Low Carbon Manufacturing: Fundamentals, Methodology and Application Case Studies

Sakda Tridech

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Abstract

The requirement and awareness of the carbon emissions reduction in several scales and application of sustainable manufacturing have been now critically reviewed as important manufacturing trends in the 21st century. The key requirements for carbon emissions reduction in this context are energy efficiency, resource utilization, waste minimization and even the reduction of total carbon footprint. The recent approaches tend to only analyse and evaluate carbon emission contents of interested engineering systems. However, a systematic approach based on strategic decision making has not been officially defined with no standards or guidelines further formulated yet. The above requirements demand a fundamentally new approach to future applications of sustainable low carbon manufacturing.

Energy and resource efficiencies and effectiveness based low carbon manufacturing (EREE-based LCM) is thus proposed in this research. The proposed EREE-based LCM is able to provide the systematic approach for integrating three key elements (energy efficiency, resource utilization and waste minimization) and taking account of them comprehensively in a scientific manner. The proposed approach demonstrates the solution for reducing carbon emissions in manufacturing systems at both the machine and shop floor levels.

An integrated framework has been developed to demonstrate the feasible approach to achieve effective EREE-based LCM at different manufacturing levels including machine, shop floor, enterprise and supply chains. The framework is established in the matrix form with appropriate tools and methodologies related to the three keys elements at each manufacturing level. The theoretical model for EREE-based LCM is also presented, which consists of three essential elements including carbon dioxide emissions evaluation, an optimization method and waste reduction methodology. The preliminary experiment and simulations are carried out to evaluate the proposed concept.

The modelling of EREE-based LCM has been developed for both the machine and shop floor levels. At the machine level, the modelling consists of the simulation of energy consumption due to the effect of machining set-up, the optimization model and waste minimization related to the optimized machining set-up. The simulation is established using sugeno type fuzzy logic. The learning method uses on experimental data (cutting trials) while the optimization model is

Abstract

created using mamdani type fuzzy logic with grey relational grade technique. At the shop floor level, the modelling is designed dependent on the cooperation with machine level modelling. The determination of the work assignment including machining set-up depends on fuzzy integer linear programming for several objectives with the evaluation of energy consumption data from machine level modelling. The simulation method is applied as the part of shop floor level modelling in order to maximize resource utilization and minimize undesired waste. The output from the shop floor level modelling is machine production a planning with preventive plan that can minimize the total carbon footprint.

The axiomatic design theory has been applied to generate the comprehensive conceptual model E-R-W-C (energy, resource, waste and carbon footprint) of EREE-based LCM as a generic perspective of the systematic modelling. The implementation of EREE-based LCM on both the machine and shop floor levels are demonstrated using MATLAB toolbox and ProModel based simulation. The proposed concept, framework and modelling have been further evaluated and validated through case studies and experimental results.

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Abbreviations

AHP	Analytical Hierarchy Process
AI	Artifact Intelligent
ANFIS	Neuro Fuzzy Inference Systems
BOM	Bill of Materials
BSI	The British Standard
CFCs	Chlorofluorocarbons
CH_4	Methane
CHP	Combined Heat and Power
CNC	Computer Numerical Control
CO_2	Carbon Dioxide
DM	Devolved Manufacturing
EIO	Enterprise Input-Output Model
EREE	Energy Resource Efficiency and Effectiveness
ERP	Enterprise Resource Planning
FIS	Fuzzy Inference System
FMS	Flexible Manufacturing
GA	Genetic Algorithm
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GUI	Graphical User Interface
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
JIT	Just In Time
LCA	Life Cycle Assessment

Abbreviations

LCM	Low Carbon Manufacturing
LP	Linear Programming Solution
MADM	Multi-Attribute Decision Making
MC	Mass Customization
MCDM	Multi-Criteria Decision Making
MODM	Multi-Objective Decision Making
MPS	Master Production Planning
MRR	Material Removal Rate
N_2O	Nitrous Oxide
OA	Orthogonal Array
OR	Operations Research
PMPP	Poss Mass Production Paradigm
RSM	Response Surface Methodology

Nomenclature

C_{ijk}	set-up cost for operation j of workpiece i performing on machine k
E_{ijk}	energy consumption using for operation j of workpiece i performing on machine k
f_t	the feed per tooth (mm)
F	force (N)
I	current (amp)
m	machine type; $m \in \{1,2,...,M\}$
N_f	number of teeth
N_s	spindle speed (RPM)
o	operation for workpiece w; $o \in \{1,2,...,O_W\}$
P	power (watt or hp)
R	distance (m)
RPM	rotational speed
S_{mw}	set of workpiece can perform on machine m
S_{ow}	set of operation of workpiece can perform on machine m
S_{wo}	set of machine can perform operation o of workpiece w
T	time (sec)
T_{ijk}	production time used for operation j of workpiece i performing on machine k
V	voltage (volt)
V_f	feed rate (mm/minute)
w	workpiece type; $w \in \{1,2,...,W\}$

Nomenclature

W	work (N·m)
X_{ijk}	operation j of workpiece i performing on machine k
φ	angle of the wave form
$\emptyset V$	angular speed (ω)
$f_1(x)$	function of total energy consumption
$f_2(x)$	function of total cost of operation
$f_3(x)$	function of total production time
τ	torque (N·m)

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Chapter 1 Introduction

1.1 Background of the research

1.1.1 Overview of the current carbon emissions crisis

Greenhouse gas

A greenhouse gas (GHG) is normally referred to as a gas in the atmosphere layer that absorbs and emits radiation within the thermal infrared range. This process is fundamental to the “greenhouse gas effect” (Pepper 2006). Typically, the primary greenhouse gases include carbon dioxide (CO_2), nitrous oxide (N_2O), chlorofluorocarbons (CFCs), methane (CH_4) and tropospheric ozone. From 1899 to 1960, many researchers believed that the effect of greenhouse gas could be beneficial and neutral to human kind due to the effect of the warming temperature on the world’s atmosphere. The major advantage from this effect was to prevent the beginning of the new ice age in the future. However, many researchers critically noticed that the large scale of geophysical resources that can’t be reproduced or renewable is crucially affected by the exponential growth of the human population. With this clue, researchers have determined that the effects of greenhouse gas are a harmful factor for the ecosystem and society (Trenberth 1995).

Source of carbon dioxide (CO_2)

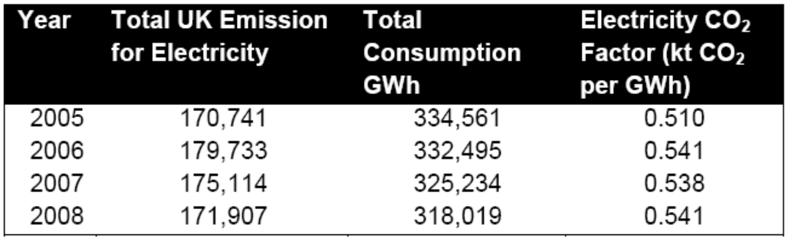
The rise in carbon dioxide emissions is now considered as the main effect on the global warming problem from the greenhouse gas. The amount of carbon dioxide emissions has approximately increased by 25% since the beginning of the industrial revolution in the early eighteenth century. CO_2 is normally emitted from the industrial process by burning fossil fuels. Fossil fuels are commonly used for electric power generation, transportation, heating and cooling processes and in manufacturing. The burning of coal and wood also emits CO_2. Taking the current situation into account, it is expected that developing countries will emit greenhouse gases at the same level or even higher than the emissions levels of developed countries as a result of the rise in energy and food demand associated with the increase in the human population (Trenberth 1995).

1.1.2 The current attempt at carbon reduction in industrial sectors

Today, the increase in carbon dioxide (CO_2) emissions is becoming the crucial factor in the global warming problem, especially in industrial sectors. As the main source of carbon emissions, all types of energy transformed from fossil fuels play the most important role in this critical problem (Kone A. C. 2010). The environmental impacts at the local, national and global levels have been rising as the population increases, which leads to more energy consumption. With this information, it can be implied that the reduction plan of carbon emissions using purely policy based approaches might not be enough at the present. In the industrial sector, it was reported that the industrialised and developing countries have the greatest responsibility to take action on the reduction of carbon emissions according to the Kyoto Protocol (Omer 2008). The agreement and framework in the Kyoto Protocol, it significantly states that developed countries must decrease their total emissions of green house gas (GHG) by at least 5% based on 1990 levels. This action has to be taken during 2008-2012 (Mirasgedis 2002; Erdogdu 2010). As different sectors have become aware of the negative outcomes from this problem, many researchers have begun to develop solutions in the forms of methodology and innovation such as renewable energy planning, energy resource allocation, transportation energy management or electric utility planning (Pohekar 2004). Therefore, it is essential to develop a systematic approach for Low Carbon Manufacturing (LCM), which is related to the manufacturing process that produces low carbon emissions and uses energy and resources efficiently and effectively during the process (Tridech 2008).

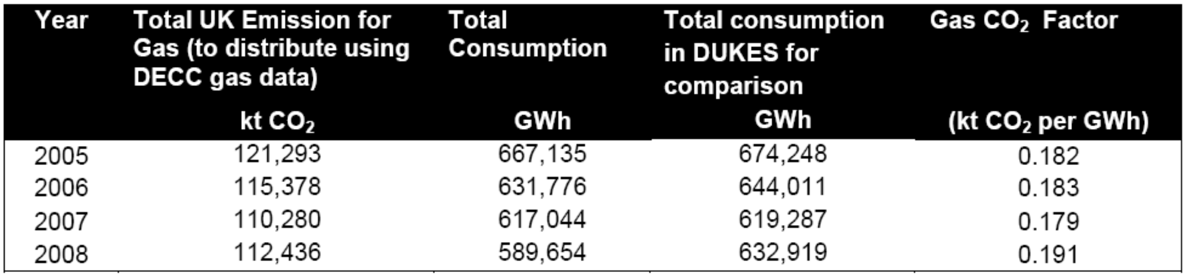
In relation to sustainability problems, many manufacturers have been suffering the crucial effect of resources and supplies being changed, especially in terms of energy and raw materials. For instance, energy prices and demand have rapidly increased and oil production is predicted to intensively produce to reach its maximum capacity due to the higher level of demand compared to the supply level. In addition, in the case of materials, the consumption rate and price of steel have doubled in the last decade and the demand is also expected to surpass the supply level as well as oil production. As a result of this crisis, the introduction of a carbon trading system such as the EU Emission Trading Scheme regarding the requirement of carbon footprint reduction and manufacturing cost effectiveness is now a high priority to be considered (Mehling 2009).

Due to the demand for energy expressed in Tables 1.1 and 1.2 (electricity and gas) below, it can be implied that the amount of carbon emissions between 2005 and 2008 is still at a high level (Department of Energy and Climate Change (DECC) 2008). In 2008, the Department of Energy and Climate Change in the UK responded to the awareness of the global warming problem by creating a national plan called The Climate Change Act 2008. It provides a clear and legally binding framework for the UK in order to satisfy the objective of decreasing the amount of greenhouse gas emissions and also ensuring that this development plan is compatible with the climate change crisis. In the details of the Climate Change Act 2008, the main target is to reduce the amount of greenhouse gas emissions by at least 80% by 2050. This target includes reducing carbon dioxide emissions by at least 26% compared to the emissions level in 1990 as a reference base. From this target, the reduction of greenhouse gas in 2020 is also set to decrease at least by 34%. This goal was adjusted and advised by the Committee on Climate Change and the UK share of the EU 2020 target (Department of Energy and Climate Change 2009). In addition, the limitations of carbon emissions for several countries provided by the IPCC are presented in Tables 1.3 and 1.4 (Intergovernmental Panel on Climate Change (IPCC) 1997).



Year	Total UK Emission for Electricity	Total Consumption GWh	Electricity CO_2 Factor (kt CO_2 per GWh)
2005	170,741	334,561	0.510
2006	179,733	332,495	0.541
2007	175,114	325,234	0.538
2008	171,907	318,019	0.541

Table 1.1 Electricity consumption trends 2005-2008 (DECC 2008)



Year	Total UK Emission for Gas (to distribute using DECC gas data) kt CO_2	Total Consumption GWh	Total consumption in DUKES for comparison GWh	Gas CO_2 Factor (kt CO_2 per GWh)
2005	121,293	667,135	674,248	0.182
2006	115,378	631,776	644,011	0.183
2007	110,280	617,044	619,287	0.179
2008	112,436	589,654	632,919	0.191

Table 1.2 Gas consumption trends 2005-2008 (DECC 2008)

Country	Emissions limitation proposals
Austria, Germany	Reduce CO_2 emissions 10 per cent by 2005, and by 15-20 per cent by 2010
Belgium	Reduce CO_2 emissions by 10-20 per cent by 2010
Denmark	Reduce CO_2 emissions 20 per cent by 2005, and by 50 per cent by 2030
Switzerland	Reduce CO_2, N_2O and CH_4 emissions by 10 per cent by 2010
United Kingdom	Reduce ghg emissions by 5-10 per cent by 2010
Netherlands	Reduce ghg emissions by an average 1-2 per cent per year (from 2000)
France	Reduce per capita ghg emissions by 7-10 per cent over 2000-2010

Table 1.3 Emissions limitation proposals for European countries (IPCC 1997)

Country	Interpolated fossil CO_2 emissions (GtC/year)					
	2000	2005	2010	2020	2030	2100
Austria, Germany	4.59	4.13	3.67			
Belgium	4.59	4.13	3.67			
Denmark	4.59	3.67	3.40	2.85	2.29	
Switzerland	4.59	4.36	4.13			
United Kingdom	4.59	4.36	4.13			
Netherlands	4.59	4.37	4.15	3.75	3.40	1.68
France	4.59	4.34	4.10	3.79	3.49	1.34

Table 1.4 Emissions limitation proposals for European countries: 2000-2100 (IPCC 1997)

For the initial step of achieving low carbon manufacturing, there are now two methodologies being broadly applied: carbon footprint assessment (by multiplying emission factor with consumed energy) and an introduction for a low carbon industrial strategy(Intergovernmental Panel on Climate Change (IPCC) 2006; Department of Energy and Climate Change (DECC) 2009). The conventional emission factors provided by the IPCC are presented in Table 1.5. Due to the requirements of carbon reduction as a global topic, the standard for carbon footprint assessment is critically essential for the first step towards low carbon manufacturing. For instance, The British Standard (BSI) and the Department for Environment Food and Rural Affairs (Defra) provide a public guideline for assessing the product life cycle of green house gas emissions, which is called PAS2050 (British Standards Institute 2008). In the past, many companies have concentrated on measuring their own emissions. However, a methodology that can assess the total emissions on the value stream or even supply chains is much more necessary.

Fuel	Carbon Emission Factor (t C/Tj)
Liquid Fossil	
Primary fuels	
Crude oil	20.0
Orimulsion	22.0
Natural Gas Liquids	17.2
Secondary fuels/products	
Gasoline	18.9
Jet Kerosene	19.5
Other Kerosene	19.6
Shale Oil	20.0
Gas/Diesel Oil	20.2
Residual Fuel Oil	21.1
LPG	17.2

Table 1.5 Emissions factors from IPCC (IPCC 2006)

Although carbon footprint evaluation is now available as an official guideline, the systematic methodology that can achieve energy efficiency and effectiveness and eventually lower carbon footprints has not been made available yet, despite the fact that this issue has been discussed as a timely topic in order to find out the scientific manner. For instance, the Department of Business, Enterprise and Regulatory Reform and the Department of Energy and Climate Change in the UK recently introduced a pilot campaign called "Low Carbon Industrial Strategy: A Vision" to inspire enterprises to create a low carbon economy (Department for Business Enterprise and Regulatory Reform and Department of Energy and Climate Change 2009). This guideline specifically suggests the important four drivers to create a Low Carbon Industry:

(1) Achieving energy efficiency to save businesses, consumers and the public services money
(2) Encouragement in critical factors for the UK's low carbon industry platform such as renewable energy, nuclear power, Carbon Capture and Storage and a 'smart' grid
(3) Applying low carbon industry concepts to the future UK automotive industry
(4) Providing support for research and development, human skills and demonstration for every business area

1.1.3 Trends and challenges for low carbon manufacturing in CNC based manufacturing systems

Nowadays, the term of mass customization can be referred to as the capability that can generate goods and services at a high production rate. This technology can also give manufacturers the ability to customize product specifications due to customer needs (Slack, 2004). This includes Internet based manufacturing, which can remotely control output and customization. Logically, consumers normally expect the outputs/products that can precisely fulfill their requirements and even have valuable manufacturing features of quality that is produced on time and for the right costs. Hence, many manufacturers have suffered the impact of the current manufacturing platform that has moved forward to the new suitable technologies and processes to gain high value manufacturing.

However, the future trend of world manufacturing cannot just rely on conventional manufacturing performance due to the emergence of the sustainable development concept and even the national crisis of carbon dioxide reduction. From this point of view, it is very essential for current products and services to be integrated with the characterizations of the sustainable principle (Jovane 2008). Thus, manufacturers must address environmental issues together with conventional manufacturing performance and also prepare new methodologies and innovations to cope with the future manufacturing demand of society (Byrne 1993).

And yet, the existing low carbon manufacturing for CNC based manufacturing systems and even generic modelling are not systematically formulated. Even though, renewable energy, alternative fuels and new innovation devices for energy have been rapidly developed to solve the global warming problem and fulfill sustainable development, the methodologies and processes that can improve and transform the existing system to a low carbon industry are not available at this moment. In CNC based manufacturing, there are many variables and factors that can affect the total energy consumption and eventually total carbon emissions, such as machining operation set-up, resource allocation and arrangement and waste minimization management. Therefore, it is very essential and necessary to develop a scientifically novel approach of CNC based low carbon manufacturing at both machine and shop-floor level.

1.2 Aims and objectives of the research

The proposed LCM concept should have the ability to reduce the total amount of the carbon footprint in existing manufacturing systems. However, since the LCM concept is very complicated in terms of the use of energy with efficiency and effectiveness, utilizing available resources and concerning the process environment, this complexity, therefore, affects the design process of conceptual modelling to integrate all of the important aspects. The design of a systematic approach and framework are critically required. For the development of an LCM framework and conceptual modelling, various scientific tools are incorporated such as artificial intelligece (AI), optimization algorithms, experimental design and system simulation. Such modelling enables decision makers to evaluate the energy consumption from processes, resource allocation optimization and undesired wastes that are associated with the final carbon footprint. The main objective of the framework is to provide the appropriate solution for every manufacturing level (machine, shop-floor, enterprise and supply chain level) in order to achieve energy efficiency, resource utilization and waste minimization.

Therefore, the overall aim of the project is to investigate and develop an innovative and industrially feasible approach and methodology for Low Carbon Manufacturing (LCM).

The specific objectives for this research include:

(1) To critically review the state of the art of low carbon manufacturing and its implementation perspectives
(2) To develop the framework for CNC based low carbon manufacturing
(3) To design the LCM modelling for both the machine and shop-floor levels
(4) To implement LCM modelling with optimization and simulation aspects
(5) To evaluate and validate the proposed LCM and its framework with case studies

1.3 Structure of the thesis

The thesis is divided into seven chapters as shown in Fig. 1.1, on the following page.

Chapter 1 introduces the background, problems and research aims/objectives.

Chapter 2 reviews the state of the art of sustainable manufacturing, the concept, characteristics and approaches regarding the current sustainable and low carbon manufacturing development, which is then followed by multi-criteria decision making techniques such as Analytical Hierarchy Process (AHP), Fuzzzy Logic, the Taguchi Method, Linear and Non-linear Programming. The topic of flexible manufacturing associated with energy and environmental aspects is also briefly reviewed.

Chapter 3 explains related methodologies used in this research. It can be categorized into two parts: experimental design (cutting trials) and computer programming such as fuzzy logic and the use of the genetic algorithm toolbox (MATLAB based) and a discrete event system simulation tool (ProModel).

Chapter 4 proposes an integrated framework for low carbon manufacturing development including state of the art, framework architecture (matrix form), a theoretical model and the introduction of LCM modelling for machine and shop-floor levels together with guidelines for a systematic approach.

Chapter 5 discusses the development of LCM modelling at machine level by using fuzzy inference engine together with an optimization model (fuzzy-grey relational grade). This chapter also provides a cooperative method between preventive maintenance information and optimal results in order to achieve energy efficiency, resource utilization, waste minimization and eventually a low carbon footprint at machine level.

This chapter also presents the implementation for LCM at shop-floor level. The conventional flexible manufacturing process mechanism is used to formulate mathematical modelling using fuzzy integer programming with several objectives. The development of simulation modelling is also presented in cooperation with optimal results from the optimization model. The chapter, then, concludes with the introduction of a production plan that can minimize the total carbon footprint while the other objectives are also satisfied.

Chapter 6 evaluates the proposed LCM and its framework with case studies.

Chapter 7 draws conclusions that result from this research. Recommendations are also provided for future work.

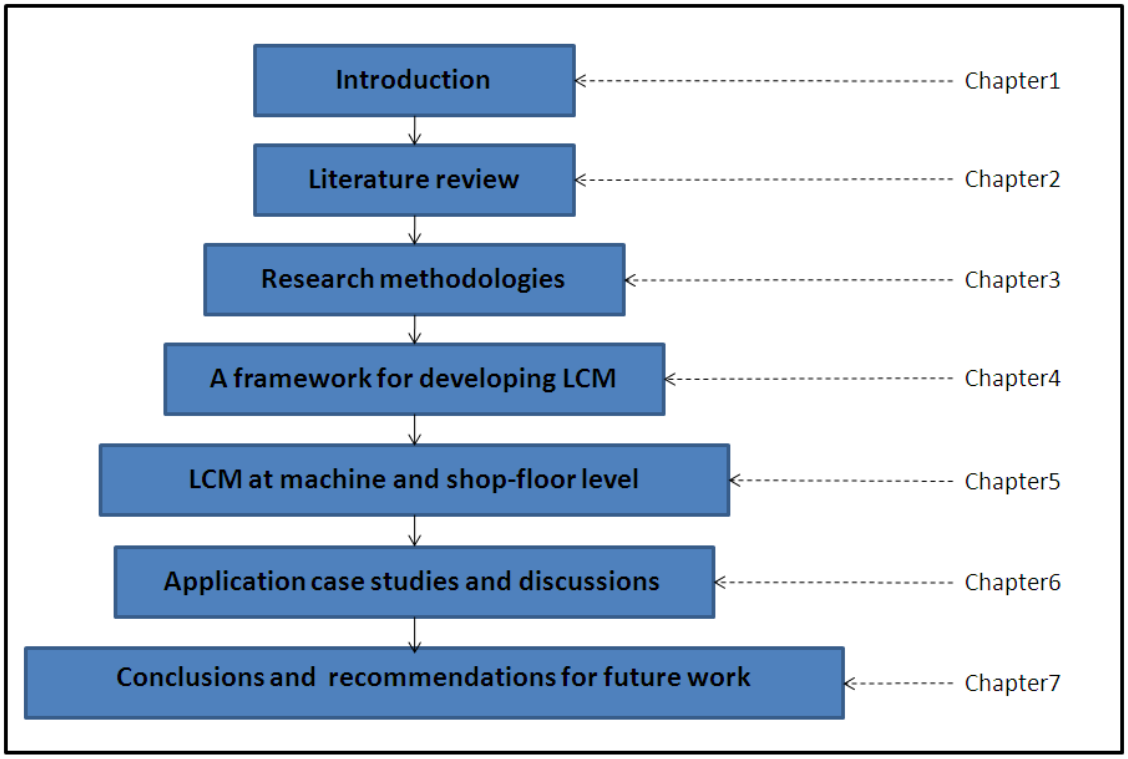


Fig. 1.1 Structure of the thesis

Chapter 2 Literature review

2.1 Introduction

In this chapter, the state of the art of sustainable manufacturing is first reviewed. The concept, characteristics and the initial design of low carbon manufacturing are then discussed. Multi criteria decision making techniques are well explored especially regarding those that experimental data is based on (fuzzy logic and the Taguchi Method) and those based on a mathematical model that is based on objectives and constraints (linear programming, multi objective programming, integer programming and fuzzy programming). This chapter then analyzes the needs and trend of low carbon manufacturing in relation to flexible manufacturing. The trends of UK energy demands and a comparison of machining conditions are also briefly discussed.

2.2 State of the art of sustainable manufacturing

The procedure of using resources that enables companies to meet human needs while the environment is preserved for the present and the future is called sustainable development. The term sustainable development was first used in 1987 in the Brundtland Report (Bhamra 2007). It was defined as development that meets the needs of the present without compromising the ability of future generations to meet their own needs (World Comission on Environment and Development 1987). From this point of view, it is obvious that successful sustainable development must be fulfilled with economic prosperity, environmental quality and social quality (Elkington 1997). On the other hand, the environmental impact from enterprise and manufacturing processes has been considered as a timely topic in recent decades. From this point of view, it leads to the requirement of environmental responsibility as associated to products and processes (Jovane 2008). Some requirements can refer to ISO 14000 and 14001, which is used by organizations to design and implement effective environmental management systems (British Standards Institute 2004). Conventionally, quality, cost, delivery and resource efficiency (Q, C, D and efficiency) are essential for the enterprise when the global competition is considered (Morita 2010). It can be implied that the current manufacturing systems cannot be relied up on in the coming future because the world’s natural resources are required by their demands (O'Brien 1999). Thus, the term of sustainable manufacturing, which combines the mechanism of pollution prevention and product stewardship (Rusinko 2007), is even essential for manufacturing systems. Currently, most sustainable development models are related to three dimensions: economic, social and environment (Azapagic, 2004). However, due to the wide spectrum of sustainable development, the review in this chapter is specifically based upon on the research work of environmental sustainability that is associated with enterprise and the manufacturing process.

