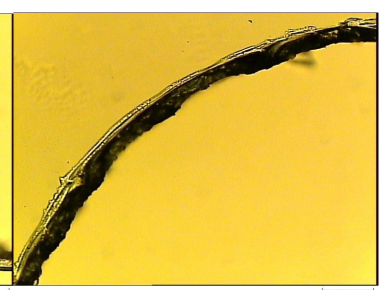


Fig. 9. One completed glass wafer

(a) on Kern machine (b) on Takang

Fig. 10. Holes drilled on two machines

effects of spindle stiffness on edge chipping will be investigated in the future experimental study.

5.0 Conclusion

This paper presents the development of a near chipping-free micro-drilling process for glass wafer. Finite Element theoretical study has been carried out to get an early indication of optimized machining parameters for obtaining good edge quality. The finding by FE simulation has been further proved by drilling tests. The experimental results show that near chipping-free holes can be obtained by using high concentration of multilayered diamond drilling with 2500 rpm spindle speed and 0.25 mm/min feed rate. Drilling tests on two different types of machine tools show stiffness of spindle also has an important effect on edge quality.

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