2.2.1 Current research areas in sustainable manufacturing

Current research in sustainable manufacturing mainly involves the understanding of the utilization of renewable energy/new innovations, the role of operational models (operational research) on environmental management, waste reduction using a JIT (just-in-time) system, the implementation of energy efficiency, sustainable policy and analysis of environmental issues on machining systems.

2.2.1.1 The role of an operational model on environmental management

According to the rapid growth of the economic scale, the conflict between economic and sustainable development and sustainable development /environmental quality has been emerged red as a result. It can be implied that the decision makers, thus, need the proper tools or methodologies to satisfy their environmental objectives (Bloemhof-Ruwaard 1995). Stenam (1991), then, suggested that an optimization method can be considered as a feasible tool when the situation of selecting a solution from a set of alternative solutions is occurred (Sterman 1991). The definition of operation research given by the Operational Research Society (UK) is "The distinctive approach is to develop a scientific model of the system incorporating measurements of factors, such as chance and risk, with which to predict and compare the outcomes of alternative strategies or controls." (Urry, 1991).

The implementation of an operation model to the sustainable problem has been investigated by many researchers since 1990. For instance, Beek (1992) introduced the role of operational research as an effective tool to cope with environmental problems (Beek 1992). In relation to the example of using a mathematical model for a sustainable problem, Wang et al. (2006) proposed the implementation of using an interval fuzzy multi objective programming to cope with an integrated watershed management problem. The model formulation is constructed with several objectives: maximization of social benefit and minimization of soil loss, nitrogen loss, phosphorus loss, and chemical oxygen demand discharge, while the constraints are subjected to cropland, fish pound, forest area, tourism capacity, water supply, sewage plant augment, sewage water discharge, COD discharge, TN loss, TP loss, capital and technical. The optimal solution can return the proper planning regarding to sustainable watershed management (Wang 2006). In addition, the mathematical model is also used to solve the watershed problem by Yuan et al. in 2008 (Yuan 2008). The multi objective model is used for application of water resource allocation, water environment assessment and water quality management.

While the operational model is broadly used for management of environmental problems, it can also be integrated with product and process life cycles. Bloemhof-Ruwaard (1995) demonstrated the methodology to reduce environmental impact by integrating an operational model with the information from product and process life cycle. The methodology begins by using life cycle analysis (LCA) to gather relevant data and, then, an analytic hierarchy process (AHP) is used to determine the weight factor of the environmental index. Finally, a linear programming model (LP) is formulated by using an environmental index as an input to reduce the environmental impact (Bloemhof-Ruwaard 1995).

2.2.1.2 Waste reduction using lean manufacturing

Obviously, the term of JIT (just-in-time) refers to a set of management practice that have the main objective of eliminating all wastes and maximize the utilization of human resources (Monden 1994). Richard et al. (2010) proposed that the implementations of JIT (see Fig. 2.1) such as focused factory, reduced setup times, group technology, total productive maintenance, multifunction employees, uniform workload, just-in-time purchasing, Kanban, total quality control and quality circles should be accomplished by organizations in order to achieve sustainable operations (Richard 2010). In addition, Ranky et al. (2010) also suggest the application of a lean and green design concept to gain sustainable green, eco-friendly, quality products that satisfy customer needs and produce the exact amount demanded. This can lead to a reduction in inventory waste and cost throughout the whole supply network (Ranky 2010). From this advantage, the concept of a pull system that integrates flexibility and real time response can, therefore, play an important role in the ERP model (Chin-Tsai L. 2011).

Fig. 2.1 A JIT factory design (Ranky 2010)

From the viewpoint of operational levels, the concept of total productive maintenance is very essential to the lowest level of process hierarchy. The operators who operate the machine can learn and understand the basics of machine maintenance. So, they can make a decision to stop and perform preventive maintenance at the appropriate moment because the operational line should be stopped without penalty when the error that has affected the product quality can be detected (Ranky 2010). The success of total productive maintenance can strengthen the performance of machine operation and minimize undesired problems in the machine functions. It can also improve machine utilization/productivity and on-time delivery.

Another concept in JIT that needs to be considered in terms of sustainability is to stay as lean, agile, reconfigurable and flexible as possible because conventional manufacturing is required in order to respond quickly to the market by providing quality products/services with a low cost of production (Mishra 2006). An example of a reconfigurable machine is presented in Fig. 2.2.

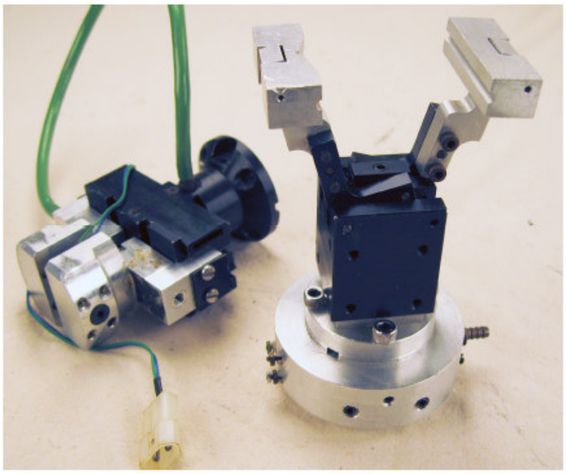


Fig. 2.2 Reconfigurable machines (Ranky 2010)

2.2.1.3 Environmental issues on machining systems

At present, the machining process cannot be classified as clean production. This situation, in regard to manufacturing trends, will not be suitable for the requirements of the coming future (Byrne 1993). Obviously, machining can be referred to as a material removal process or, in other words, a metal cutting process using various types of cutting tools. During the machining process, the operation can be wasteful in term of materials and energy. In Fig. 2.3, the overall perspective of the cutting process is presented with the most important processes such as tool preparation, material production, material removal, machine tool construction, cutting fluid and cleaning. It is obvious that the greatest environmental impact regarding the material removal process comes from energy consumption. Thus, the estimation of energy use in the removal process often requires specific cutting energies. Energy analysis in the material removal process can be divided into three phases: constant start-up operations (idle), run-time operations (positioning, loading etc.) and material removal operations (in cut). Table 2.1demonstrates the energy analysis of four machines: Toyota's production machine center, the Bridgeport automated milling machine 1998, Cincinnati Milacron milling machine 1988 and Bridgeport's manual milling machine 1985. The proportion of machine energy use shown in Table 2.1 indicates that the machine center from Toyota production spent most energy consumption on the start-up/idle phase (85.2%) while the other three machines spent most of their energy consumption on the material removal process. Focusing on the environmental impact from the machining process, the main effect comes from energy consumption, which is electricity. Normally, the traditional electrical generation that was used during the last century is fossil fuel (coal buring) (Hughes 2009). It is obvious that most electricity generation is produced from burning coal which is the source of carbon dioxide emissions (Table 2.2). Therefore, it can be concluded that carbon dioxide is the main environmental impact from the machining process. However, there are also other emissions that occur from other processes of electricity generation: nitrogen monoxide (NO_x) and sulphur dioxide (SO2). In addition, the impact to the environment from cutting fluid is the large amount of water resources that have to be used to dilute soluble oil (typically diluted with 95% of water by volume) while there are sulphur dioxide emissions from material production when metal is smelting (Dahmus 2004).

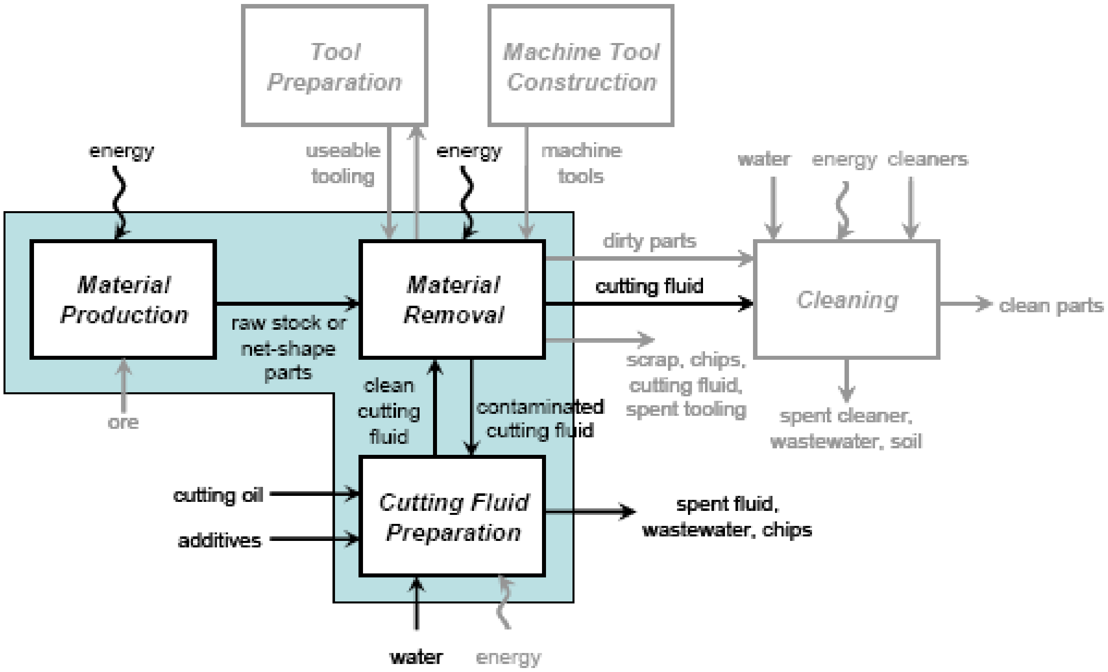
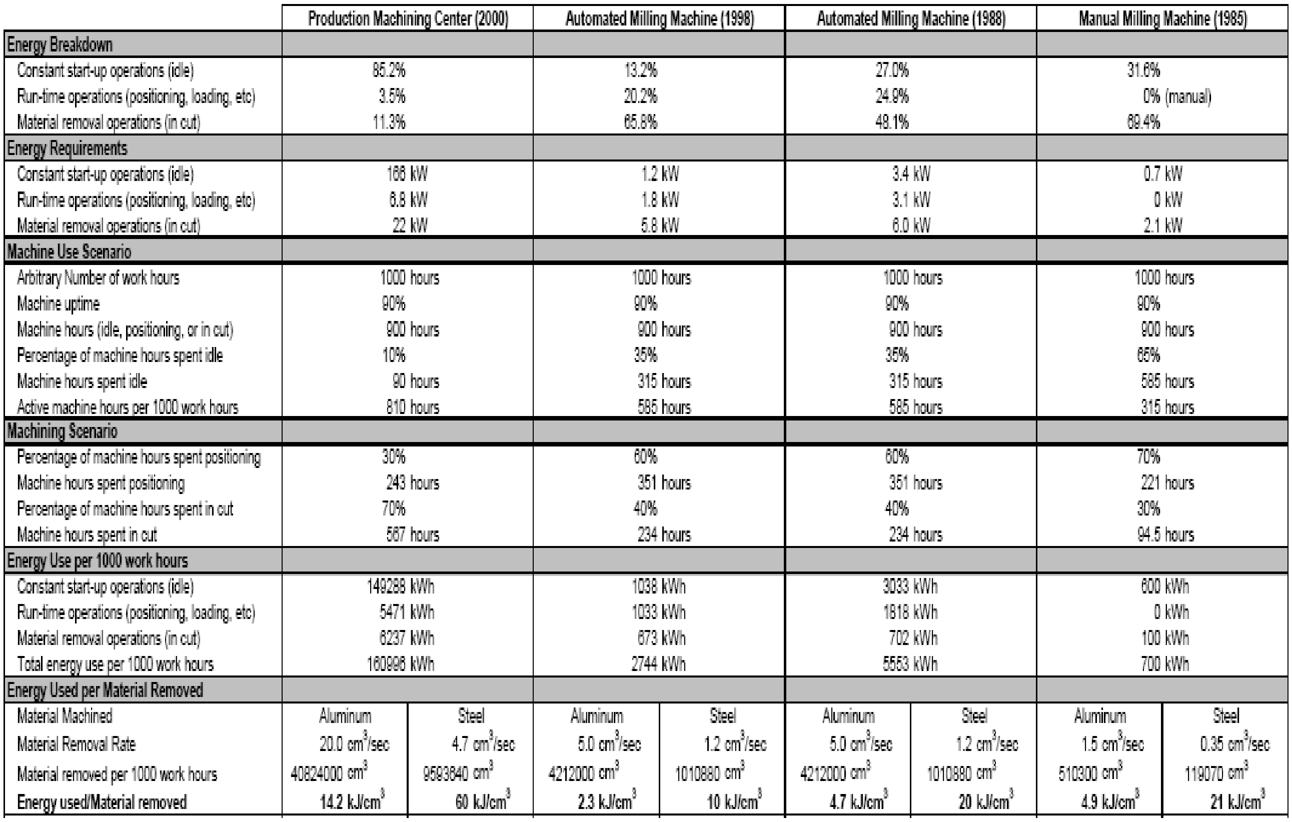


Fig. 2.3 Conventional machining process (Dahmus 2004)



	Production Machining Center (2000)		Automated Milling Machine (1998)		Automated Milling Machine (1988)		Manual Milling Machine (1985)	
Energy Breakdown								
Constant start-up operations (idle)	85.2%		13.2%		27.0%		31.6%	
Run-time operations (positioning, loading, etc)	3.5%		20.2%		24.9%		0% (manual)	
Material removal operations (in cut)	11.3%		65.8%		48.1%		69.4%	
Energy Requirements								
Constant start-up operations (idle)	166 kW		1.2 kW		3.4 kW		0.7 kW	
Run-time operations (positioning, loading, etc)	6.8 kW		1.8 kW		3.1 kW		0 kW	
Material removal operations (in cut)	22 kW		5.8 kW		6.0 kW		2.1 kW	
Machine Use Scenario								
Arbitrary Number of work hours	1000 hours		1000 hours		1000 hours		1000 hours	
Machine uptime	90%		90%		90%		90%	
Machine hours (idle, positioning, or in cut)	900 hours		900 hours		900 hours		900 hours	
Percentage of machine hours spent idle	10%		35%		35%		65%	
Machine hours spent idle	90 hours		315 hours		315 hours		585 hours	
Active machine hours per 1000 work hours	810 hours		585 hours		585 hours		315 hours	
Machining Scenario								
Percentage of machine hours spent positioning	30%		60%		60%		70%	
Machine hours spent positioning	243 hours		351 hours		351 hours		221 hours	
Percentage of machine hours spent in cut	70%		40%		40%		30%	
Machine hours spent in cut	567 hours		234 hours		234 hours		94.5 hours	
Energy Use per 1000 work hours								
Constant start-up operations (idle)	149288 kWh		1038 kWh		3033 kWh		600 kWh	
Run-time operations (positioning, loading, etc)	5471 kWh		1033 kWh		1818 kWh		0 kWh	
Material removal operations (in cut)	6237 kWh		673 kWh		702 kWh		100 kWh	
Total energy use per 1000 work hours	160996 kWh		2744 kWh		5553 kWh		700 kWh	
Energy Used per Material Removed								
Material Machined	Aluminum	Steel	Aluminum	Steel	Aluminum	Steel	Aluminum	Steel
Material Removal Rate	20.0 cm^3/sec	4.7 cm^3/sec	5.0 cm^3/sec	1.2 cm^3/sec	5.0 cm^3/sec	1.2 cm^3/sec	1.5 cm^3/sec	0.35 cm^3/sec
Material removed per 1000 work hours	40824000 cm^3	9593640 cm^3	4212000 cm^3	1010880 cm^3	4212000 cm^3	1010880 cm^3	510300 cm^3	119070 cm^3
Energy used/Material removed	**14.2 kJ/cm^3**	**60 kJ/cm^3**	**2.3 kJ/cm^3**	**10 kJ/cm^3**	**4.7 kJ/cm^3**	**20 kJ/cm^3**	**4.9 kJ/cm^3**	**21 kJ/cm^3**

Table 2.1 Energy analysis on commercial machines (Dahmus 2004)

Thousand tons of oil equivalent (unit)	2004	2005	2006	2007	2008
Coal	764	767	768	766	801
Blast furnace gas	790	801	780	767	664
Coke oven gas	107	162	161	169	168
Natural gas	61	44	39	37	58
Petroleum	32	19	20	28	44
Other	64	70	55	56	54

Table 2.2 Energy consumption using in iron and steel manufacturing of UK industry (Department-of-Energy-and-Climate-Change-(DECC) 2009)

Furthermore, Munoz et al. (1995) also investigated the environmental impact from the machine process by proposing the model for evaluating the environmental impact of the machining process including mechanics of machining, tool wear and cutting fluid flow (Fig. 2.4). In order to evaluate the impact factors such as toxicity, flammability, and mass flow characteristics of waste streams, the Analytic Hierarchy Process (AHP) with pair-wise comparison is used to determine the weight of toxicity, and flammability. The results from the model can also indicate the overall tradeoff between energy, waste-stream mass and the process-time factor (Munoz 1995).

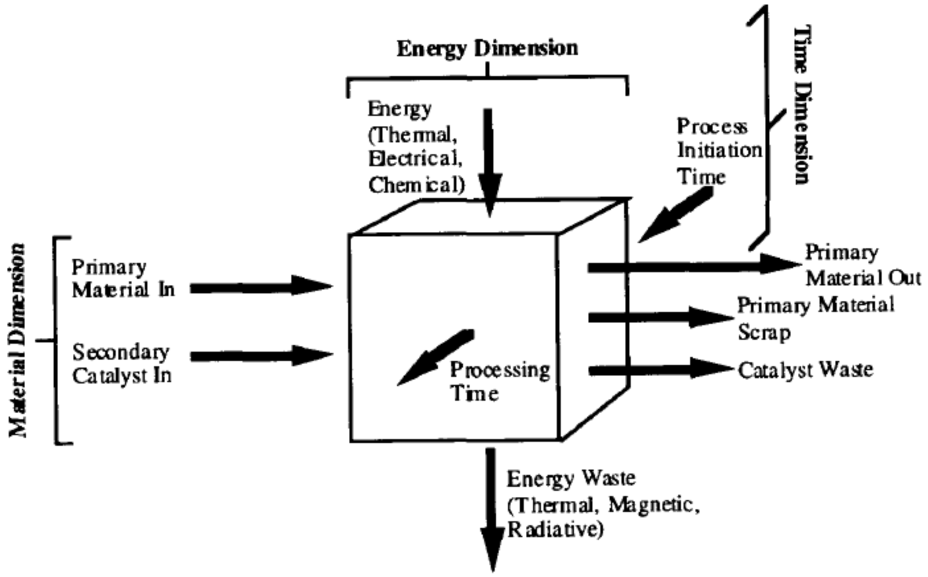


Fig. 2.4 The environment of the manufacturing process (Munoz 1995)

2.2.1.4 Strategic planning for sustainable manufacturing

Due to an evolutionary economics configuration that involves technological and public policy, it can be used to analyze the relationship between technological change, sustainable development and industrial competitiveness. Thus, the management of wider social responsibility (local, national and international level) by searching for a suitable 'win-win' strategy for the firm, can be an essential role (Faucheux 1998). It can be implied that the interaction between environmental objectives and typical manufacturing performance has returned in the form of compromise between public advantage and individual costs. From this clue, the development of innovation for the industrial sector, which conforms to environmental regulations, must be followed with three criteria: environmental objectives can be completed using flexible methods, innovation developers have to be encouraged to achieve required goals and governing the considered boundaries in simultaneous ways (Porter 1995). Jovane et al. (2008) classified the role of strategies for sustainable manufacturing into two levels: macro and meso level (Jovane 2008).

Considering the macro level of sustainable manufacturing, the implementation of environmental concern is considered to be the essential key factor while the economic issue is used as a tool for accessing the social dimension. In the last decade, many countries have been developing their international and domestic policies to catch up with environmental concerns while economic and social perspectives are still moving in the right direction. For example, the Department of Commerce governed by the US government, aims to support the co-operation between public and private sectors to achieve effective sustainable manufacturing as a result of the requirements of global competitiveness (United States Department of Commerce 2004). In China, the awareness of the importance of energy policy is now taken into account due to the rapid expansion of the China's economy which requires large amounts of energy consumption (70% of China's primary energy supply is coal). Thus, China has been taking action to enable the role of renewable energy and R&D as a top-down approach in the form of policy. The proposal of this policy aims to gather energy conservation and economic support together. For instance, the Chinese government applied the regulation of an electricity surcharge by 0.2 cent/kWh in order to support the use of renewable energy while the Ministry of Finance launched a new regulation for the import of wind turbines by refunding tax in order to stimulate the utilization of wind energy (Chai 2010).

At the meso level, the characteristic of sustainable manufacturing relies on products/services, processes and business models that are related to economical, social and environmental topics. Hence, many researchers have been trying to make efforts to develop strategies associated with products/services life cycles and enterprise business models. For instance, Tomiya proposed a developed conception called the Poss Mass Production Paradigm (PMPP), which aims to disconnect the explanation of economics from a material and energy consumption angle while the quality of life issue can be satisfied based on the conventional life cycle model (Fig. 2.5). To implement this concept, the idea of closing the life cycle loop, which refers to recycling, remanufacturing, refurbishing, cascading and reuse, is used as the main methodology to reduce the production of artifacts (Tomiya 1999). For another example of developed modelling, Kuhtz et al. (2010) proposed the application of using an enterprise input-output model (EIO) to investigate the amount of energy consumptions together with the pollution levels of tile manufacturing (Fig. 2.6). According to the operational mechanism of this model, the flow (raw material, energy, product and waste etc.) of the considered manufacturing line evaluates how the combination of input can be rearranged to satisfy environmental constraints such as the reduction of energy use but keeping other output flow constraints (Kuhtz 2010).

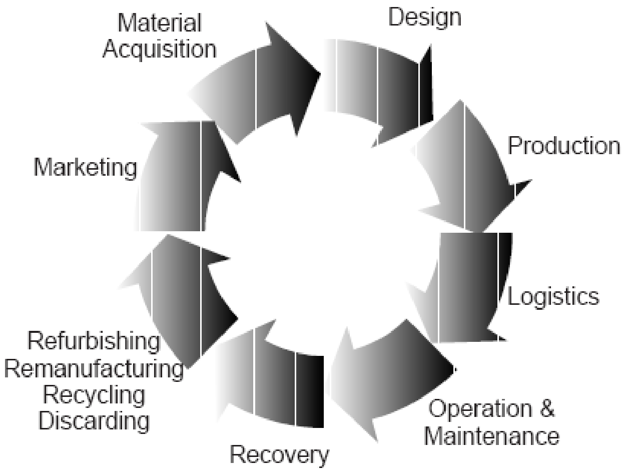


Fig. 2.5 The conventional life cycle (Tomiya 1999)

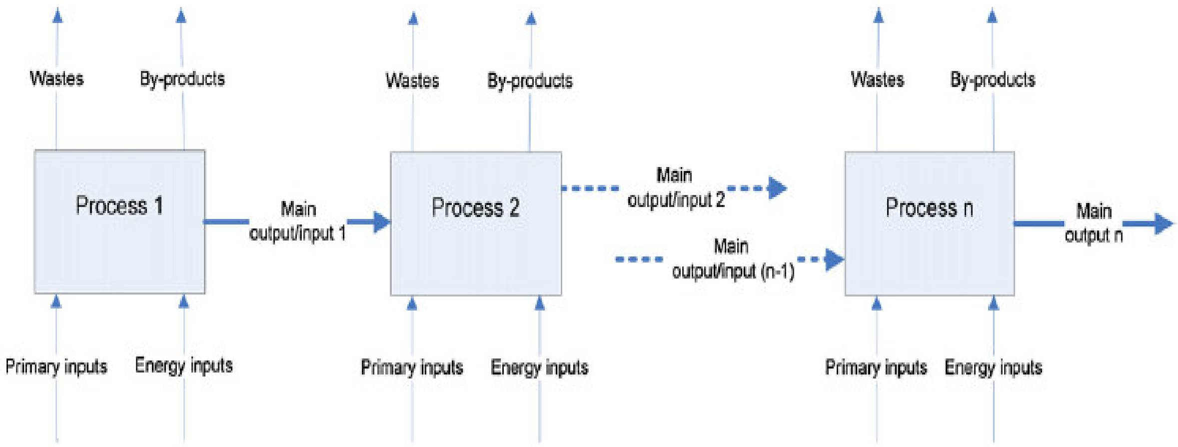


Fig. 2.6 The EIO model (Kuhz 2010)

2.2.1.5 The utilization of renewable energy

According to the energy trend related to the time period, the proportion of non-renewable energy in the usage of total energy distinctively increased in the middle of the nineteenth century (80-90%). It is expected that the utilization of fossil fuel will be classified as the essential aspect of exponential growth in energy usage regarding energy demand activities in the near future. Therefore, the usage of renewable energy, nuclear-fusion energy and even the combination between two alternatives are suggested to be the main energy supply of human kind in the long term period. Normally, sources of renewable energy can be classified as solar radiation, wind, ocean waves, water flows, heat flows and so on (Sorensen 2002).

Solar radiation

Currently, the energy from sun irradiance equals to 3.9 x 10^{26} W (Sorensen 2002). In South East England, there is 20 W/m^2 and 80 W/m^2 of solar irradiance on the vertical and horizontal surface respectively on a cloudy day (Eastop 1990). Conventionally, the application of utilizing solar energy is used as energy conversion for generating electricity energy in a photovoltaic cell or solar cell. Photovoltaic (PV) cells or photocells which, provides monochromatic light, can transform radiation into electrical energy with 100% efficiency (Rosa, 2009).

Wind

In order to utilize wind as a source of renewable energy, it can be implemented by installing the instrument/device that can transform kinetic energy into mechanical energy (Sorensen 2002). The application of wind energy can be used to generate electricity, as can solar energy. Thus, Hoicka et al. (2011) presented the investigation of whether a combination of utilizing wind and solar energy for electricity generation in Ontario (Canada) is effective or not. The results indicated that a combination between two types of renewable energy is more constant in terms of energy production opposed to simply relying on a single source (solar/wind). This advantage can be further useful in term of future energy supply for both global demand and manufacturing systems (Hoicka 2011).

Water flows

Hydropower, which is the use of water as a source of renewable energy, is one of the oldest renewable energy sources for generating electricity in rural areas using economical and clean mechanisms (Kosa 2011). The construction of a dam can be considered as a factor that can control the movement of streams. This could imply that the higher the level of water storage the better the conversion to kinetic energy at the required time is (Sorensen 2002). In 2011, Kosa et al. (2011) presented the investigation of utilizing micro-hydropower technology for electrical generation in two different water sources: a run-of-river scheme and reservoir scheme. This investigation was taken at the Nakhon Ratchasima province, which located in Thailand. The results distinctively show that there was a vast gap between electrical energy obtained from the different sources: 6000 KW and 320 KW from reservoir and run-off-river respectively (Kosa 2011). In a manufacturing system, it could be an advantage for an enterprise if they can install suitable technologies that can utilize a renewable source to create the primary energy input at the other production flows regarding to the zero carbon manufacturing model presented by Ball et al. 2009 (Ball 2009). According to the concept of this model presented in Fig. 2.7, the cycle of process flow can be classified as environmental friendly production when the input energy is clean.

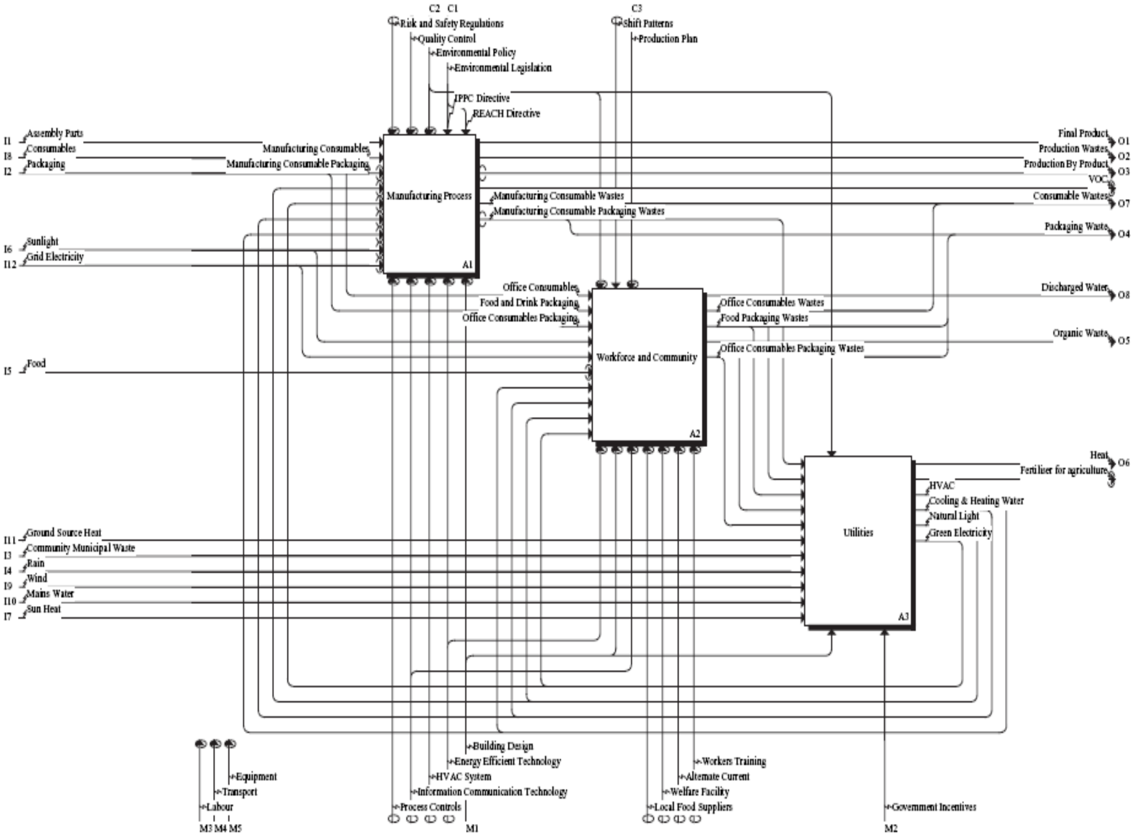


Fig. 2.7 The utilization of renewable energy source (Ball 2009)

Biological conversion

Currently, many research works has explored bio-energy as an alternative solution for carbon emission reduction. For instance, Nguyen (2010) investigated the potential of using sugar cane as a primary source instead of using fossil fuel in Thailand, with the requirements of the Kyoto protocol in mind. The research results conclude that sugar cane is efficient enough to replace fossil fuel. However, schemes have arisen where the supply method for bio-energy and the effective utilization of bio-energy are considered. Fossil fuels rather than biomass fuels have been still broadly consumed for electricity generation because electricity generation using fossil fuels are cheaper than utilizing biomass fuels (Allen 1998). Thus, Allen (1998) proposed a cost effective supply chain model of transporting biomass fuel in order to promote the utilization of alternative renewable energy. Moreover, Gold et al. (2011) proposed the application of a supply chain model and related logistics to strengthen the reliable supply of biomass fuels to bio-energy plants. Fig. 2.8 illustrates a logical chain of transporting an energy supply to a bio-energy plant. The main operations in the chain include harvesting/collection, storage, transport and pre-treatment methods (Gold 2011). To increase the effective utilization of bio-energy for the enterprise, the conversion of waste from the output of the previous processes can be used as a primary input for later processes. This has been implemented by many companies (Ball 2009). For instance, Conoco Phillips Immingham used the technology of combined heat and power (CHP) to generate electricity using natural waste as a primary input to cope with CO_2 emissions problems (Ball 2009). Typically, the term of CHP (combined heat and power) can be referred to as a system that can utilize heat waste. For instance, the heating system for household unit can be supplied by waste energy from electricity generation (Fresis, 2008).

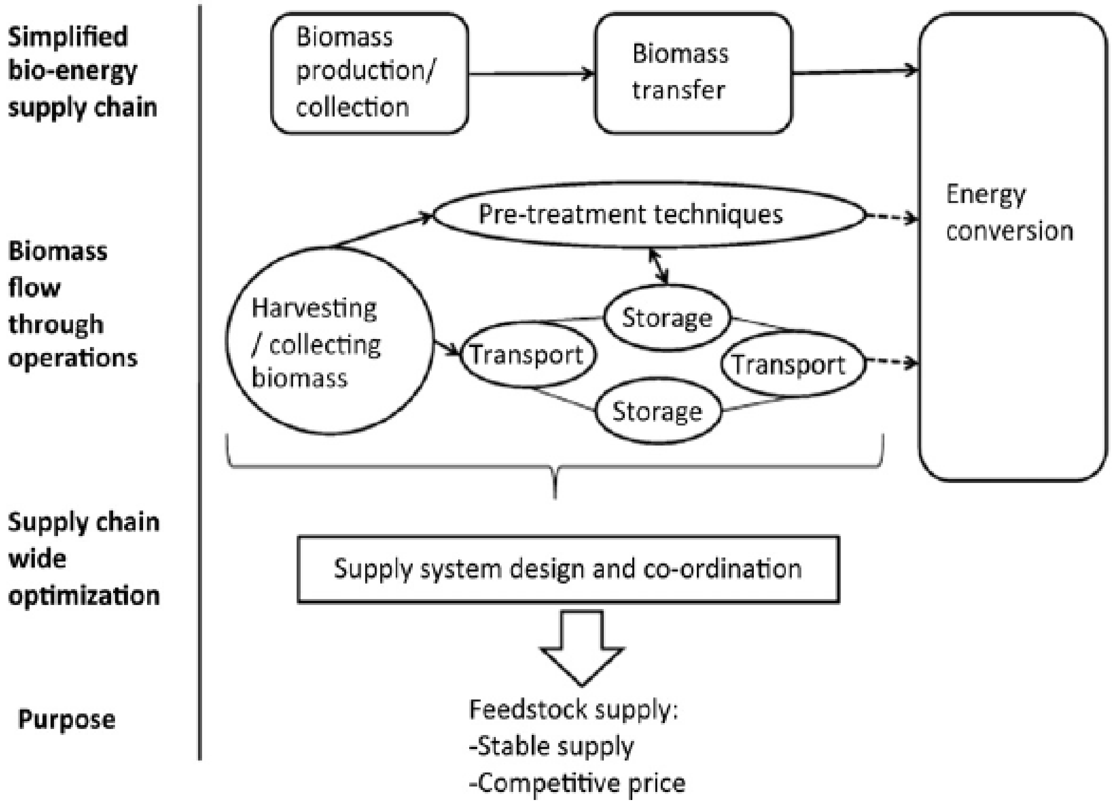


Fig. 2.8 The logic flow of energy supply for bio-energy (Gold 2011)

2.3 Low carbon manufacturing

2.3.1 Characteristics of low carbon manufacturing

Despite awareness of the global warming problem in relation to the rise of carbon dioxide emissions, the current manufacturing processes are only concerned with typical manufacturing performances such as cost, profit, lead time, total production time and quality of product/service etc. From this point of view, the ordinary industrial process used at present must integrate with the environmental aspects to satisfy the requirements of the Kyoto Protocol to reduce the total amount of carbon dioxide emissions as a national responsibility (Omer 2008). As a result, the concept of low carbon manufacturing (LCM) has been emerging in the last decade. LCM refers to a manufacturing process that produces low total carbon emissions intensity and uses energy and resources efficiently and effectively during the process (Tridech 2008).

The essential concept of LCM is initially demonstrated based on the concept of sustainable manufacturing and the principle of life cycle assessment (LCA). On the other hand, the evaluation of carbon dioxide emissions from each step in the process chain must conform to BSI:2008 standards using appropriated emission factors in relation to the amount of energy consumption (British-Standards-Institute 2008). In 2007, the Department of Environment, Foods and Rural Affairs produced the support guidelines for a Publicly Available Specification (PAS) development in order to provide useful information on existing life cycle methodologies to meet the PAS requirement. In this guideline, a SWOT analysis was used as an assessment method to evaluate characterizations of related methodology such as strengths, weakness, opportunities and threats. It can be concluded from this guideline that the core of carbon reduction is calculation of emissions (Minx 2007). It can be concluded that development of an accurate estimation of Green House Gas (GHG) emissions is very essential for firms that aim to reduce carbon emissions (Minx 2007).

The initial conceptual model of LCM at the enterprise level, proposed by Ball in 2009, is given in Fig. 2.9. The main idea of this model is to present the implementation of technologies for generating renewable energy at the proper point in the manufacturing system by using the IDEF0 modelling based approach. The hierarchy of energy flow of the whole enterprise can be analyzed. In addition, the systematic method to utilize waste as a source of renewable energy is also presented in this model. However, this model is only classified as a qualitative model which is not classified as dynamic modelling. As such, evaluation and validation using simulation and qualitative methods are necessary for this model according to the author suggestion (Ball 2009).

Fig. 2.10 presents another modelling for LCM, as presented by Song in 2010. The model embeds the estimation of GHG emissions for every step of the product design using a bill of materials (BOM). In addition, Fig. 2.11 illustrates the integrated system between databases of GHS emissions of component parts and the BOM structure of the product. The objective of this system is to seek the selection of components/parts that can satisfy the target of GHS emissions. If the selected solution fails to achieve the objective, an alternative set of components/parts that conform to the requirement of customer and production capacity will be provided until the solution satisfies the goal (Song 2010).

Although the concept of renewable energy and estimation of GHG emissions are broadly used to develop the method and framework for LCM, the use of energy consumption with effectiveness and efficiency also can be another feasible solution. Fig. 2.12 represents the capture of a developed system called a "Process Chain Simulator", which was proposed by Hermann in 2009. The main feature of this system is to eliminate the conflict between energy consumption, production time and electricity costs (Herrmann 2009).

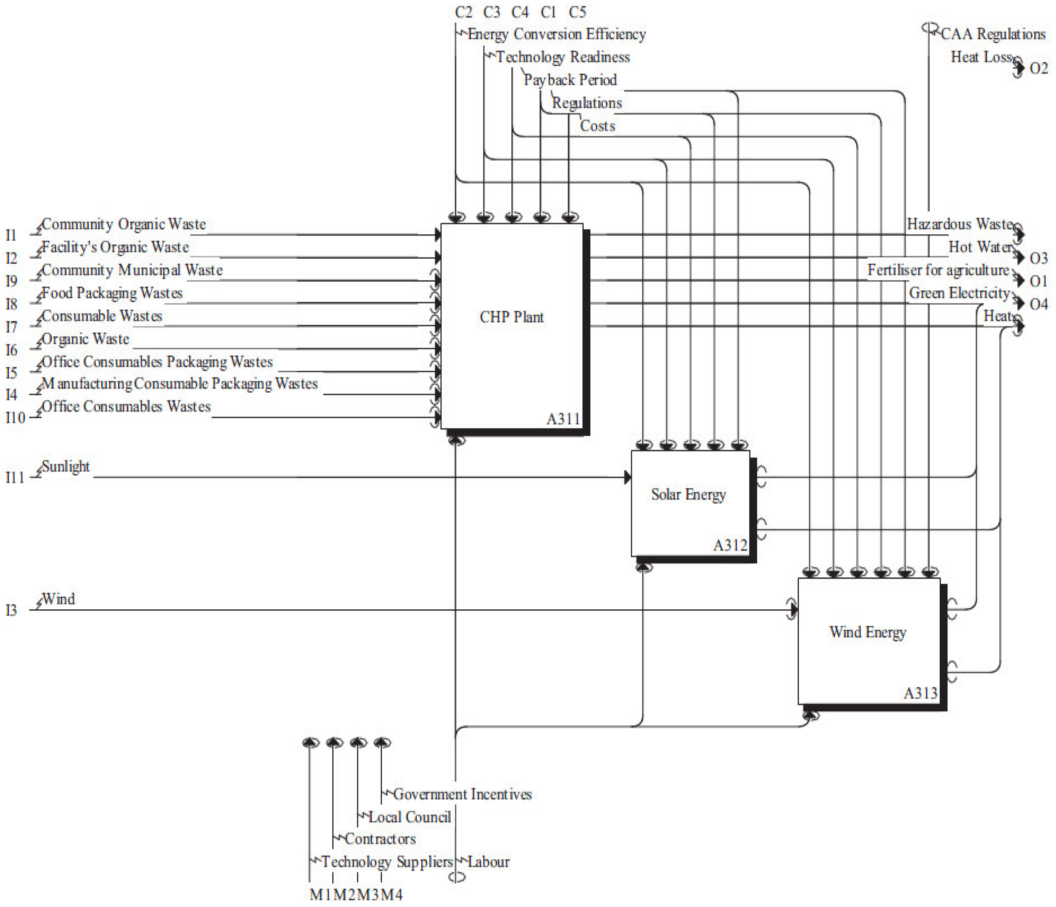


Fig. 2.9 The conceptual model for zero carbon manufacturing (Ball 2009)

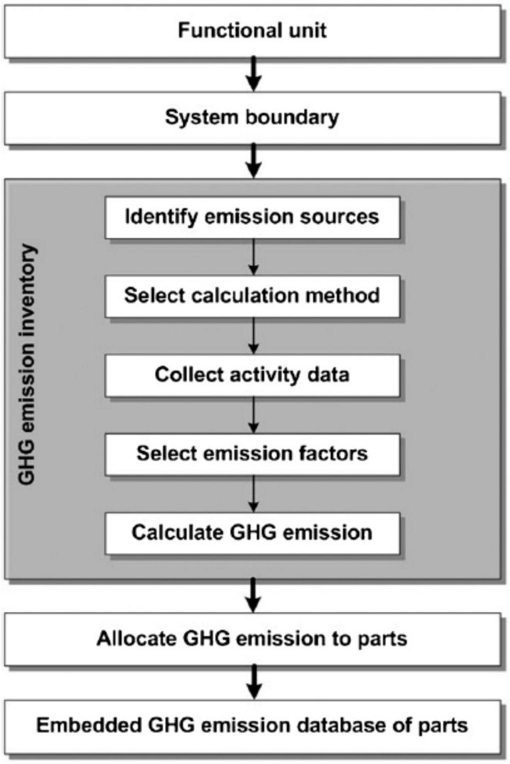


Fig. 2.10 Process for developing an embedded GHG emissions database (Song 2010)

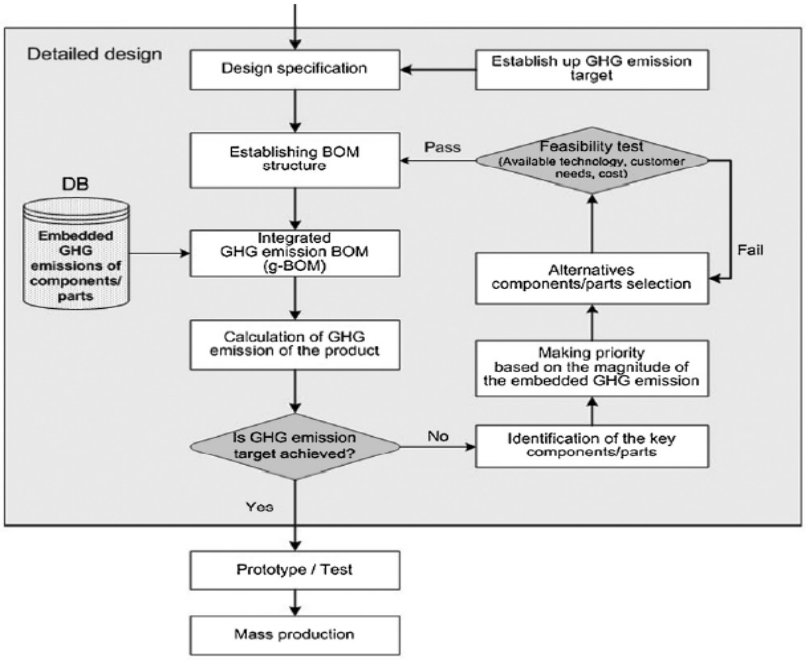


Fig. 2.11 Design process in the low carbon product design system (Song 2010)

Scenario specifications					Production time	Electricity consumption	Electricity costs (per month)	Output rate	Energy efficiency	Electricity cost efficiency
Name	Qty line 1	Qty line 2	Lot size	Asynchr.	[min]	[kWh]	[€]	[parts/min]	[parts/min]/ [kWh]	[parts/min]/ [€]
S1	0	200	25	n	! 278,43	! 148,52	✓ 2001,23	0,718	4,836E-03	3,589E-04
S2	0	200	50	n	✗ 303,52	✓ 127,95	✓ 1714,23	0,659	5,150E-03	3,844E-04
S3	0	200	100	n	✗ 353,48	✓ 123,23	✓ 1511,99	0,566	4,591E-03	3,742E-04
S4	50	150	25	n	✓ 220,12	✗ 172,85	✗ 3472,46	0,909	5,257E-03	2,617E-04
S5	50	150	50	n	! 245,10	! 155,90	! 2929,74	0,816	5,234E-03	2,785E-04
S6	50	150	25	y	✓ 220,15	✗ 170,06	! 3126,14	0,908	5,342E-03	2,906E-04
S7	50	150	50	y	! 245,15	! 152,78	! 2474,42	0,816	5,340E-03	3,297E-04
S8	100	100	25	n	✓ 161,77	! 155,29	✗ 4006,58	1,236	7,961E-03	3,086E-04
S9	100	100	50	n	✓ 186,87	✓ 138,42	✗ 3295,39	1,070	7,732E-03	3,248E-04
S10	100	100	100	n	! 236,82	✓ 139,26	! 2680,01	0,845	6,065E-03	3,151E-04
S11	100	100	25	y	✓ 178,45	✗ 159,18	✗ 3414,55	1,121	7,041E-03	3,282E-04
S12	100	100	50	y	✓ 203,40	! 141,96	! 2720,72	0,983	6,926E-03	3,614E-04
S13	100	100	100	y	! 253,43	! 143,93	✓ 2199,30	0,789	5,483E-03	3,588E-04
S9*	100	100	50	n	✓ 186,87	✓ 138,42	! 3097,39	1,070	7,732E-03	3,455E-04

Fig. 2.12 The evaluation system for energy efficiency (Hermann 2009)

2.3.2 The initial design for a low carbon manufacturing system

Currently, the manufacturing process that uses energy to perform can be illustrated in Fig. 2.13 (Gutowski 2006). It is obvious that the outputs from the manufacturing process are product, wastes and waste energy. Thus, the estimation and assessment for the environmental impact from the manufacturing system called "Life Cycle Assessment (LCA)" has emerged. The key procedure of this method is the identification of product requirements such as energy, materials and the emissions and waste released into the environment (Heilala 2008). The holistic approach of LCA for an EU platform is presented in Fig 2.14. Beyond the advantage of LCA, the guideline for assessing the amount of carbon footprint is constructed, which is called "PAS 2050" by British Standards (British-Standards-Institute 2008). This method specifically concerns the source of GHG while the LCA includes all environmental impacts. For the first step of carbon footprint reduction, it is very important to understand where the carbon emissions come from. In Fig. 2.15, the example of calculating carbon dioxide emissions using PAS2050 is presented using the transportation of wheat in flour production. Each activity from this example is classified and provided with activity data then multiplied with a proper emissions factor. The result from this calculation is carbon dioxide emissions in units of kg CO_2e. However, the systematic approach for low carbon manufacturing specifically for CNC based manufacturing does not yet exist today even though the research for reduction of carbon dioxide emissions is being broadly developed.

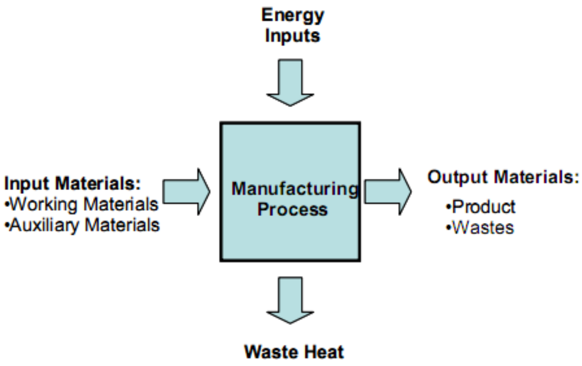


Fig. 2.13 Energy and materials inputs and outputs of manufacturing process (Gutowski 2006)

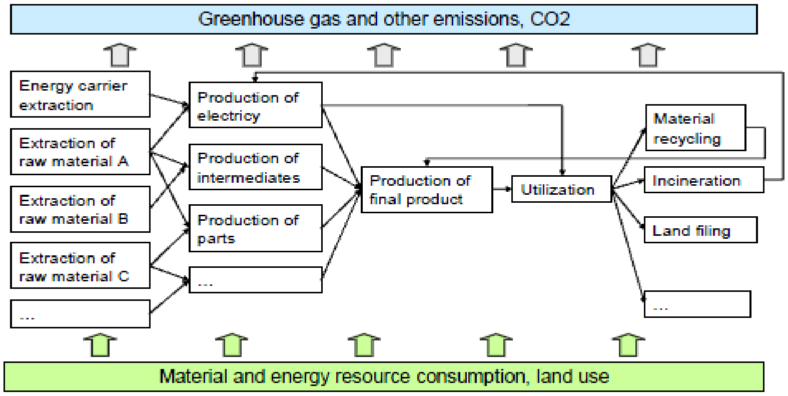


Fig. 2.14 Product life cycle based on EU-LCA platform (Heilala 2008)

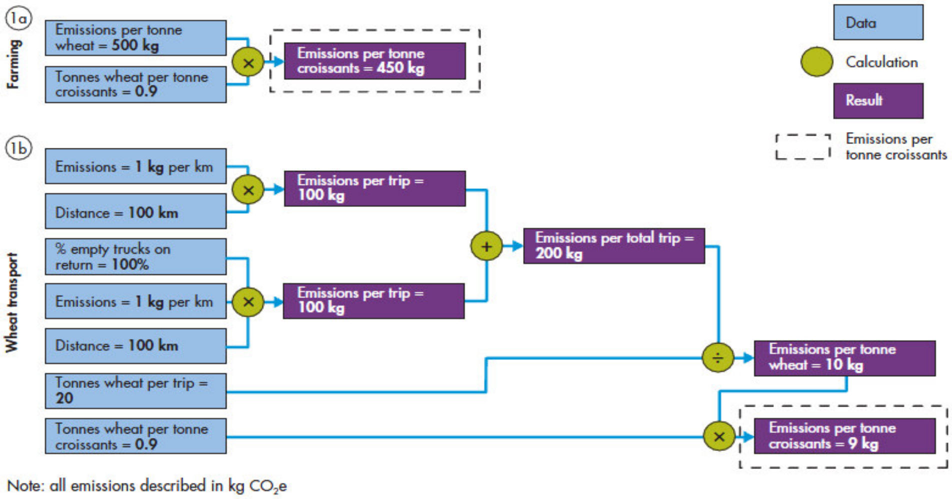


Fig. 2.15 The example of carbon footprint calculation using PAS2050 (PAS 2050)

2.4 Multi-criteria decision making techniques

Typically, the term multi-criteria decision making (MCDM) can refers to the method used to solve the conflict between objectives and return the proper solution from the set of alternative solutions. Normally, the configuration of MCDM, which is a branch of Operations Research (OR) models can be categorized into Multi-Objective Decision Making (MODM) and Multi-Attribute Decision Making (MADM) (Pohekar 2004; Pohekar 2004; Cristobal 2011).

The main distinction between MODM and MADM is their method of the decision making process. For the MODM, the problem details are transformed into a mathematical formulation which has three main parts: objective functions, constraints and range of decision variables. After the mathematical formulation was completed, all equations are arranged into matrix vectors that are ready for the optimization algorithm. The result of using the MODM method is the best alternative (optimal solution) which can satisfy all objectives functions in the considered problem formulation. On the other hand, it can be implied that alternative solutions from the MODM method are not predetermined regarding, the only optimal solution that can return from the optimization process. In the scope of Operations Research, types of mathematical formulation are linear programming, multi-objective/goal programming, integer programming, fuzzy programming and nonlinear programming. For MADM, each possible alternative is predetermined before the best solution is returned to the decision maker. Typically, the structure of MADM consists of goal, criteria and possible alternatives. The normalization of value and comparison methods are used in the decision process when MADM is selected to find out the best solution. MODM and MADM are compatible with quantitative and qualitative problems (Cristobal 2011). The example of contemporary MADM methods used in decision making in various fields are an Analytical Hierarchy Process (AHP), PROMETHEE, ELECTRE and Multi-attribute utility theory etc. In the next section, the details of related decision making methods used in this research are discussed.

2.4.1 Analytical Hierarchy Process (AHP)

According to the fundamentals of the AHP method, it was firstly demonstrated by Saaty in 1980 (Saaty 2008). The procedure for seeking the best solution in AHP is a top-down process by decomposing the goal into criteria/sub criteria and alternative solutions at the bottom level. All criteria are compared to each other regarding their relative preference. Saaty proposed the fundamental scale of 1-9, which is used to indicate the relative preferences between two criteria. The scale of 1 means equal importance, 3 means moderate importance, 5 means strong importance, 7 means very strong importance and 9 means extreme importance. The method which is called ‘pairwise’ comparison arranges preference values into the matrix form then normalization of the value is applied to each value related to its array position. After this method is completed, the vector of priority is obtained. Using the same method on the lower level of the structure (if sub-criteria are not considered in the structure, this level referred to group of alternative solutions), the priorities from the upper level are used at this level to weight the priorities. This process is repeated until the final priorities (the lowest level) are calculated. The overall or final priority regarding to the main goal for each possible solution is then determined. The possible solution that has the highest value of final priority is selected as best the alternative. The result satisfies the main objective subjected to considered criteria. The major advantage for using the AHP method is the incompatible determination between factors (both criteria and possible solutions). However, the decision maker must assure that the determination is compatible in order to achieve the most acceptable solution. The example of structure established in AHP method is presented in Fig 2.16.

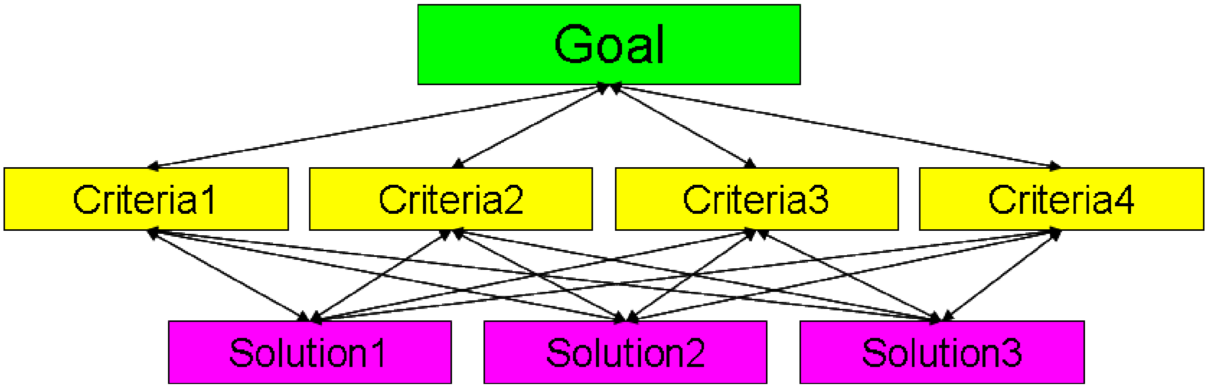


Fig 2.16 The example of hierarchy structure using AHP method

2.4.2 Fuzzy Logic

In 1965, Zadeh (Zadeh 1965) proposed the concept of fuzzy logic, which can be used to represent the uncertain event with a fuzzy set. With this concept, the process of fuzzy inference which allows the user to gain output from providing related input includes membership functions, logical operations and If-Then rules. The process can determine which decisions can be made. This is called the fuzzy inference system (FIS). Normally, the FIS can be illustrated in five functional blocks as shown in Fig 2.17 (Sivanandam 2007).

1. Rule base: fuzzy rules (If-Then) are composed and stored in this section
2. Data base: the group of fuzzy sets that contain membership functions used together with fuzzy rules
3. Decision making unit: logical operations are applied in this section
4. Fuzzification interface: converts the crisp input data into degree value depending on the related membership function
5. Defuzzification interface: converts fuzzy value to a crisp output

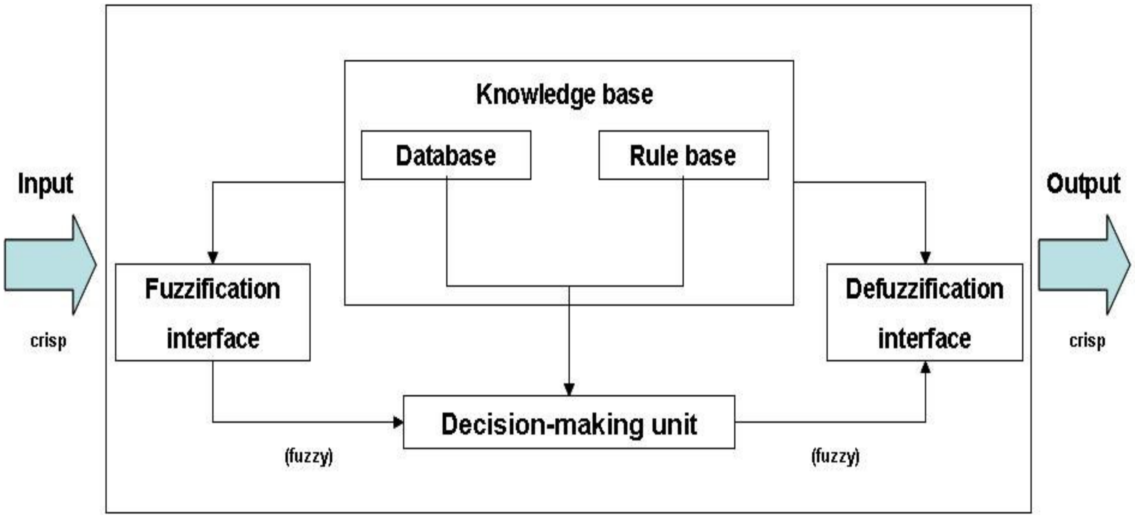


Fig. 2.17 Fuzzy inference system (Sivanandam 2007)

The basic concept of fuzzy logic can be classified as a rule based system using Artificial Intelligence (AI). Nowadays, the combination of using fuzzy logic with neuro-systems and genetic algorithms, which can be referred to 'soft computing', has been rapidly expanding. The essential concept of soft computing which is vastly different from hard computing is the compatibility with uncertain/imprecise event regarding real world problems. The implementation of soft computing could play an important role in the system/design stage when machine learning based manufacturing would be used rather than a conventional manufacturing system. The major advantages of fuzzy logic are described as follows (MATLAB 2010):

(1) Fuzzy logic can cope with imprecise data: most data from the observation is imprecise even though it was carefully observed. Fuzzy reasoning therefore constructs this concept into process
(2) Nonlinear functions can be modelled within fuzzy logic: the fuzzy system can be established to conform with sets of input and output data by using adaptive techniques called Neuro Fuzzy Inference Systems (ANFIS)
(3) Fuzzy logic is compatible with the conventional control system: implementation of fuzzy logic does not need to replace the existing control system
(4) The basic concept of fuzzy logic is based on the natural language: human communication is used as the fundamental of fuzzy logic development. This concept can be referred to as an adaptation of a qualitative description.

2.4.3 The Taguchi Method

The Taguchi Method was first introduced by Dr. Genichi Taguchi in 1950 and concerned to research and development on the theme of productivity and product quality improvement during World War II era. He noticed in his observations that the major impacts on the time and budget of an enterprise are engineering experiments and testing. From this observation, he suggested that quality could be achieved by a prevention method instead of inspection screening and salvaging. From this point of view, the origin of his development is based on process optimization of engineering experiments because the optimal design was installed into a product, which is the best solution to enhance quality. This method is called the ‘Taguchi Method’. The main concept of this method is to adjust the variation around the response value to the target value. In the experimental design process, the orthogonal array (OA) is used as the main tool in the Taguchi Method in order to reduce the number of experimental set-ups (Taguchi 2005; Roy 1990; Ross 1996). In the experimental design, the method that has been most widely used is ‘factorial design’. This method uses probability concepts to calculate all possible combinations of interested factors. However, there could be critical issues in conventional processes when research and development are in progress because there are many factors related to the process. Therefore, there are many experiments needed when factorial design is used. For instance, there are three important parameters in the cutting process using a CNC turning machine (cutting speed, tool size and depth of cut) and each parameter has three different levels (low, medium and high). The number of cutting trials that must be taken based on factorial design is 3^3 = 27 cutting trials. However, the number of cutting trials can be reduced to 9 cutting trials by using an L9 orthogonal array. There are four main steps to accomplish the Taguchi Method:

(1) Determine the parameters related to the process that are required to observe and optimize

(2) Design and perform an experimental set-up based on selected parameters and orthogonal array

(3) Analyze the data obtained from running experiment and evaluate the optimal condition related to all parameters

(4) Run the confirmation test using the optimal condition

After the experiment was designed and conducted, the next, most crucial stage in the Taguchi Method is the analysis phase. There are three aspects that the decision maker can expect from this analysis phase: the optimal condition related to the experimental design, the contribution of factors on the interested response and prediction of response value using the optimal condition. For instance, an investigation of cutting parameters (cutting speed, tool size and depth of cut) was taken to observe a response (fuzzy reasoning grade). Each parameter has three different levels (low, medium and high). There are 9 cutting trials to be taken when an L9 orthogonal array was used for the experimental design. The data from cutting trials is illustrated in Table 2.3. In order to analyze results, there is a method to evaluate the effect of each factor according to the goal/objective. In this example, the objective is to maximize the value of the fuzzy reasoning grade. Therefore, the higher the better.

Experiments	Factors			Fuzzy reasoning grade
	Cutting speed (mm/min)	Tool size (mm)	Depth of cut (mm)	
1	1	1	1	0.7237
2	1	2	2	0.5905
3	1	3	3	0.7056
4	2	1	2	0.5000
5	2	2	3	0.5620
6	2	3	1	0.5814
7	3	1	3	0.7752
8	3	2	1	0.6770
9	3	3	2	0.6231

Table 2.3 Fuzzy reasoning grade related to each experiment

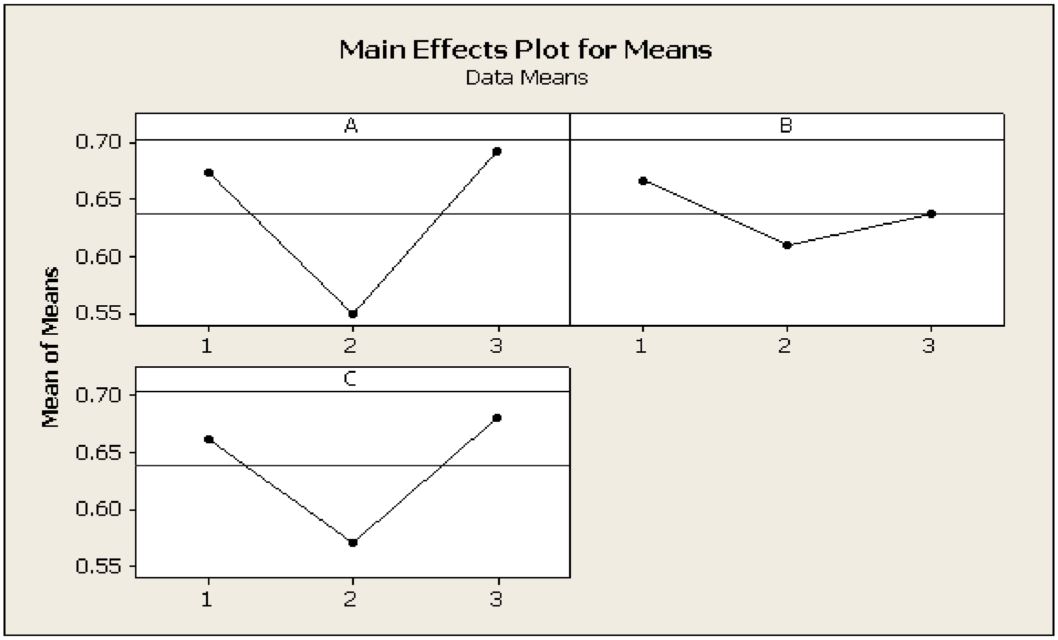


Fig. 2.18 Main effect plot using MINITAB

Machine parameter	Grey-fuzzy reasoning grade using FIS based		
	Level 1	Level 2	Level 3
Cutting speeds (ft/min)	0.6733	0.5478	0.6918
Tool size (mm)	0.6663	0.6098	0.6367
Depth of cut (mm)	0.6607	0.5712	0.6809

Table 2.4 Response of parameter on the response

From the experimental data in Table 2.3, the contribution of each factor on the response can be calculated and expressed in Table 2.4. It is obvious that the optimal condition that can maximize the value of fuzzy reasoning grade is cutting speed level 3, tool size level 1 and depth of cut level 3. Moreover, the factor effects are plotted using MINITAB to compare the different levels of all the factors on the response.

2.5 Flexible manufacturing

The definition of flexible manufacturing (FMS) refers to the manufacturing system that has an ability to change regarding to the production plan. The conventional flexible manufacturing system is based on a set of computer numerically controlled machines (CNC) and supporting workstations that are connected by an automated material handling system and controlled by a central computer (Askin 1993, Qiao 2006). This concept was developed to enable a manufacturing system to operate with highly customized production requirements, provide a quick response to the market and have high flexibility (Suri 1998). However, the current environmental impact of performing flexible manufacturing has become a critical problem for the global warming crisis since FMS uses electricity as its main energy consumption, which is a source of carbon dioxide emissions. From Fig. 2.20, it is obvious that the industrial sector needs to take even more responsibility as it used 28% of the electricity demand of the entire UK in 2008 (Department of Energy and Climate Change (DECC) 2009). More evidence that can be used to support the awareness of the climate change crisis from flexible manufacturing is seen in the pie graph located on the right hand side of Fig. 2.19. The electricity demand from the industries of, engineering and iron and steel are 36%, 18% and 4% respectively, which can be summarized to 58% of the total electricity demand for the industrial sector. Typically, the deeper analysis of using a CNC machine with energy efficiency focuses on its energy consumption during the production process, as it is not constant over time. Fig. 2.20 represents a conventional CNC machine drawing with a relationship between the power supply object and its machining parameters (cutting speed, tool size and depth of cut) in terms of the energy consumption. In addition, Fig. 2.21 (a) and (b) presents the comparison of different machine set-ups on the five axis CNC turning machine to cut aluminum material. The first and second cutting trials were set-up with cutting speeds: 400 in/mm, Tool: Ø12 mm, Depth of cut: 1mm and cutting speeds: 500 in/mm, Tool: Ø12mm, Depth of cut: 2mm, respectively. It is quite obvious from the results that different operations require different levels of energy consumption. This implies that it is very essential to investigate in depth to apply the concept of sustainable development for the machine level. However, the solution of the flexible manufacturing on the energy consumption crisis is not enough even if the machine level can provide the initial solution for development. According to Stecke (1983), the main advantage of implementing flexible manufacturing into the considered system is to gain the ability of automated mass customization by using automatic handling systems and numerical controlled machines (Stecke 1983). However, these automatic devices cannot perform a pending task if the required cutting tools have not been attached in tool magazines since the process of previous work. Therefore, it can be implied that the major problem in a flexible manufacturing system is the requirement of effective production planning. This could mean that the concept of sustainable development must also be integrated into the management of FMS (at shop floor level) when the considered system is constructed with different machines. There are also many types of products with different process sequences at the shop-floor level. Hence, the requirement of a systematic approach is to integrate energy efficiency with the typical manufacturing performance, which can be eventually crucial to low carbon manufacturing. The next chapter will present the scope and boundary for developing low carbon manufacturing for FMS.

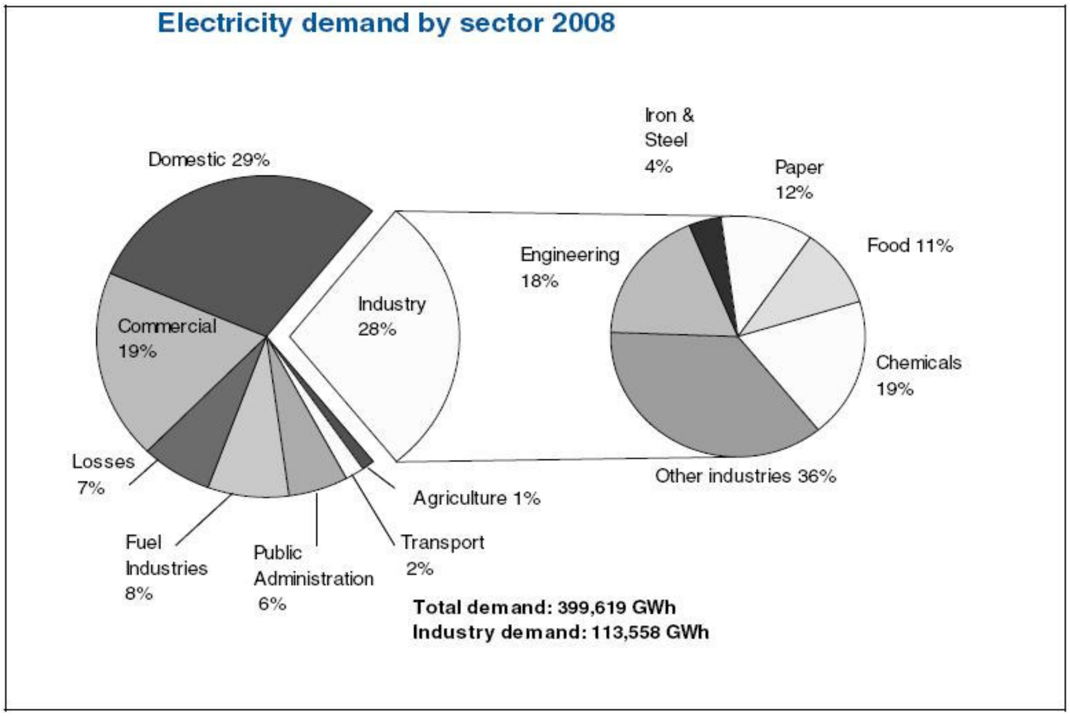


Fig. 2.19 UK electricity demand by sectors in 2008 (DECC 2009)

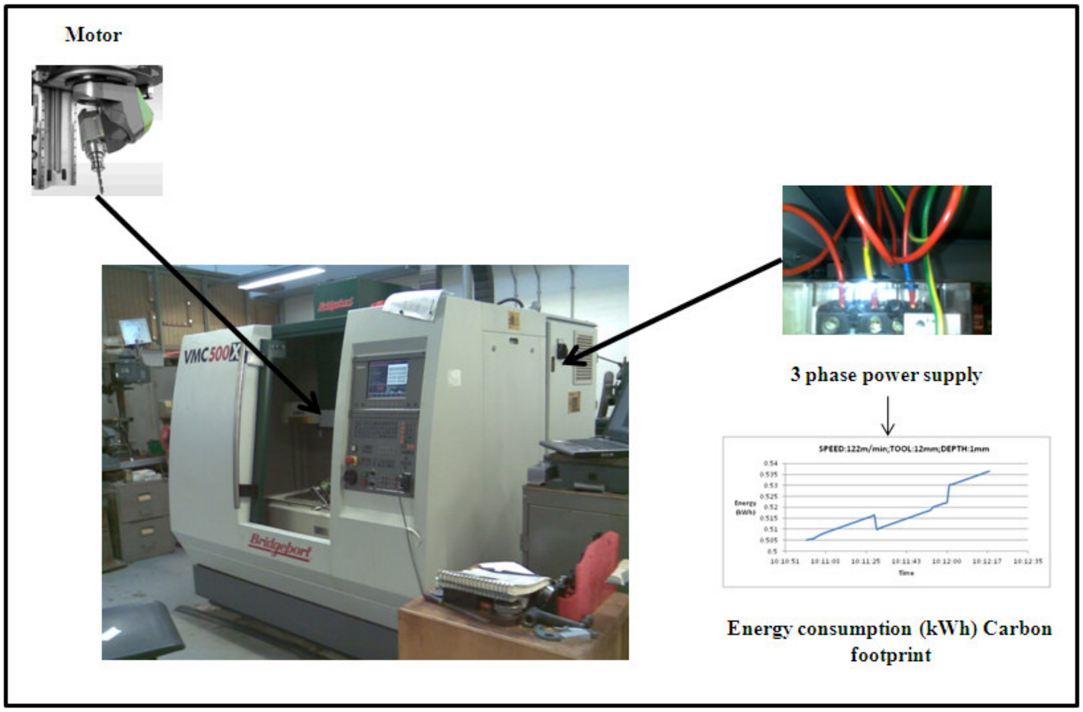
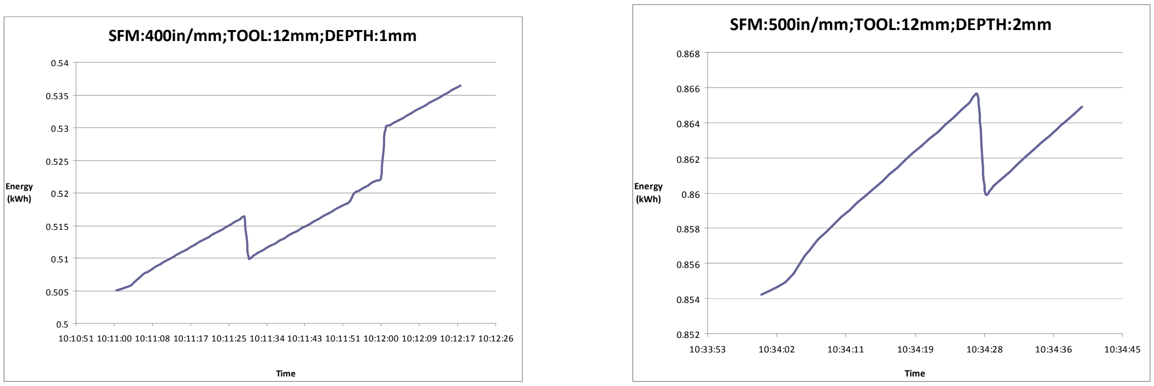


Fig. 2.20 The diagram of a typical CNC machine



(a) (b)

Fig. 2.21 The comparison between different machine setups

2.6 Axiomatic design

This is the systematical design approach that transforms the information from customer needs into a process solution between four domains: customer domain, functional domain, physical domain and process domain. In Fig. 2.22, it represents the logic of information transformation in terms of an aixiomatic design mechanism. The domain on the left hand side (CA) refers to ‘what we want to achieve’ while the domain on the right hand side represents ‘how we propose to satisfy the requirements specified in the left domain’ according to Suh (2001) (Suh 2001).

At the initial step of the design process, the customer needs from the domain CA is converted in to the form of a vector called vector {CAs}. Then, the details from vector {CAs} are translated into functional requirements vector {FRs} which is the part of functional domain. In order to satisfy the vector {FRs}, the vector {DPs} is established as the design parameters for the requirements. Finally, production processes for the product are characterized by developing the process variables {PVs} vector, which conforms to the vector {DPs}.

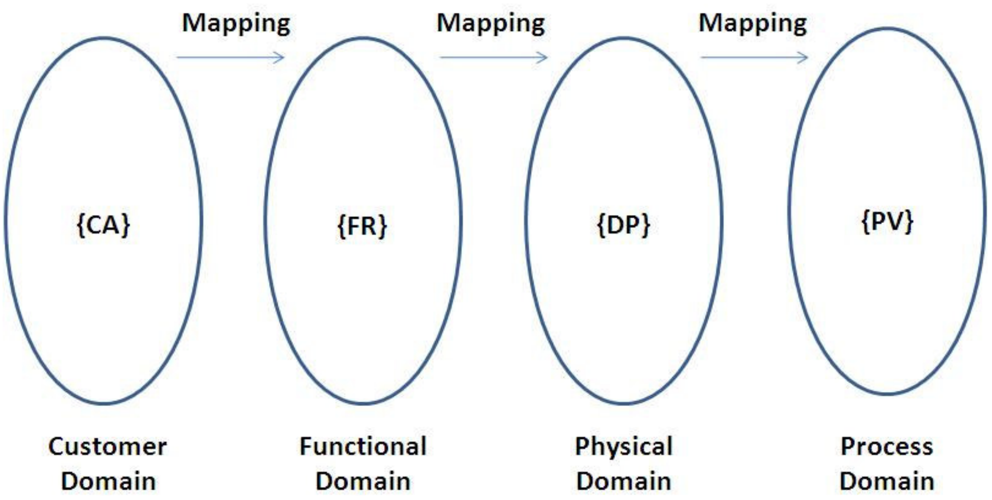


Fig. 2.22 Four domains in Axiomatic Design (Suh 2001)

The axiomatic design, hence, starts with the general requirement as the highest level of objectives which need to be decomposed into lower level sub-requirements for deeper details. In the Fig. 2.23, the design parameters at the highest level $\{DP_0\}$ are determined relating to the highest level of the physical domain on the left hand side $\{FR_0\}$. Then, the design process is backward to the functional domain to decompose the sub-level functional requirements which can satisfy the above level. According to the example in Fig. 2.23, there are $\{FR_1\}$ and $\{FR_2\}$ at the second layer decomposition, which are determined to cope with $\{FR_0\}$. The process of decomposition must be repeated layer by layer as discussed until the design can be realistically implemented (the final stage). The logic of determination between functional domain and physical domain that establishes the proper vector until the lowest level is completed, is called zigzagging (Suh, 2001).

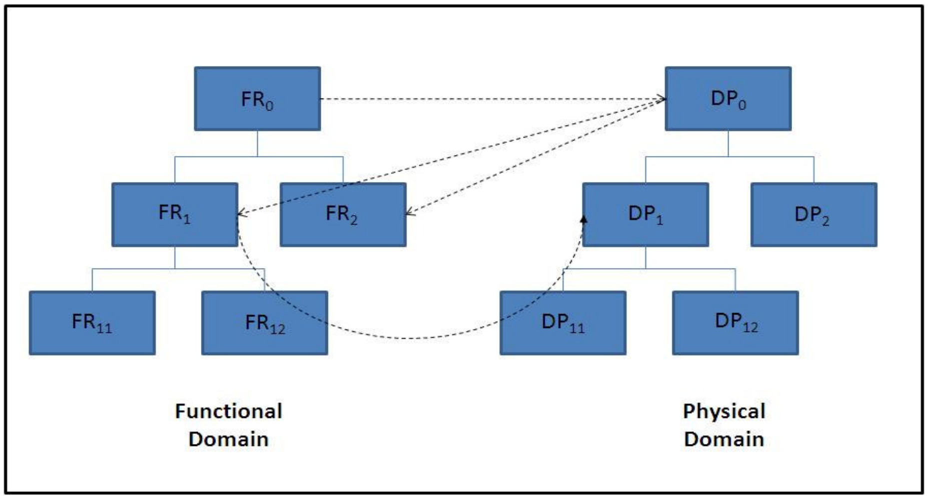


Fig. 2.23 Zigzagging in Axiomatic Design (Suh 2001)

From the mapping process, the relationship can be described between the considered objectives (functional domain) and the proper solutions (physical domain) in the form of characteristic vectors. The example of the mathematical relationship between function requirement {FR} and design parameter {DP} is illustrated in Equation 2.1 where A_{11} represents the effect of DP_1 on FR_1 and A_{21} represents the effect of DP_1 on FR_2 etc. Normally, the position in the design matrix is replaced with the symbol 'x' if there is an effect in the relationship and the symbol '0' if there is no effect.

$$\begin{bmatrix} FR_1 \\ FR_2 \end{bmatrix} = \begin{bmatrix} A_{11} & 0 \\ A_{21} & A_{22} \end{bmatrix} \begin{bmatrix} DP_1 \\ DP_2 \end{bmatrix} \tag{2.1}$$

There is an important rule that must be achieved for the determination of the relationship between functional requirements and design solutions. It is called the Independence Axiom. The selected design solution must be such that each one of the {FR} can be satisfied without a effecting the other {FR} when there are more than two functional requirements. In the mathematical relationship, the design matrix can only be satisfied when the matrix formation is diagonal or triangular. The design matrix is called an uncoupled design when the design matrix is diagonal because each functional requirement can be only satisfied by one design parameter. On the other hand, the design matrix is called a decoupled design when the triangular matrix was established because the functional requirement can only be achieved if and only if the design parameters are determined in a proper sequence. The design matrix will be a coupled design if the other form of matrix, which is called a full matrix, is used. Thus, the design matrix must be arranged in a diagonal or triangular form in order to satisfy several functional requirements.

2.7 Summary

This chapter has reviewed the state of the art of sustainable manufacturing related to manufacturing systems including machine components and their management together with a critical review of various decision making techniques and the requirement to apply the low carbon manufacturing concept to flexible manufacturing.

Sustainable manufacturing has some distinct characteristics and the literature review investigated the current research themes and related tools/techniques. It is clear that the demonstration of low carbon manufacturing (LCM) is a novel approach with a realistic potential of solving the crisis of energy demand and the global warming problem, as given in Chapter One. Currently, the standard methods for reducing the amount of carbon footprint normally rely on evaluation/assessment tools such as life cycle assessment (LCA). Although many research works have investigated this area, the systematic approach for reducing the carbon footprint, which does not require the new investment for new technologies and renewable energy, has not yet been established. The integration of energy efficiency, resource utilization and waste minimization seems to offer great prospects. This is essentially the LCM proposed in this research.

An integrated framework as a general design of a systematic approach should be developed by applying the most suitable tools and theory. There will be a further discussion related to this in the next chapter.

Chapter 3 Research methodology

3.1 Introduction

According to the literature review in the previous chapter, many research works on sustainable manufacturing and environmental issues have been specifically paid attention to, including evaluation, optimization, decision making and assessment. From this background, a systematic method to implement low carbon manufacturing for real practice is very important. In this chapter, all methodologies including experimental set-up, experimental design, prediction tool, optimization tool and simulation tool are presented in a systematic way. This chapter also would like to present the integration of different powerful tools in order to cope with energy efficiency, resource utilization and waste minimization.

3.2 The scope of the research methodology

In this research, methodologies are divided into four stages as illustrated in Fig. 3.1: critical review previous research related to attempt on low carbon manufacturing, development of low carbon manufacturing concept, modeling of EREE-based low carbon manufacturing and implementation. The details of each stage are described as follow:

(1) Critical review related research: previous research works especially on sustainable manufacturing and energy efficiency manufacturing platform are critical reviewed in order to investigate the existing sustainable manufacturing platform and knowledge gap for developing low carbon manufacturing. This section is discussed in chapter 2.
(2) Development of low carbon manufacturing conception: information from previous research works and requirements of contemporary regulations are gathered to formulate characterization and theoretical model for low carbon manufacturing. In addition, framework for different manufacturing levels is also proposed in this section according to developed characterizations. This stage is discussed in chapter 4.
(3) Modelling of EREE-based low carbon manufacturing: the modelling is developed to explain interaction between characterizations discussed in chapter 4 to gain low amount of carbon emissions. The modelling is formulated in the form of matrix using Axiomatrix Design discussed in chapter 2. The details of this stage are illustrated in chapter 5.

(4) Implementation and validation: the modelling of EREE-based LCM is implemented into the forms of applications for both machine and shop-floor level. In machine level, cutting trials on CNC milling machine were taken as primary data to develop simulation and optimization model. Fuzzy logic is used to implement EREE-based LCM at machine level. To implement EREE-based LCM at shop-floor level, there are two applications developed at this part: optimization and simulation model. Optimization model is formulated in the form of mathematical model which is interacted with application of machine level while simulation model is developed based on discrete event system simulation. Genetic algorithm is used in optimization part while ProModel simulation tool is used in the second part. The implementation of the modelling is discussed in chapter 5 and validation which is performed by two case studies is discussed chapter 6.

The rest of this chapter will demonstrate selected tools using in this research including experimental set-up (machines and devices) and software.

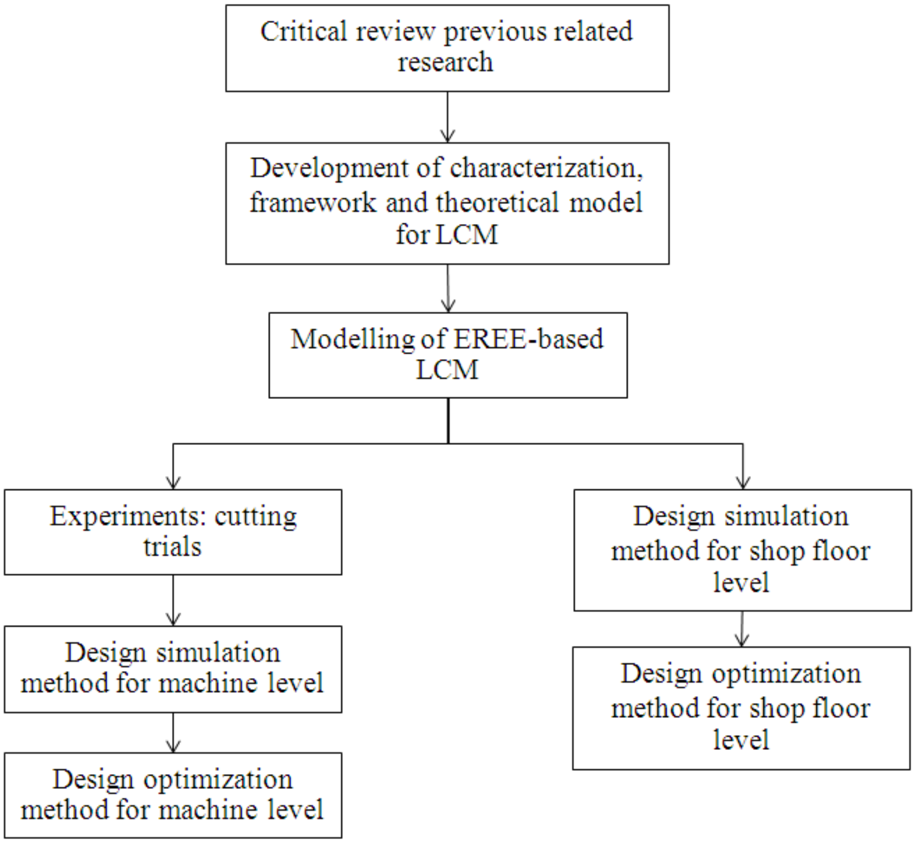


Fig. 3.1 The scope of research methodology

3.3 The experimental set-up

3.3.1 CNC milling machine

To investigate energy consumption in cutting trials, two CNC machines have been used in this research. First of all, a Bridegeport CNC machine is used to perform a set of experiments. The power supply of this machine is a three phase (delta type) input, which does not have a neutral line. The configuration of the machine platform and power supply system is illustrated in Fig. 3.2 and fig. 3.3 logically. In addition, the machine specifications are shown in Table 3.1.

Feedrate Range	36 m/min (X & Y), 0-20m/min (Z)
Spindle Drive	10 kW
Spindle Torque	48 Nm
Spindle Speed Range	40-8,000 rpm
Voltage Supply	420 V
Current Supply	0-20 A

Table 3.1 Specifications of the Bridgeport machine

Fig. 3.2 Breidgeport CNC milling machine

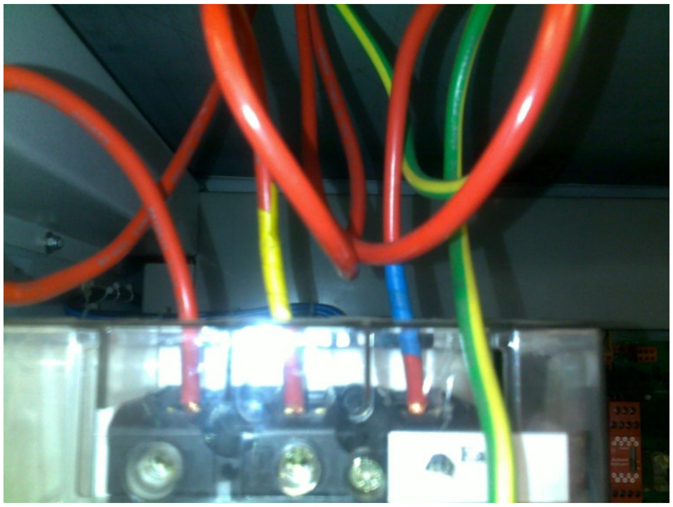


Fig. 3.3 Three phase power supply of the Bridgeport CNC milling machine

Secondly, a commercial CNC at a laboratory located in Thailand is used to investigate energy consumption from cutting trials. The specifications of the CNC machine are illustrated in Table 3.2 and its portrait is expressed in Fig. 3.4.

Spindle Drive	10 kW
Feed Rate	35 m/min
Spindle Speed Range	0-6000 rpm
Voltage Supply	420 V
Current Supply	0-20 A

Table 3.2 Specifications of the CNC milling machine

Fig. 3.4 Snapshot of the CNC milling machine in the Thailand laboratory

3.3.2 Data acquisition of electrical energy

The measurement of energy consumption in cutting processes can be classified as the most critical aspect of this research. Hence, the determination of data acquisition is also an important part of the research methodology. ISO-TECH IPM 3005 and Primus PC-02, which are designed to measure electrical energy consumption of electrical three phase systems, are used to record real time data during the manufacturing process. The device creates a magnetic field on the current loop which enables the detection of the variation of used current. This is the major advantage compared to a conventional amp meter. The configuration of ISO-TECH IPM 3005 and the connection method with the supply system is illustrated in Fig. 3.4 and 3.5 repectively. Furthermore, the specifications of the device are presented in Table 3.2.

Fig. 3.5 ISO-TECH IPM 3005

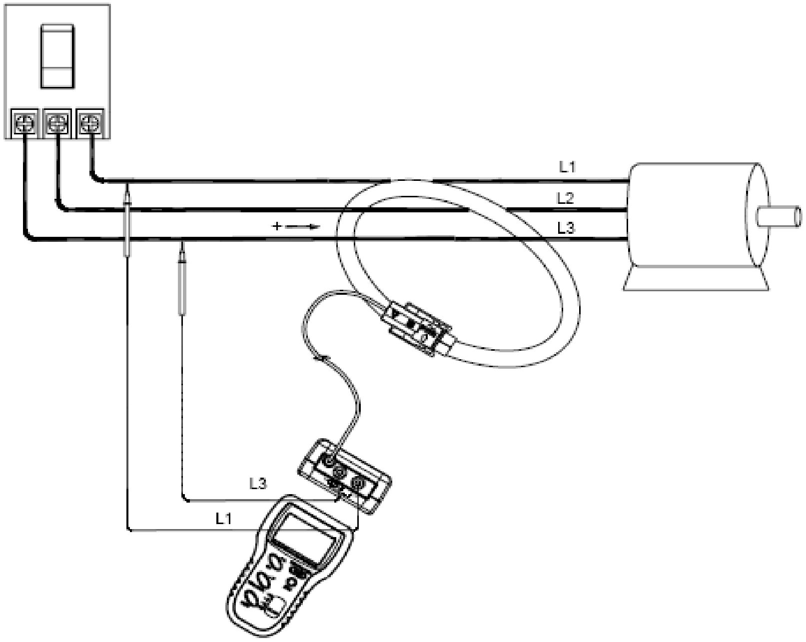


Fig. 3.6 Connection method of the device to power supply

Current Range	0-3000 A
Voltage Range	600 V AC
Frequency	50/60 Hz
Power Factor	0-1

Table 3.3 The specifications of ISO-TECH IPM 3005

Secondly, the specifications of Primus PC-02 and its snapshot are presented in Table 3.4 and Fig. 3.7 respectively. It can be used to measure both delta and star three phase systems.

System	3phase/4wire or 3phase/3wire
Voltage	250 VLN (Vb) / 400 VLL
Current	250 mA to 5 A/ 20 A to 5000 A with CT
Frequency	45 to 55 Hz
Input loading volt current	Less than 0.1 VA
	Less than 0.1 VA

Table 3.4 The specifications of Primus PC-02

Fig. 3.7 Setup of Primus PC-02

3.4 Software tools

3.4.1 Fuzzy logic toolbox

The MATLAB based Fuzzy logic toolbox is a powerful tool that can be used to create a fuzzy inference system (FIS) (MATLAB 2010). In the toolbox environment, FIS can be edited by a graphical user interface (GUI). There are five primary functions in the toolbox, which are illustrated as follows;

The FIS editor: this is the first function that is required to be completed first before going to other functions. The FIS editor is used to edit the number of input and output variables. Moreover, it is also used to design the type of inference system (mamdani or sugeno type).

The membership function editor: it is used to design and determine the shape of the membership function related to the considered variable. This section includes both input and output variables.

The rule editor: rules can determine the level of output variable from the interaction between input variables. For example, if the cutting speed is low and the tool size is low and depth of cut is low then the total energy consumption is high.

The rule viewer: this MATLAB technical computing environment can display what operation looks like. This function can also be used to evaluate the value of output variable by editing directly at the membership function graph or edit the value of input variable.

The surface viewer: it can generate 3-D surface dimensions of the output variable cooperate with two input variables (x, y and z axis)

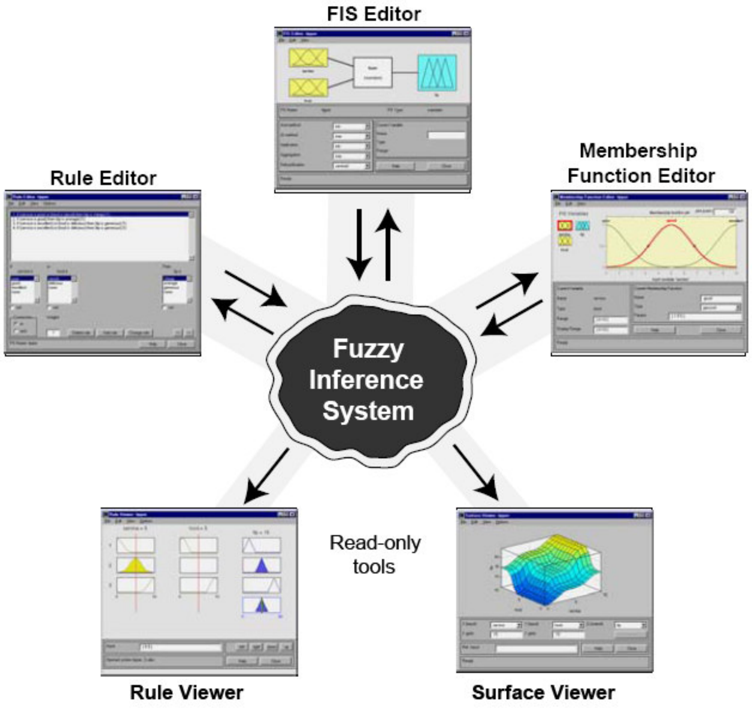


Fig 3.8 Fuzzy logic toolbox on MATLAB based

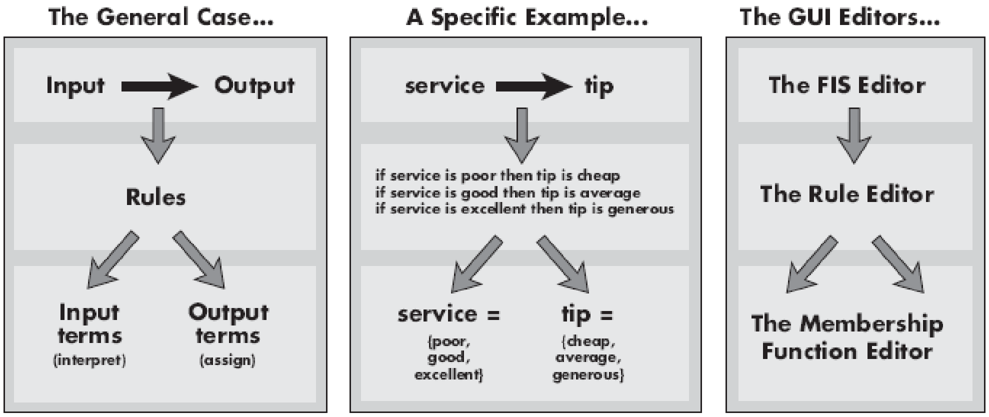


Fig 3.9 The relation between event and FIS GUI

3.4.2 ProModel

ProModel software is designed for discrete event system simulation which represents the chronicle sequence of events (ProModel-Corporation 2006). Fig. 3.10 represents the characteristic of a discrete event using simulation results. This result was obtained from using a machine in a specific simulation period. The result can illustrate the utilization period of the considered object and also the unavailable period including idle time, maintenance down time and down time shift. The time scale resolution in this software can be adjusted in the range between 0.1 hours to 0.00001 seconds. ProModel provides a powerful simulation tool for designing a manufacturing system with useful data analysis and realistic animation graphics. The fundamentals of simulation in a discrete event concept are based on random number generation using a data distribution function. The main advantage for using ProModel is to intensively analyze resource utilization, production capacity, productivity and inventory levels. Normally, this tool is suitable for modelling with assembly lines, job shop (different sequence processes), transfer lines, for applying JIT (just in time) and KANBAN systems, flexible manufacturing systems and supply chain/logistic management.

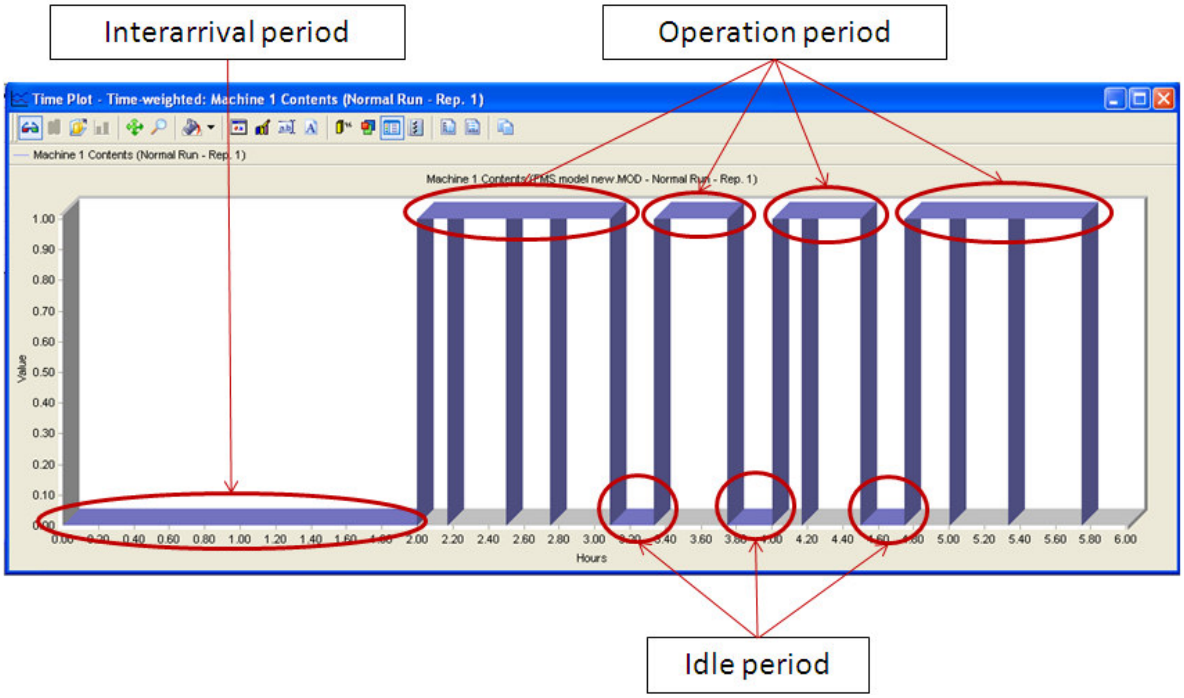


Fig. 3.10 The time weight simulation result using ProModel

To establish a model, there are four common objects in ProModel that are necessary for model development:

Location: location in this system refers to as a place that is assigned to process/perform and storage entities or even determine decision making. Normally, locations are used to model elements such as machine centers, warehouse locations, network servers and transaction processing centers

Entity: any objects that are processed in the model are called entities. For instance, an entity can be products, materials, goods, documents, people and phone calls etc.

Resource: resources represent an object that is used for one or more of the following tasks: conveying entities, supporting operations on entities at locations, operating maintenance on locations or other resources. Resources can be a person, device, equipment etc.

Process: process can determine the routing of each entity throughout the system and also arrange operation sequences that need to be performed at each location.

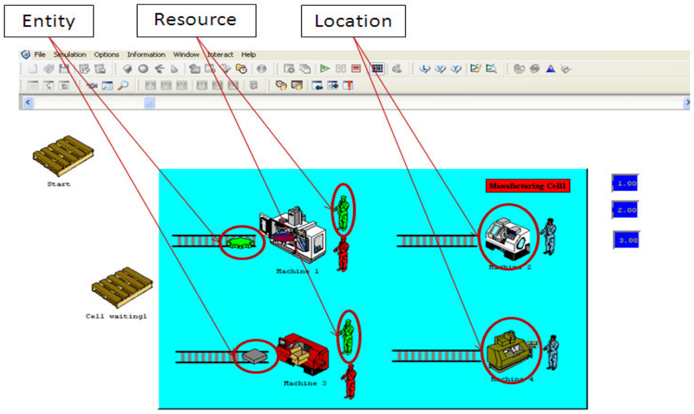


Fig. 3.11 Environments in the model

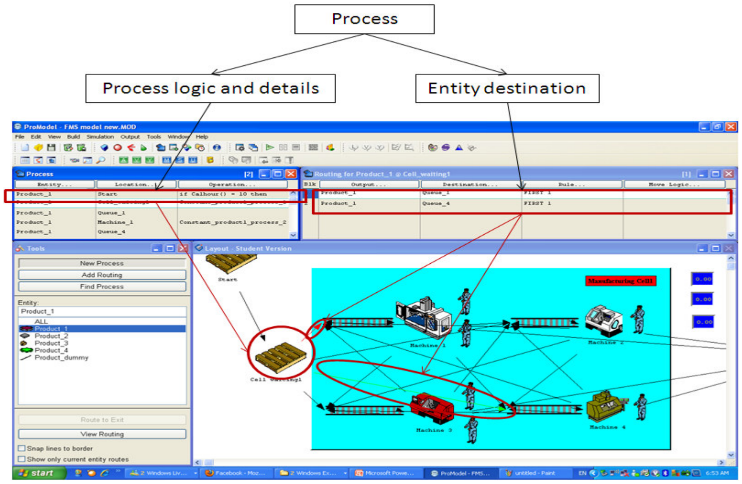


Fig. 3.12 Processing editor in ProModel

Fig. 3.11 demonstrates important elements constructed in a flexible manufacturing model. There are four types of machines (location) that are supported by operators (resource) to perform four types of products (entity). The snapshot of processing editor in ProModel is illustrated in Fig. 3.12, which is the same flexible manufacturing model that is presented in Fig. 3.11. This example shows the processing environment in the waiting area for product type A. It has to be waiting at this location (using a command to control this sequence) before determining which machine should be used to perform (routing logic).

3.4.3 MATLAB based Genetic Algorithm toolbox

A genetic algorithm (GA) is one of the optimization methods that is used to solve both constraint and unconstraint problems by using natural selection methodology (MATLAB 2010). Its main algorithm is based on biological evolution by repeatedly modifying a population of individual solutions. In every cycle, the algorithm randomly selects from the current population as parents to generate children for the new generation by using cross over and mutation rules. Normally, the modified iteration is terminated when either the maximum number of population generations has been reached or the tolerance of fitness function value is satisfied by the optimized solution. In addition, the solution returned from the algorithm might not be a global solution but just a local solution when the iteration was terminated by the maximum population limit.

In this research, the genetic algorithm toolbox with MATLAB is used to solve the problem constructed with objective function, constraints and range of variables (interested decision variables). The mathematical formulation can be transformed into basic language in M-file commands. In case of linear form problems, constraints can be arranged easily in the form of a matrix in the command line. However, constraints are also required to transform into M-file as well as objective function when the non-linear problem needs to be solved. The important parameters that are determined before running the algorithm are illustrated as follow

```
[x fval] = ga(@fitnessfun, nvars, A, b, Aeq, beq, lb, ub, nonlcon, options)
```

Where

x: represents the final value of each decision variable that satisfies the terminated condition.

fval: represents the value of objective function using the value of optimized solution

@fitnessfun: represents the objective function (M-file)

nvars: number of design variables

A and b: used for creating matrix and vector for inequality constraints

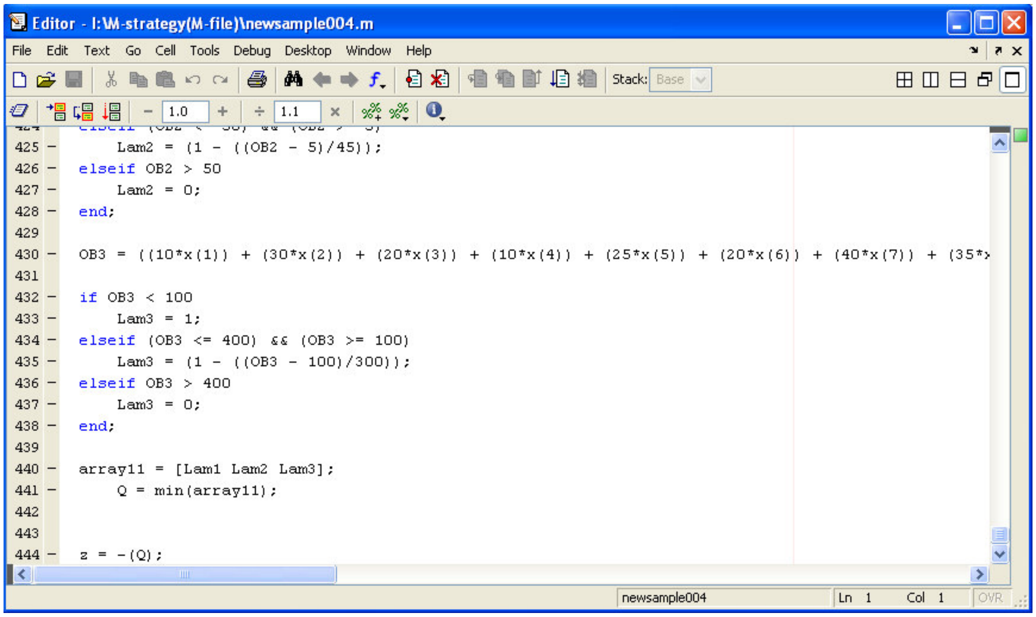
Aeq and beq: used for creating matrix and vector for equality constraints

lb and ub: represent lower bound and upper bound of decision variable range

nonlcon: represents mathematical formulation of nonlinear constraint (M-file)

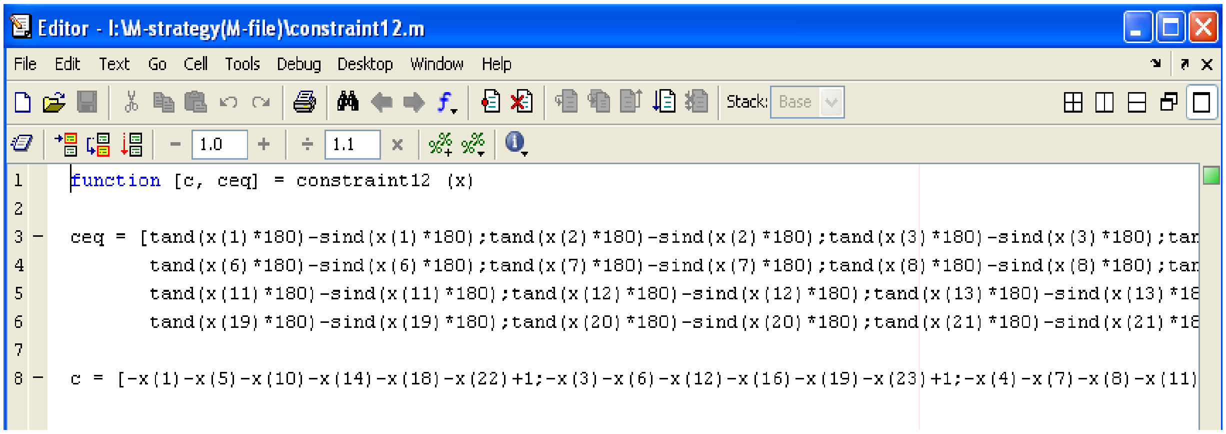
options: represents genetic algorithm set-up such as generation limit, time limit, tolerance of constraint and tolerance of fitness function etc.

In Figs 3.13 and 3.14, the snapshots of objective function and nonlinear constraints creation on M-file are presented respectively. These two screenshots are established based on a fuzzy integer programming for a flexible manufacturing problem. Fig. 3.15 presents the snapshot of using a genetic algorithm from the command line in MATLAB workspace.



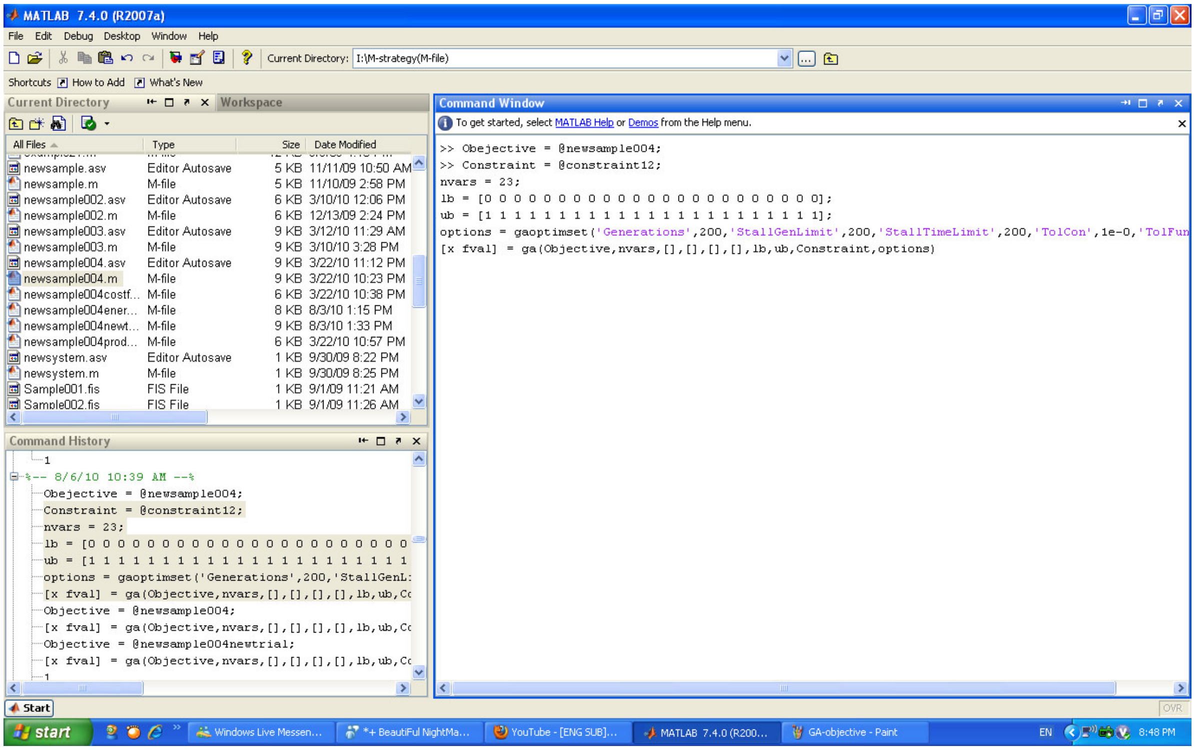
```
        Lam2 = (1 - ((OB2 - 5)/45));
    elseif OB2 > 50
        Lam2 = 0;
    end;

    OB3 = ((10*x(1)) + (30*x(2)) + (20*x(3)) + (10*x(4)) + (25*x(5)) + (20*x(6)) + (40*x(7)) + (35*

    if OB3 < 100
        Lam3 = 1;
    elseif (OB3 <= 400) && (OB3 >= 100)
        Lam3 = (1 - ((OB3 - 100)/300));
    elseif OB3 > 400
        Lam3 = 0;
    end;

    array11 = [Lam1 Lam2 Lam3];
        Q = min(array11);


    z = -(Q);
```

Fig 3.13 Objective establishment in M-file



```
function [c, ceq] = constraint12 (x)

ceq = [tand(x(1)*180)-sind(x(1)*180);tand(x(2)*180)-sind(x(2)*180);tand(x(3)*180)-sind(x(3)*180);tan
        tand(x(6)*180)-sind(x(6)*180);tand(x(7)*180)-sind(x(7)*180);tand(x(8)*180)-sind(x(8)*180);tan
        tand(x(11)*180)-sind(x(11)*180);tand(x(12)*180)-sind(x(12)*180);tand(x(13)*180)-sind(x(13)*18
        tand(x(19)*180)-sind(x(19)*180);tand(x(20)*180)-sind(x(20)*180);tand(x(21)*180)-sind(x(21)*18

c = [-x(1)-x(5)-x(10)-x(14)-x(18)-x(22)+1;-x(3)-x(6)-x(12)-x(16)-x(19)-x(23)+1;-x(4)-x(7)-x(8)-x(11)
```

Fig 3.14 Constraint establishment in M-file



All Files	Type	Size	Date Modified
newsample.asv	Editor Autosave	5 KB	11/11/09 10:50 AM
newsample.m	M-file	5 KB	11/10/09 2:58 PM
newsample002.asv	Editor Autosave	6 KB	3/10/10 12:06 PM
newsample002.m	M-file	6 KB	12/13/09 2:24 PM
newsample003.asv	Editor Autosave	9 KB	3/12/10 11:29 AM
newsample003.m	M-file	9 KB	3/10/10 3:28 PM
newsample004.asv	Editor Autosave	9 KB	3/22/10 11:12 PM
newsample004.m	M-file	9 KB	3/22/10 10:23 PM
newsample004costf...	M-file	6 KB	3/22/10 10:38 PM
newsample004ener...	M-file	8 KB	8/3/10 1:15 PM
newsample004newt...	M-file	9 KB	8/3/10 1:33 PM
newsample004prod...	M-file	6 KB	3/22/10 10:57 PM
newsystem.asv	Editor Autosave	1 KB	9/30/09 8:22 PM
newsystem.m	M-file	1 KB	9/30/09 8:25 PM
Sample001.fis	FIS File	1 KB	9/1/09 11:21 AM
Sample002.fis	FIS File	1 KB	9/1/09 11:26 AM

```
  1
%-- 8/6/10 10:39 AM --%
  Obejective = @newsample004;
  Constraint = @constraint12;
  nvars = 23;
  lb = [0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
  ub = [1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
  options = gaoptimset('Generations',200,'StallGenL
  [x fval] = ga(Objective,nvars,[],[],[],[],lb,ub,Co
  Objective = @newsample004;
  [x fval] = ga(Objective,nvars,[],[],[],[],lb,ub,Co
  Objective = @newsample004newtrial;
  [x fval] = ga(Objective,nvars,[],[],[],[],lb,ub,Co
  1
```

To get started, select MATLAB Help or Demos from the Help menu.

```
>> Obejective = @newsample004;
>> Constraint = @constraint12;
nvars = 23;
lb = [0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0];
ub = [1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1];
options = gaoptimset('Generations',200,'StallGenLimit',200,'StallTimeLimit',200,'TolCon',1e-0,'TolFun
[x fval] = ga(Objective,nvars,[],[],[],[],lb,ub,Constraint,options)
```

Fig 3.15 Running GA from command line

3.5 Summary

Methodologies for developing low carbon manufacturing concepts in this research were presented in this chapter. Methodologies rely on experimental trials and computer based programming in order to accomplish three different purposes: learning based system, optimization (decision making) and simulation. The key part of this chapter is the way to deploy different tools that have originally different theoretical backgrounds in a logical way, right place and right purpose. Methodologies presented in this chapter are both related to machine level and shopfloor level.

Chapter 4 A framework for developing EREE-based LCM

4.1 Introduction

Due to the literature review in the chapter three, although the awareness on formulating low carbon manufacturing concept has been mentioned as a timely topic, the systematic approach for transforming the existing system into low carbon industry has not been robust defined. However, many countries are now suffering the requirement from cooperation in carbon dioxide emissions protocol in order to cope with global warming problem and also enhance sustainability. From the national scale, it also leads to the smaller scale that uses carbon based energy such as industrial sectors, companies and enterprises etc. to provide new methodologies/solutions that can satisfy the target of carbon dioxide reduction in national scale. For this reason, the LCM must be able not only to reduce the total amount of carbon dioxide emissions but also integrate the sustainable ability in itself. This has important implications for the architecture of the framework and the development of LCM.

Moreover, it is clear from the literature review that optimization techniques and waste reduction methodologies such as lean manufacturing are taken in several researches in environmental and sustainable areas. It has the potential to integrate these methodologies to develop initial LCM. A more practical of combining essential approaches will be demonstrated in the following sections in this chapter.

4.2 State of the Art

Recently, the term of sustainable manufacturing has been discussed across the value stream (manufacturing process throughout supply chain) in order to make awareness of using energy and resource more efficient and effective. On the other hand, this term can be used broadly for environmental impact topics. Thus, the concept of low carbon manufacturing is emerging to specifically reduce carbon footprint and energy consumption by applying the principle of sustainable manufacturing while essential manufacturing performances (cost, quality and time) can still be simultaneously achieved. However, a schism arises when exploring the strategic framework, approaches, systematic implementation and application perspectives which are still ambiguous. Many researchers have been investigating the methods for reducing carbon emissions in different scale of manufacturing systems, e.g. shop-floor, enterprise and supply chains. A summary of the work above is provided in Table 4.1 and a discussion follows. Many researchers, particularly in the period of 2007-2009, attempted to develop models for predicting and reducing carbon emission in large scale systems. For example, Parikh et al. proposed a model using linear functions to evaluate amount of carbon emissions (Parikh 2009). Flower et al. proposed the estimation model for carbon emission based on an emission factor of the energy source co-operating with the associated production process (Flower 2007), while Heilala et al. used the machine data from manufacturers with the time spent in a specific operational process to evaluate carbon emission and energy consumption in magnitudinous view (Heilala 2008). It can thus be concluded that the establishment of predicted carbon emission models plays the important role in carbon reduction. Moving forward to manufacturing systems, the wasted energy occurred in processes becomes the significant sign of inefficient and ineffective usage of energy and resource utilization. Lean manufacturing can be considered as a tool to cope with this problem.

Research efforts	Modelling, procedure and objective	Manufacturing level
Parikh et al.	Modelling of CO_2 emissions for economic scale	Supply Chain
Flower et al.	Modelling of green house gas for concrete manufacturer	Enterprise/Factory
Heilala et al.	Simulation system for sustainable manufacturing	Shop-floor and Factory
Ball et al.	Material, process and waste flow modelling	Shop-floor and Factory
Davis	Waste free manufacturing procedures and concept	Shop-floor and Factory
Jabbour et al.	Investigation of green supply chain in Brazil	Supply Chain
Humphrey et al.	Environmental and energy criteria for supplier selection	Supply Chain
Makatsoris et al.	Design of supply chain and fulfillment system	Factory and Supply chain
Bateman et al.	Devolved manufacturing: factory less concept	Factory and Supply chain
Cheng et al.	e-manufacturing approach	Factory and Supply Chain

Table 4.1 Modelling efforts in EREE-related manufacturing research

Additionally, it might not be sufficient for the whole enterprise to reduce carbon emissions and energy consumptions by focusing only on manufacturing systems. Ball et al. proposed the concept of utilizing energy and waste of the facility and utility by applying the waste from one process to be used as an input to another process (Ball 2009). This can be combined with the workplace organization method as presented by Davis et al. (Davis 1999). This concept demonstrates the procedure to seek out waste that can be found in the organization to implement waste free manufacturing. At the supply chain level, many researchers unveiled that most industrial sectors and companies have not taken account of sustainable criteria and environmental impact, which is meant inefficient energy wise on the value stream (Jabbour 2009). In the mean time, Humphreys et al. proposed the model integrated with environmental and energy criteria for suppliers' selection, which leads to the green supply chain (Humphreys 2003). In management of supply chains, Makatsoris et al. developed the model using e-manufacturing to maximize production planning together with supply chains planning with the real time system (Makatsoris 2004). Bateman et al. developed the concept of 'factory less' to improve supply chains performance with less transportation using Devolved Manufacturing as an approach (Bateman 2006). This concept can reduce the carbon emission from the value stream network. Moreover, Cheng et al. suggested that the concept of extended supply chains network performance using e-manufacturing has the high potential for success (Cheng 2008). From the literatures having been critically reviewed, it can be concluded that the approach to reduce carbon footprint and energy consumption is likely to play an important role in manufacturing systems. However, the core framework and specific approach applicable to every level of manufacturing operations have not been investigated systematically yet. The knowledge gap needs to be fulfilled and implementation and application perspectives need to be investigated and well understood.

4.2.1 Carbon Emissions Analysis

In the past decade, many countries have been conscious to develop the procedures for reducing carbon emissions. Fan et al. (Fan 2007) 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 (Golove 1996) 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.

4.2.2 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 Gungor and Gupta (1999) (Gungor 1999). Carbon emissions and energy efficiency have never been a critical factor in operation optimization. However, Mouzon et al. (Mouzon 2007) 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.

4.2.3 Desktop and Micro Factory

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 (Okazaki 2004) 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 (Mishima 2006) 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 concept of desk-top and micro factory can be applied to the LCM by reducing the unnecessary carbon contents from manufacturing systems.

4.2.4 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 (Bateman 2006) 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 concept” 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.

4.3 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 exceedingly uses energy more than available capacity/constraint (low energy efficiency) simultaneously without optimal operational setting to run process or system can lead to the high volume of carbon dioxide intensity to atmosphere (Fig. 4.1). Therefore, the main characterization of LCM can be categorized into specific five terms as follows:

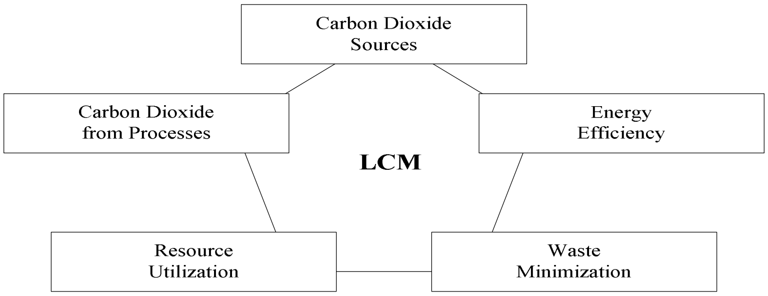


Fig. 4.1 Characterization of Low Carbon Manufacturing

(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 because the conventional electricity generation consumes fossil fuel which is the source of carbon dioxide.

(2) Low carbon dioxide from process: this can be referred to the process that directly generates carbon intensity to the atmosphere e.g. chemical process using crude oil or fossil fuel. The amount of carbon intensity can be reduced if the optimal process parameters can be determined when energy consumption rate or carbon emissions are considered as an objective to be minimized.

(3) Energy efficiency: energy efficiency can be explained as a percentage of output of energy from process (in watt or joules) divided by the input amount of energy (Edwards 2012). Hence, this parameter in LCM concept should be higher than conventional industrial processes.

(4) Waste minimization: This term can be meant as how waste can be dislodged or minimized according to the reference (Mulholland 2001). If the third criteria above are categorized into carbon dioxide emissions due to machines and equipment, the term ‘waste’ represents undesired manufacturing wastes that affect on the total carbon emissions. 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.

(5) Resource utilization: Sivasubramanian et al. (Sivasubramanian 2003) 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.

4.4 EREE-Based LCM: Conception and a Framework

According to the characterization of low carbon manufacturing, energy efficiency, resource utilization and waste minimization are the key goals for realizing low carbon manufacturing and consequently essential for its conception and quantitative analysis and modelling (E-R-W-C modelling). The key constituents as formulated for the conception and framework are presented in Table 4.2, in the format of a matrix highlighting the manufacturing levels (column) against their individual characterizations (row). In the matrix, each cell represents the possible solution for a specific manufacturing level to successfully complete relevant characterization. For example, the matrix cell 1-1 represents recommended methods for the machine/process level to achieve energy efficiency. The descriptions of proposed potential solutions for each manufacturing level are further discussed in the rest of this section. Fig. 4.2 further illustrates intricate relationships among the constituents of EREE-based LCM, which also demonstrates the LCM outcomes are not only focused on the conventional manufacturing performance but also sustainability and low carbon footprint.

Machine/Process: Most machines and processes consume energy in differential ways due to their components and parts built with and procedures of the processes. Evaluation of energy consumption from the machine/process is the essential part of studying the machine energy efficiency/effectiveness. It is difficult to predict energy consumption from the process involving multiple parameters setting such as cutting speed, depth of cut, feed rate, using cooling and lubrication, etc. Therefore, the energy consumption modelling for the machine/process must be carefully undertaken and laborious.

	Machine/Process	Shop-floor	Enterprise	Supply Chains
(1) Energy Efficiency	-Machine energy consumption modelling -Process energy consumption modelling	-Multi objective optimization -Multi energy consumption optimization	-Work place organization -Utility flow planning	-Green supply chain concept -Supplier selection criteria
(2) Resource Utilization	-Material processes -Process planning -Machine layout	-Manufacturing cell layout -Flexible manufacturing -Process scheduling optimization	-Facility layout -Operation strategies -Process planning and optimization -Resource flow planning	-Collaborative of supply network and production planning -Information system management
(3) Waste Minimization	-Component scrapping -Machine downtime -Idle time -Operator error	-Lean manufacturing -Point-of-use manufacturing	-Lean manufacturing -Point-of-use manufacturing	-Factory less concept -E-manufacturing -Devolved manufacturing
(4) Carbon Footprint	-Establishing models on carbon footprint based on (1) (2) (3) above	-Establishing models on carbon footprint based on (1) (2) (3) above	-Establishing models on carbon footprint based on (1) (2) (3) above	-Establishing models on carbon footprint based on (1) (2) (3) above

Table 4.2. The characterization of EREE-based low carbon manufacturing

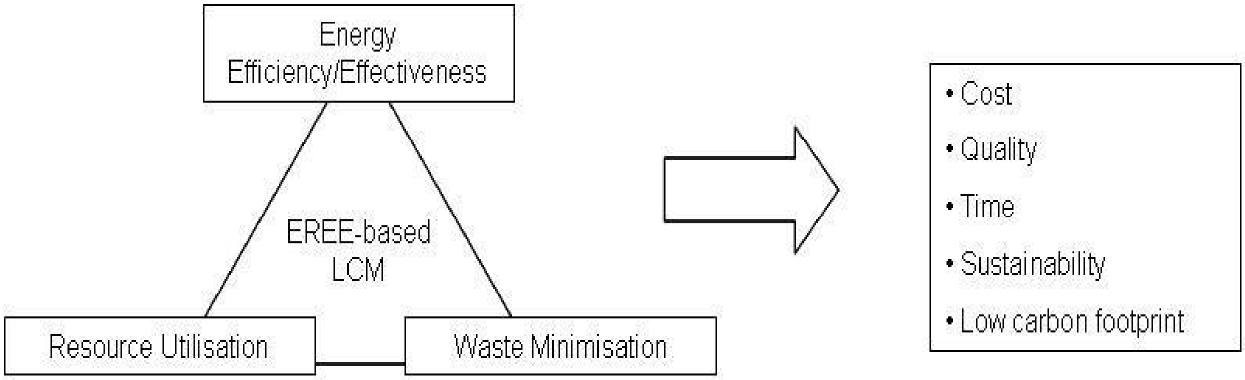


Fig. 4.2 The conception and outcome of EREE-based LCM

To better utilize the resource at the machine and process, the questions firstly arriving in the production engineer’s mind are likely: what work should be assigned to this machine? when this machine should be started and stopped? where this machine should be located? All of the question must be well attempted in order to maximize the machine's utilisation for and in the production process. To comply this step, the machine/process utilization must be co-operated with energy consumption modelling so as to maximize the utilization and minimize the energy consumption, and eliminate the waste in the machine and process. The typical wastes on a machine come from components scrapping, machine down time, idle time and operator errors. These wastes may cause imperfect machine/process conditions which again lead to undesired energy and resource efficiency and effectiveness.

Shop-floor: This level refers to the floor of the workshop where technicians and engineers work on the machine and manufacturing cell. In order to make energy efficient for shop-floor, the model for predicting energy consumption is a key of success at this stage as well as shop-floor level. However, the complexity arises when there are many machines to be involved (many energy consumption models). In addition, the solution can be more complex when the production objectives include not only energy consumption but also quality, time and cost. Therefore, the multi objective optimisation method can be appropriate solution. The value of energy consumption can compromise with other production performance e.g. minimizing energy consumption and maximizing profit. Moving forward to resource utilisation, layout/position for machines in shop floor might be an essential issue because of the complexity in process planning. When machines/processes with same specific function are categorized in the same location, it could be more convenience for process planning with maximized utilisation of each machine/process. Thus, the principle of manufacturing cell layout and flexible manufacturing can be applied to cope with this problem. These concepts must be combined with multi objective optimisation including energy consumption model while to optimize the process scheduling. As a result, the requirement of resource utilisation for the machine/process can be provided at this stage. Furthermore, the conditions of the machine/process are also important for the shop-floor (manufacturing cell). Lean manufacturing, therefore, can be applied to eliminate unnecessary waste at shop-floor. Maintenance system can play an important role in this concept because when shop-floor reliability improves, it can reflex in reduction of each machine/process down time and component scrapping. Finally, the method of carbon footprint modelling based on E-R-W-C can be applied just same as that for the machine/process level.

Enterprise: There are many departments/sections in a manufacturing enterprise which can be implied to many kinds of processes and functions occurred in the enterprise. On the other hand, this means the complexity in evaluation of energy consumption at this stage due to the different kinds of consumed energy (electricity, fossil fuel, resources, etc.). Hence, the concept of workplace organization is suitable because the enterprise can seek out what kind of wastes occurring from the specific area, then the concept of utility flow planning is used together to efficiently consume energy at each department/section of the enterprise. When energy requirement is determined in large scale, master process planning, which can be referred as master production planning (MPS), is involved together to likely make resource planning comprehensively. With effective process planning, the production manager can provide operation strategies which can compromise between customer demands and available energy requirement. This strategy also performs as the top-down process to shop-floor level because each manufacturing cell receives work order after operation strategy was finished. To realize energy consumption reduction for the enterprise, the concept of lean manufacturing can also be used at this level as well as at shop-floor level. Taking account of inventory management, the concept of making to order is not just for warehouse control but it can also reduce the waste in terms of energy and resource when demand was changed. For carbon footprint modelling, E-R-W-C method can be applied same as the previous two levels.

Supply Chain: Nowadays, the role of supply chains has highly impact on the whole value stream in the competitive marketplace. The supplier selection becomes the successive key for an enterprise to fulfil enterprise supply chain network. In order to make effective value stream, most enterprises determine their supply chains based the conventional supplier performance, e.g. delivery quality, cost and response time. However, the total performance of supply chain network might not be sufficient for the contemporary manufacturing system due to the lack of energy and environmental concern. On the other hand, it could be implied that the supply network could have the effectiveness of quality, cost and delivery but the energy and environmental inefficiency. Hence, the concept of green supply chain has high potential to be a feasible solution at this stage. The criteria of supplier selection must have insertion of energy concern in itself with the questions: how much the energy consumption is in the production process? does the company have energy policy support? how does the company process wastes from the production line? As a result, the total energy effectiveness of value stream can be improved by applying the new method of supplier selection. However, the completion of low carbon manufacturing for supply chain level might be imperfect because of ineffective resource utilisation. This could be meant that the poorly organized supply chain network between suppliers and manufacturers can lead to waste of energy and resource including over production process and unnecessary transportation, etc. Therefore, the effective information system management is very important to create effective collaboration between supply network and production planning by using e-manufacturing. With this method, the planning between suppliers and manufacturers is optimized in light of the real time response of interactive e-manufacturing system so as to maximize of resource utilisation with elimination of unnecessary waste energy. In addition, the advantage of e-manufacturing is not only for supply chain resource utilisation but also waste minimisation. The potential to complete this part with e-manufacturing is using 'factory less' concept or Devolved Manufacturing as a tool. The carbon emission from value stream is likely decreased by combining we-based technology, mass customization and rapid manufacturing, which may lead to the innovative manufacturing being carried out at the customer's door step in a rapid and EREE-oriented manner. This may further lead to point-of-use manufacturing by using mobile smart machines or 'factory box', which possibly means some modes of sustainable manufacturing in EREE context.

4.5 LCM theoretical model

According to the literature review in Chapter 2, it is obvious that the methodology for carbon dioxide emissions evaluation and assessment is very essential as initial fundamental for LCM. Optimization tools/techniques is also required to provide the effective operation when the firms need to transform their existing system to be LCM environment. In addition, the elimination of waste from manufacturing processes has been broadly investigated by many researchers in term of sustainable development and environmental concern. Therefore, the theoretical model for LCM shall compass three kinds of element, i.e. carbon dioxide emissions evaluation, optimization methods and waste reduction methodologies, as shown in Fig. 4.3, which are also described in details in the sub-sections below. Moreover, the theoretical model can be in various such as mathematical modelling and simulation model.

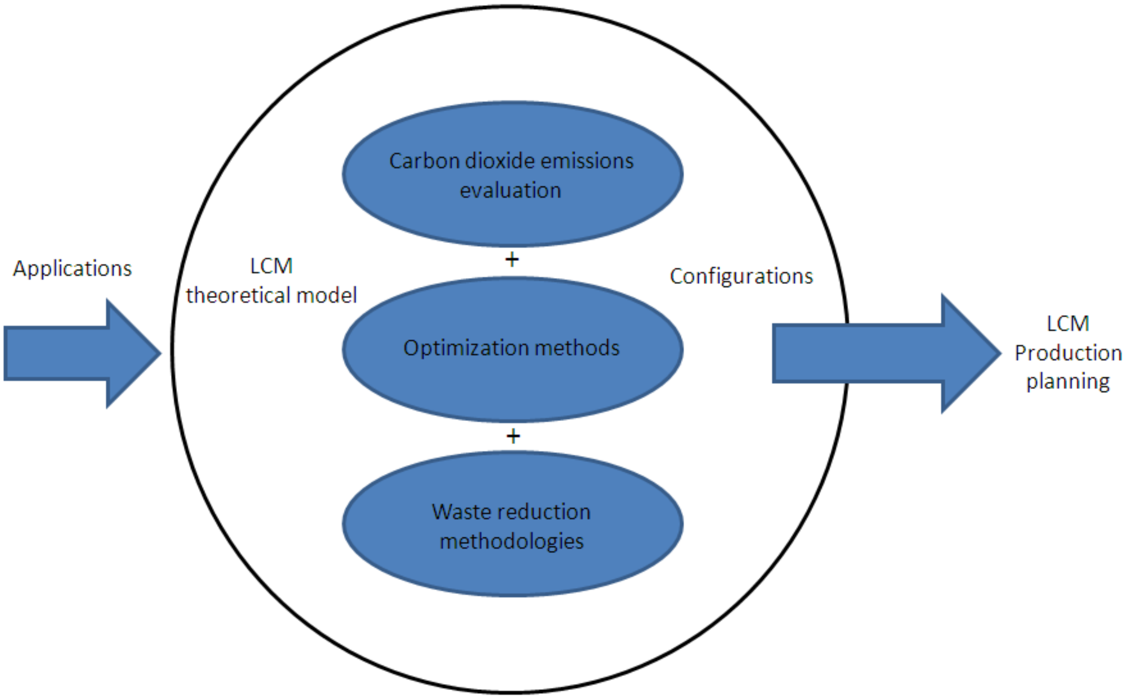


Fig. 4.3 The theoretical model of LCM

Carbon dioxide emissions evaluation

Obviously, the methodology for carbon dioxide emissions and assessment can play important role for tracking the contribution of organizations/activities on climate change and eventually accomplishing total carbon emissions. There are contemporary guidelines that are broadly used at the present such as guideline for national gas inventories by IPCC and PAS 2050. According to the guideline from IPCC, the core concept of calculation method is based on used energy conversion because burning in carbon based fuels is the source of carbon dioxide emissions. This method can enable an accurate national carbon dioxide emissions by accounting for the carbon in fuels supplied to the economy. Considering on the fuels supplied, they can be categorized into two groups: primary fuels (i.e. fuels that obtain from national resources such as coal, crude oil and natural gas) and secondary fuels or fuel products such as gasoline and lubricants which are transformed from the primary fuels. However, the supplied fuels are not only burned for heat energy but they can also be used as a raw material (or feedstock) in some manufacturing processes such as plastics and non energy use without oxidation (emissions) of the carbon. The utilization of fuels in this way is called “stored carbon”. This amount must be deducted when amount of energy consumption is determined for carbon dioxide emissions calculation. Thus, IPCC suggests an initial approach for carbon dioxide emissions calculation into six steps as follows

(1) Estimate apparent fuel combustion in original units
(2) Convert to a common energy unit
(3) Multiply by emission factors to compute the carbon content
(4) Compute carbon store
(5) Correct for carbon unoxidised
(6) Convert carbon oxidized to CO_2 emissions

In PAS2050, it is also designed as an assistant guideline for carbon dioxide emissions assessment. It main concept depends on analyzing of process chains/sequences. Each process/activity must be determined whether there is carbon based fuels/energy involved in the considered process/activity or not. Then, then amount of fuel/energy is multiplied by the related coefficient. This can be implied that the main procedure of PAS 2050 and the guideline from IPCC are identical but PAS 2050 is more suitable for enterprise/systems level while the guideline from IPCC is suitable for national (large scale) level.

However, the schism arises when the well design and planning for supporting low carbon is required. Referring to the literature review, many researchers have been trying to develop methodologies and models which are not only just for assessment but also supports decision making in term of simulation and predictability. In machine based manufacturing, the systematical methodology that can evaluate the amount of energy consumption regarding to machining condition set-up is essentially required according to literature reviews. It would be rather to predict and simulate the amount of energy consumption with reliable and high precision results before performing cutting process than only applying assessment at the end of the process. Therefore, it is very essential to involve carbon dioxide emissions evaluation as one element in the LCM theoretical model. The evaluation method must be developed by extending from the conventional carbon dioxide emissions assessment/calculation.

Optimization methods

According to the literature review in Chapter2, various optimization techniques have been applied into sustainable and environmental problem to provide the optimal solution. Normally, there are two main types of optimization methodologies with their unique advantages. Their applications are determined based on the type/level of problem definition. Optimization methods can return the best solution that can satisfy requirement of objective functions and problem constraints. Therefore, it is very essential to involve optimization methods as one element of LCM theoretical model.

Multi objective decision making (MODM) are naturally formulated in the form of mathematical modelling regarding to problem descriptions. The structure of mathematical is constructed by three parts: objective functions, problem constraints and range of decision variables. In objective and constraint parts, the formulation can be established as linear and non linear equation while the final part defines type and boundary of decision variables. Types of decision variable can be both real or integer. The advantage of using MODM to cope optimization problem is capability in solving complex problem. At the present, there are various methods of searching algorithm that enable run time process to reach convergence point faster and easier such as genetic and direct search algorithms. However, there can be a major problem from optimization procedure due to searching criteria. Optimization algorithm may return global or local result. In other word, global result is referred to the true optimal result while local result represents dummy result. Therefore, the decision maker must always be aware in reliable of result from optimization method because it can affect on all three elements (energy efficiency, resource utilization and waste minimization) to achieve LCM.

Multi attribute decision making (MADM) is widely used when there are set of data/information and objectives/goals to be determined. Most of MADM calculating process normalizes all data due to their own reference methodology and objectives/goals requirement. The set of value transformed by normalization method can be compared to select the best solution. MADM is not complicate for the decision maker by its natural behavior (mathematical modelling is not required to formulated). In addition, all feasible solutions are predetermined. It can be, in other words, implied that the performances of possible solution are ordered due to the normalized value. However, the application of MADM might not be flexible as MODM because the selection of optimal solution using MADM can perform only on the available data/information while MODM can define the boundary/range of decision variables.

Waste reduction methodologies

As described in characterization of LCM, there are many types of waste that affect on the total carbon emissions from manufacturing processes. Thus, it is very essential to define waste reduction methodologies as one element of LCM theoretical model because even effective carbon dioxide emission evaluation and optimization techniques are successful implemented into production planning, it is still difficult to prevent undesired wastes from the real situation/process running. There could be fluctuation in the expected results from evaluation and optimization methods. On the other hand, it can be referred that the true LCM strategy cannot be accomplished without the effective waste reduction methodologies. According to possible wastes that can occur in manufacturing processes, the most important variable associated between wastes and total carbon emissions is time. Thus, time based simulation could be a possible solution to eliminate undesired wastes such as idle time, resource utilization and maintenance down time etc.

4.6 Implementation of LCM at Enterprise and Supply Chains Level

Three implementations have been explored at Brunel University for LCM. The configuration of implementation of LCM is shown in Fig. 4.4.

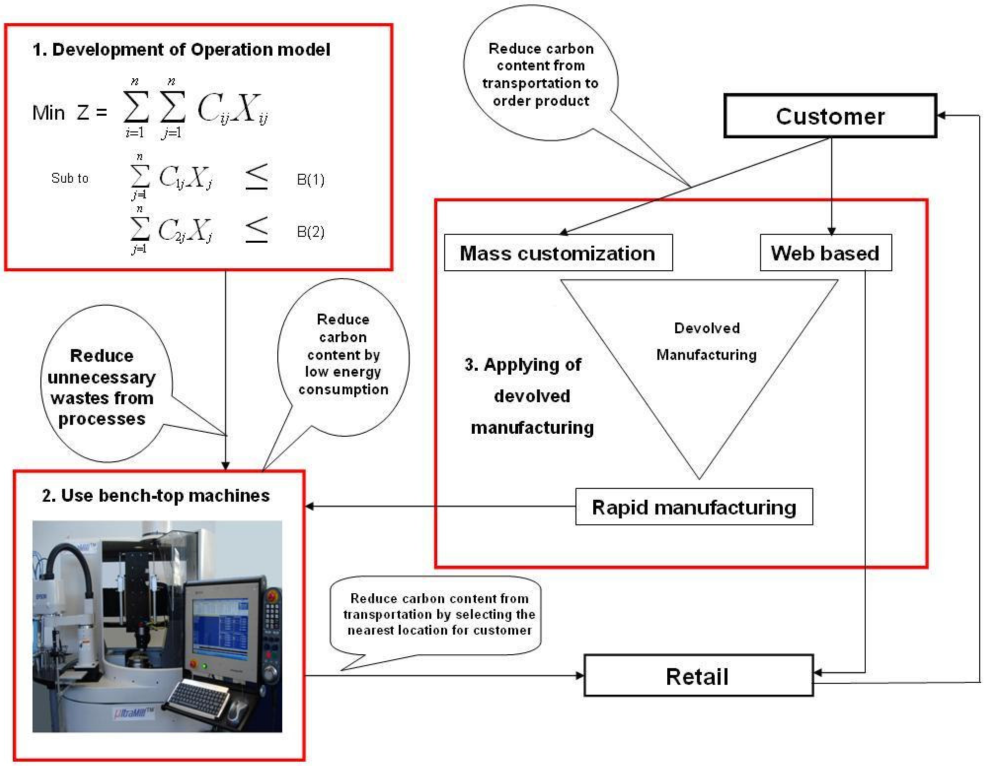


Fig. 4.4 Implementation of LCM concepts

(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 optimize both machine and process conditions with energy efficiency, resource utilization and waste minimization. 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.

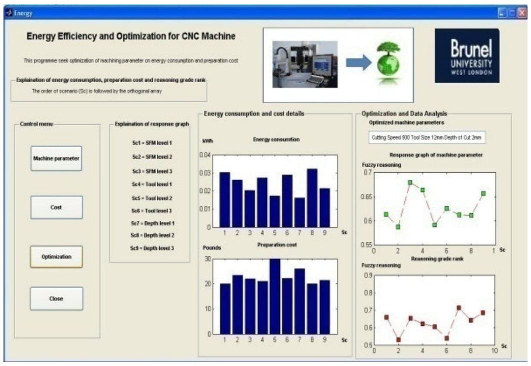
(3) Applying of Devolved manufacturing: Bateman and Cheng have introduced the concept of Devolved Manufacturing which aims at achieving mass customized rapid manufacturing in a devolved web-based manner (Bateman 2002). This method can be

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 (less transportation, less fossil fuel burning). It can be explained in another words that this approach is focused on reducing carbon emission from supply network.

4.7 Implementation of LCM at Machine and Shop-Floor Level

In this section, the application and implementation for EREE-based LCM conception and framework are explored and presented. However, the work presented is focused on two manufacturing levels: the machine/process and shop-floor level as the research project and interests concerned. The previous section covers with the approaches cooperating with the characterisation for low carbon manufacturing on different manufacturing level and then the modelling, optimisation and simulation method are used as selected tools. In Figs 4.5 and 4.6, the procedure is illustrated to establish the machine/process energy consumption modelling with the well-design experimental measurement and testing for evaluating and validating the models. In this research, the CNC based machining is carried out as on test workpieces to assess the machine energy consumption and mapping in comparsion with modelling and simulation predictions. The experiment was undertaken on cutting trial with different machining conditions (cutting speed, depth of cut, tool size) and then collecting energy consumption data computer acquitted via the power logger device. After data from the power logger was analysed, the energy consumption model is created by using fuzzy inference system (FIS) as the AI tool base (mamdani and sugeno type). In addition, sugeno type is used for energy consumption prediction while mamdani type is used for optimization. The MATLAB GUI is used to create user interface for user friendly purpose at this stage.

Fig. 4.5 Energy measurement



Energy Efficiency and Optimization for CNC Machine

This programme seek optimization of machining parameter on energy consumption and preparation cost

Explaination of energy consumption, preparation cost and reasoning grade rank

The order of scenario (Sc) is followed by the orthogonal array

Explaination of response graph

Sc1 = SFM level 1
Sc2 = SFM level 2
Sc3 = SFM level 3
Sc4 = Tool level 1
Sc5 = Tool level 2
Sc6 = Tool level 3
Sc7 = Depth level 1
Sc8 = Depth level 2
Sc9 = Depth level 3

Optimized machine parameters: Cutting Speed 600 Tool Size 12mm Depth of Cut 2mm

Fig 4.6 Energy modelling

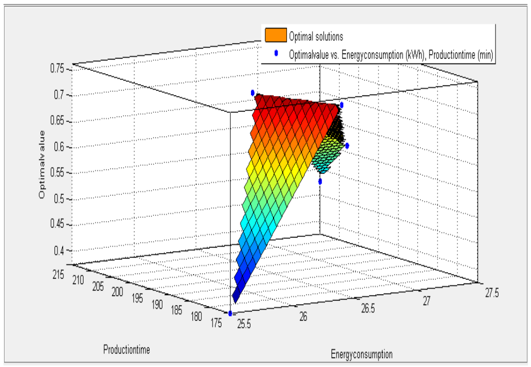
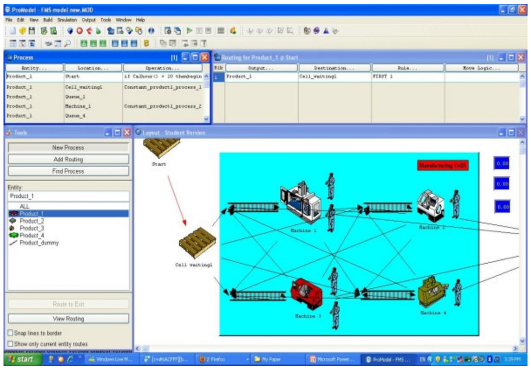


Fig. 4.7 Resource utilization



ProModel - FMS model new.MOD

Process

Entity...	Location...	Operation...
Product_1	Start	if Calhour() = 10 thenbegin
Product_1	Cell_waiting1	Constant_product1_process_1
Product_1	Queue_1	
Product_1	Machine_1	Constant_product1_process_2
Product_1	Queue_4	

Routing for Product_1 @ Start

Blk	Output...	Destination...	Rule...	Move Logic...
1	Product_1	Cell_waiting1	FIRST 1	

Fig 4.8 Discrete simulations in ProModel

The models can predict the amount of energy consumption from the machine/process while process parameters are changed. For resource optimisation modelling, the mathematical model is constructed using the theory of operations research. This model uses fuzzy set theory to make the problem formulation. However, the complexity of the problem was arrived when there are many machines and resources to be integrated on the shop-floor. Hence, this model is established as multi objective model including energy consumption criteria. Fig. 4.7 shows the exemplar result after running the optimization model using MATLAB programming. After applying this model, all resources on the shop-floor will be maximized on their utilisation against the constraints defined previously (such as: what work should this machine do? when this machine should start and stop? etc.). Finally, the criterion of waste minimisation is applied with discrete event system simulation. This method is used in order to monitor the machine regarding its energy consumption performance, resource utilization, available conditions and downtime.

However, it is not used as a stand alone system as it is controlled with the logic movement by optimization strategy from the mathematical model as described. In this research, the discrete simulation system is performed by using ProModel programming as illustrated in Fig. 4.8. With these three applications, the manufacturing process can produce a product with conventional manufacturing performance while energy consumption is minimized.

4.8 Modelling of Carbon Footprint in EREE-based LCM

Fig. 4.9 schematically illustrates the proposed modelling for carbon footprint in EREE-based LCM, i.e. ERWC modelling approach. The approach includes three elements of the energy, resource and waste modelling which can be in three different dimensions in the application space. It can be represented in term of functions in Equation (4.1). The objective of this modelling is to provide the solution for energy and resource efficiency and effectiveness for the interested manufacturing system while the waste is also reduced.

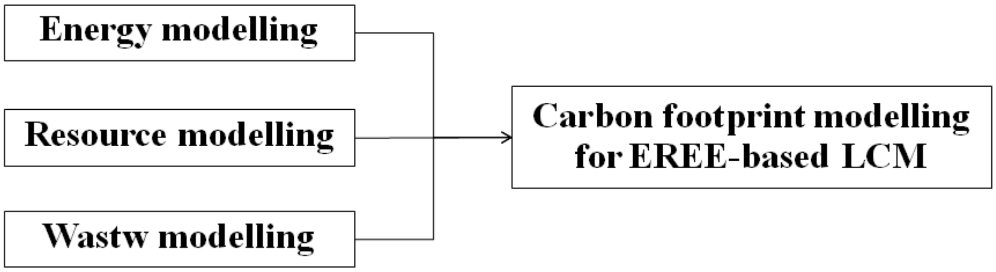


Fig. 4.9 Modelling of carbon footprint in EREE-based LCM

$$LCM_m = f(E_m, R_m, W_m) \tag{4.1}$$

LCM_m represents the modelling of carbon footprint in EREE-based LCM. It is constructed as a function of three variables: energy consumption modelling (E_m), resource optimization modelling (R_m) and waste minimization modelling (W_m). The variables inside the function can vary depending on the specific manufacturing level as described in section 3.1. The modelling details for energy consumption, resource utilization and waste are described below.

4.8.1 Machine/Process Energy Consumption

Each machine and process has different number and type of parameters that can affect the energy consumption in the process. To establish the energy model, it is, therefore, relies on the machine/process parameters and their relationship on energy consumption. The model is represented as:

$$E_m = f(\{p_1 \dots p_i \cdots p_I\}, \{r_1 \cdots r_j \cdots r_J\}) \tag{4.2}$$

In this function, p_i ($i \in \{1 \dots I\}$) denotes to the type of machining/process parameters e.g. cutting speed and feed rate, etc. r_i ($j \in \{1 \dots J\}$) refers to the relationship of the associated parameter (p_i) on energy consumption.

4.8.2 Resource Utilization

In order to maximize and optimize resource utilization, the detail of the interested system including objective function, system constraint and variables should be addressed to evaluate optimized process planning. The model is illustrated as:

$$R_m = f(\{o_1 \cdots o_a \cdots o_A\}, \{c_1 \cdots c_b \cdots c_B\}, \{v_1 \cdots v_c \cdots v_C\}) \tag{4.3}$$

where o_i ($i \in \{1 \dots A\}$) is the objective function for resource optimization modelling. c_b ($b \in \{1 \dots B\}$) means the constraint of the specific manufacturing system for resource optimization modelling and v_c ($c \in \{1 \dots C\}$) refers to the variable considered in this model. It should be noted that different system has different number of objective function and constraint then the formation of resource optimization modelling depends on the structure of the specific system.

4.8.3 Waste Minimization

Many kinds of wastes can occur in the system such as idle time, scrapped components, delay time and break down time. These kinds of wastes result in different part of the system such as energy consumption, system constraint and process planning. Thus, the waste minimization modelling described below relies on the type of the waste as its associated impact.

$$W_m = f(\{w_1 \cdots w_d \cdots w_D\}, \{a_1 \cdots a_e \cdots a_E\}) \tag{4.4}$$

where w_d ($d \in \{1 \dots D\}$) is the type of the waste occurred in the interested system and a_e ($e \in \{1 \dots E\}$) is associated level of waste w_d affecting on total waste of the system.

4.9 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. The models are presented in the form of mathematical formulation.

4.9.1 An Operational Model at Supply Chain Level

The basic concept of the operational model at supply chain level is based on the capacitated flow model (Taha 1997). The overview of network perspective is illustrated in Fig. 4.10. The amount of carbon footprint can vary depend on the chosen routine. Therefore, it is very essential to determine the optimal solution which can cope with energy/carbon footprint issue i.e. directly transport or use depot level.

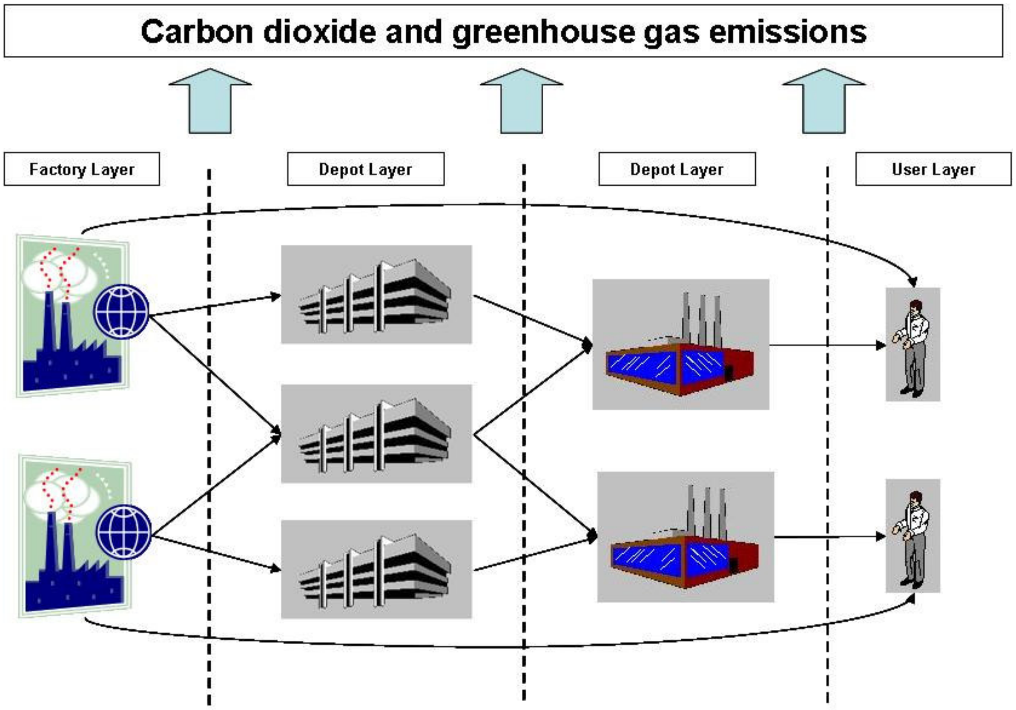


Fig. 4.10 The concept of the capacitated flow model for low carbon manufacturing

The objective function represents the summation of total used energy in unit of joules using to distribute product in the supply network operation (source: factory to sink: user). The goal of this formulation is to minimize carbon intensity in supply network by finding the optimal amount of product distribution from (X_{ij}) between node i and j. The formulation can be described as

$$\text{Min } (f = \sum_{(i,j)\in\Omega} En_{ij} X_{ij}) \tag{4.5}$$

$$\text{Subject to} \quad \sum_{\substack{k \\ (j,k)\in\Omega}} X_{jk} - \sum_{\substack{i \\ (i,j)\in\Omega}} X_{ij} = f_j \qquad \forall j \in Z$$

$$C_{ij:\min} \le X_{ij} \le C_{ij:\max} \qquad \forall i, j \in \Omega$$

$$X_{ij} \ge 0 \qquad \forall i, j \in \Omega$$

where

Z - set of node (location) in network

Ω - set of arc (path) in network

En_j - energy factor coefficient for flow X_{ij} (joules)

$C_{i,j:max}$ - maximum product capacity of arc (i,j) (upper limit in this flow)

$C_{i,j:min}$ - minimum product capacity of arc (i,j) (lower limit in this flow)

f_j - total net flow at node j (demand and supply level at specific node)

However, this model formulation is not effective enough to implement in the real world situation. Currently, the author has been developing the robustness of the model by applying multi-objective concept and improving energy modelling (objective function). With these methods, the energy consumption can be participated with other conventional manufacturing performance e.g. cost, delivery time and quality.

4.9.2 An Operational Model at Shop-Floor Level

This formulation is developed by using the theory of linear programming (LP) solution (Taha 1997). 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

$$\text{Min } (f = \sum_{i=1}^{n} \sum_{j=1}^{\phi} En_{ij} X_{ij}) \tag{4.6}$$

$$\text{Subject to} \quad \sum_{i=1}^{N} S_{ij} X_{ij} \geq P_j$$

$$\sum_{i=1}^{N} \sum_{j=1}^{\phi} C_{ij} X_{ij} \leq E$$

$$\sum_{i=1}^{N} \sum_{j=1}^{\phi} \delta_{ij} X_{ij} \leq L$$

$$X_{ij} \geq 0; i \in B; j \in A$$

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

4.10 Experiments and Results

4.10.1 The System and Processes

There are five stations in the system: preparation station, milling machine, painting machine, 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 preparation, milling, painting, inspect and packaging. Processes of spindle are machining, cutting, milling, inspect and packaging. Processing time of both two products is listed in Table 4.3 and energy consumption rate in Table 4.4/ 4.5 (Electricity and oil).

	Machine 1	Machine 2	Machine 3	Machine 4	Machine 5
	Processing time (min)	Processing time (min)	Processing time (min)	Processing time (min)	Processing time (min)
Gear	15	15	15	15	15
Spindle	15	15	15	15	15
Sum	30	30	30	30	30

Table 4.3 Processing time of the gear and spindle on each machine

	Machine 1	Machine 2	Machine 3	Machine 4	Machine 5
	Electricity consumption (KwH/cycle)	Electricity consumption (KwH/ cycle)	Electricity consumption (KwH/ cycle)	Electricity consumption (KwH/ cycle)	Electricity consumption (KwH/ cycle)
Gear	1	1	1	1	1
Spindle	3	3	3	3	3
Sum	4	4	4	4	4

Table 4.4 Electricity consumption rate to produce the product on each machine

	Machine 1	Machine 2	Machine 3	Machine 4	Machine 5
	Oil rate (Litre/cycle)	Oil rate (Litre/cycle)	Oil rate (Litre/cycle)	Oil rate (Litre/cycle)	Oil rate (Litre/cycle)
Gear	1	1	1	1	1
Spindle	2	2	2	2	2
Sum	4	4	4	4	4

Table 4.5 Oil consumption rate to produce the product on each machine

M1: preparation station; M2: milling machine, M3; painting machine; M4: inspection and M5: packaging. Energy is still provided to the devices although they do not perform any work (down and idle time) with Electricity = 90 kWh, Oil = 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.

4.10.2 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 Fig. 4.11. 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 4.5.

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

Table 4.6 Operational shift for each device

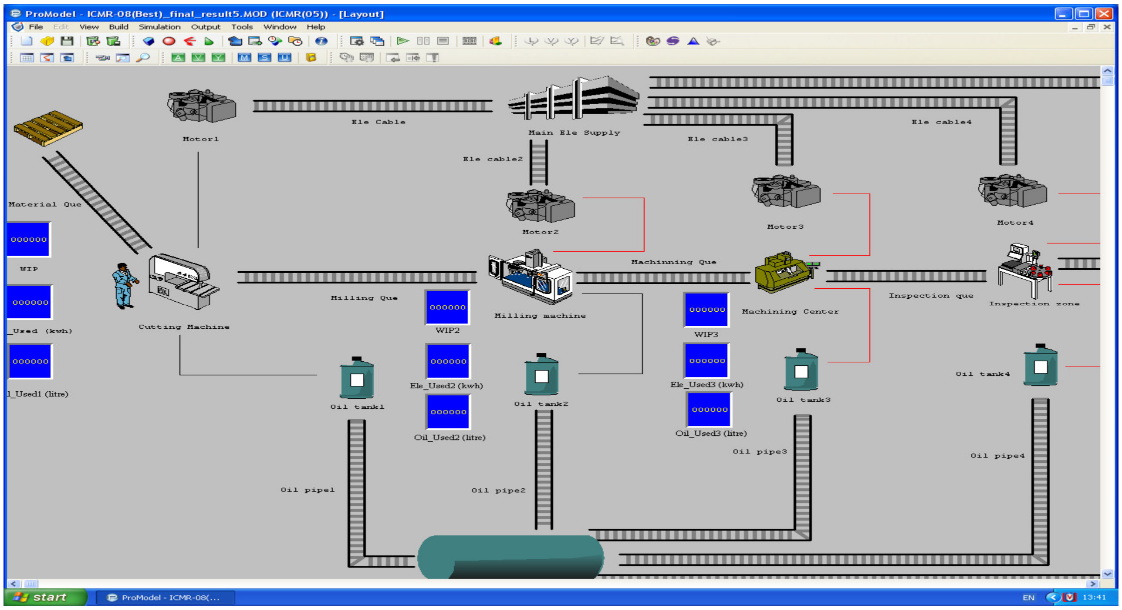
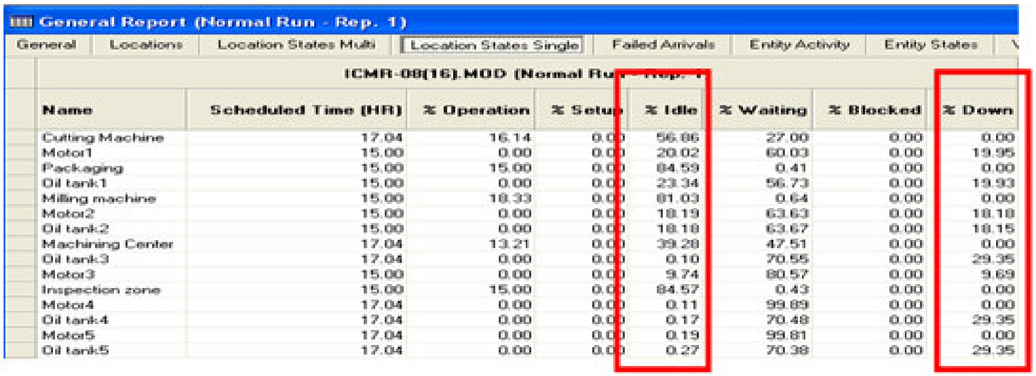


Fig. 4.11 The configuration of the systems in ProModel simulations

4.10.3 Results

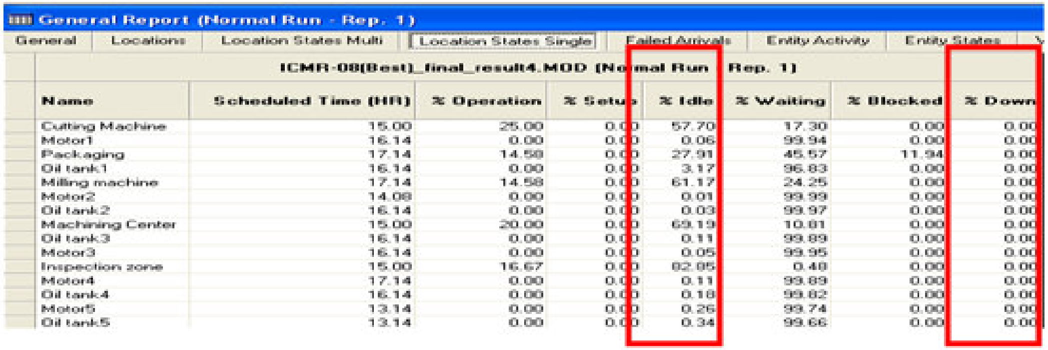
Both systems are operated from 8.00 am to 1.00 am (to get results at steady state) in the same condition including inter arrival time of entity and operating algorithm. After running system simulation by using ProModel, the comparison of location states single between two systems are shown in Figs. 4.12 and 4.13. Running the system with shop-floor model, the second system can eliminate percent of down time from operating period.



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. 4.12 Location states single of the first system



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. 4.13 Location states single of the second system

Devices in the first system reached the down time limit and cannot 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 Fig. 4.14.

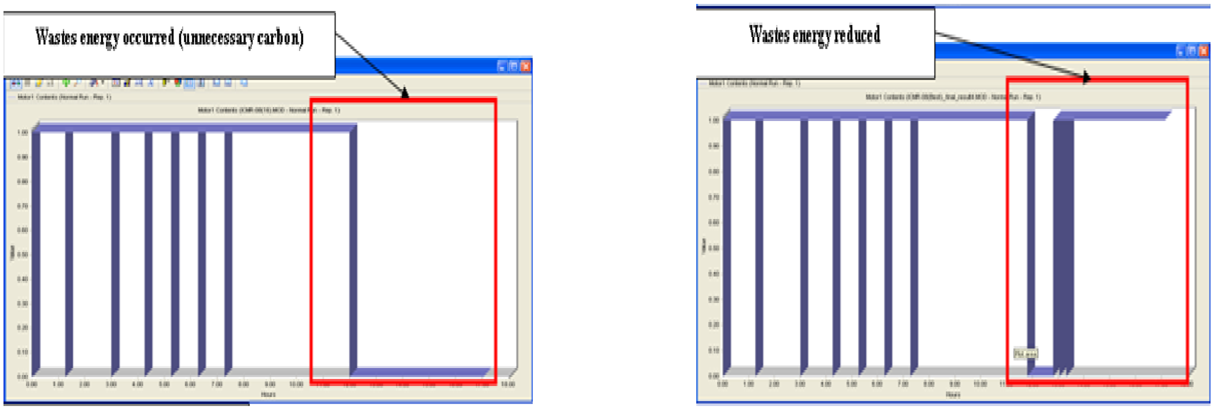
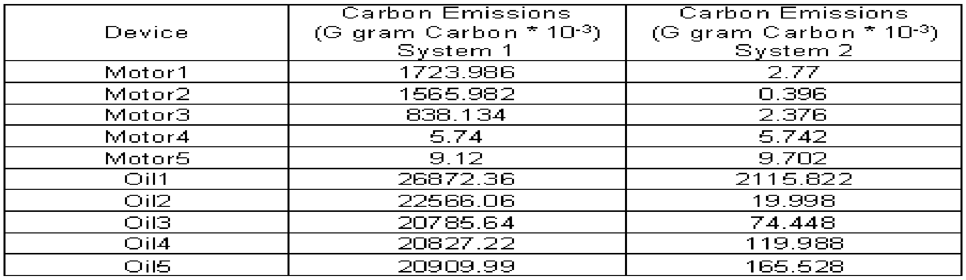


Fig. 4.14 The status of Motor1 in the first system (left) and second system (right)

4.10.4 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 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 4.6.



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

Table 4.7 Carbon emissions from the first and second systems

4.11 Summary

The framework, characterizations and initial methodologies for developing LCM have been presented in this chapter. The proposed framework presents appropriated approaches for different manufacturing levels (machine, shop-floor, enterprise and supply chain levels) corresponding with characterizations of LCM (energy efficiency, resource utilization and waste minimization) in the form of matrix. In the latter section of this chapter, the initial method for implementing LCM is presented with a case study. The earlier section is formulated as fundamental and basis while the latter section is generated as tool and application to implement LCM regarding to the previous section.

LCM has the ability to enable industrial sector to not only reduce total carbon emissions from the process but also satisfy conventional manufacturing performance by integrating important elements of LCM. In addition, the implementation of LCM can provide the optimal solution together with preventive planning from simulation results for the decision maker.

Chapter 5 Modelling of EREE-based LCM

5.1 Introduction

The modelling of EREE-based LCM at both the machine and shop-floor levels is a very important part of the proposed framework (as discussed in Chapter 4) because these two levels can be classified as the two lowest levels of conventional manufacturing (machine, shop-floor, enterprise and supply chain level). Thus, the thorough investigation of the practical methodology collectively taking account of energy efficiency, resource utilization and waste minimization so as to minimize total carbon footprint is an essential part of LCM implementation.

Whilst the guidelines for carbon footprint calculation are broadly published as international standards, the systematic approach to reduce carbon footprint during manufacturing processes is less well understood. It is therefore necessary to closely examine the modelling of EREE-based LCM and understand the influencing key parameters.

As discussed in Chapter 3, there are many factors that are required to be carefully determined at machine level in order to the minimize carbon footprint. To develop in-depth insight and knowledge about EREE-based LCM implementation at this level, the modelling and simulation with theoretical support are presented.

For the higher manufacturing level which has more complexity, the modelling is presented with the guideline of the synchronization method between machine and shop-floor level. The application from this method provides optimal results and a preventive plan that achieve minimization of the carbon footprint.

5.2 The scope and boundary of developing a system approach for low carbon manufacturing

According to the characterization of the EREE-based low carbon manufacturing, this section presents the definition of energy efficiency, resource utilization and waste minimization as a system boundary for both machine and shop-floor level. In the machine level, it is obvious that the machine is considered as the central source of energy consumption or carbon footprint occurrence while the shop-floor level is more complex in terms of determination because there are many available machines in the system. Some machines might not be selected to perform a work assignment. Therefore, the boundary for the machine level focuses at the machine operations and its environment while the shop-floor level focuses on the management of FMS system and the operational sequence with total energy consumption. The definitions of characterization in the machine level are expressed as follow;

(1) Energy efficiency: Normally, the definition of energy efficiency is referred to the objective which aims to reduce the amount of energy consumption used to provide products and services. Most development methods for energy efficiency are provided by achieving efficient technology or production process (Diesendorf 2007). With this information, it can be implied that the term of energy efficiency at the machine level is the machining operations including machine set-up and cutting process which consumes lower energy consumption while the same service can also be served. On the other hand, it can be referred to the machining operation with the minimization of energy consumption while the other objectives (maximization of profit and minimization of total production time) are also satisfied. Thus, this research aims to investigate and develop the approach and application which can be implemented to the machine level by providing the optimal machine set-up concerned with a multi objective concept. For energy efficiency at the shop-floor level, the problem of process sequence and work assignment are required to integrate with the evaluation of the impact from energy consumption. This concept means even the traditional FMS problems can be solved with optimal solution and the minimization of energy consumption must also be satisfied. Hence, this research also aims to investigate and develop the methods and tools for energy efficiency at the shop-floor level by integrating the application for the machine level as a sub sequence with the optimization method.

(2) Resource utilization: Normally, the term of resource can be referred to tangible and intangible resources which have limited availability can be scheduled/ assigned work and even utilized by users (Wysocki 2009). The type of resource can be categorized as a natural resource (non-renewable resource and renewable resource etc.), human resource (talents, skills and abilities etc.) and tangible resource (equipment, machines and vehicles etc.) while resource utilization in manufacturing systems mean the percentage that a

resource is used in the considered time period (Harrell 2003). The equation for resource utilization is expressed in Equation 5.1. Thus, this research focuses on the utilization of resources in the manufacturing process which can affect the level of energy consumption and carbon footprint such as production hours of machines, selection of cutting tools and material systems. The utilization of resources which is not related to the emission factor will not be considered.

$$\%Utilization = \frac{the\ time\ the\ resource\ is\ used}{total\ considered\ period\ of\ time} \tag{5.1}$$

(3) Waste minimization: According to the philosophy of just in time (JIT), waste from manufacturing is not only referred to as the scrap or garbage from the process but it can also represent any resource that adds cost but does not add value to the product (Tompkins 2003). Waste in JIT, thus, can be categorized into seven types as waste from overproduction, time on hand (waiting), transporting, processing itself, unnecessary stock on hand, unnecessary motion and producing defective goods (LU 1985). Hence, waste within EREE-based LCM system boundary refers to any resource that causes unnecessary energy consumption and carbon footprint (all considered wastes are related to the emission factor). For example, wastes that are focused in this research are maintenance downtime, machine down time and operator error (motion that causes unnecessary energy consumption). The preventive plan which has an objective to minimize waste in EREE-based LCM for FMS is a focus in this research.

Fig. 5.1 presents the cause of carbon footprint in FMS from energy consumption, utilization of resource and waste. The main energy consumption comes from the production process while the selection of resource (machine, cutting tool and material handling systems) and unnecessary waste (down time, idle time and error motion) related to emission factors are also determined for the total carbon footprint.

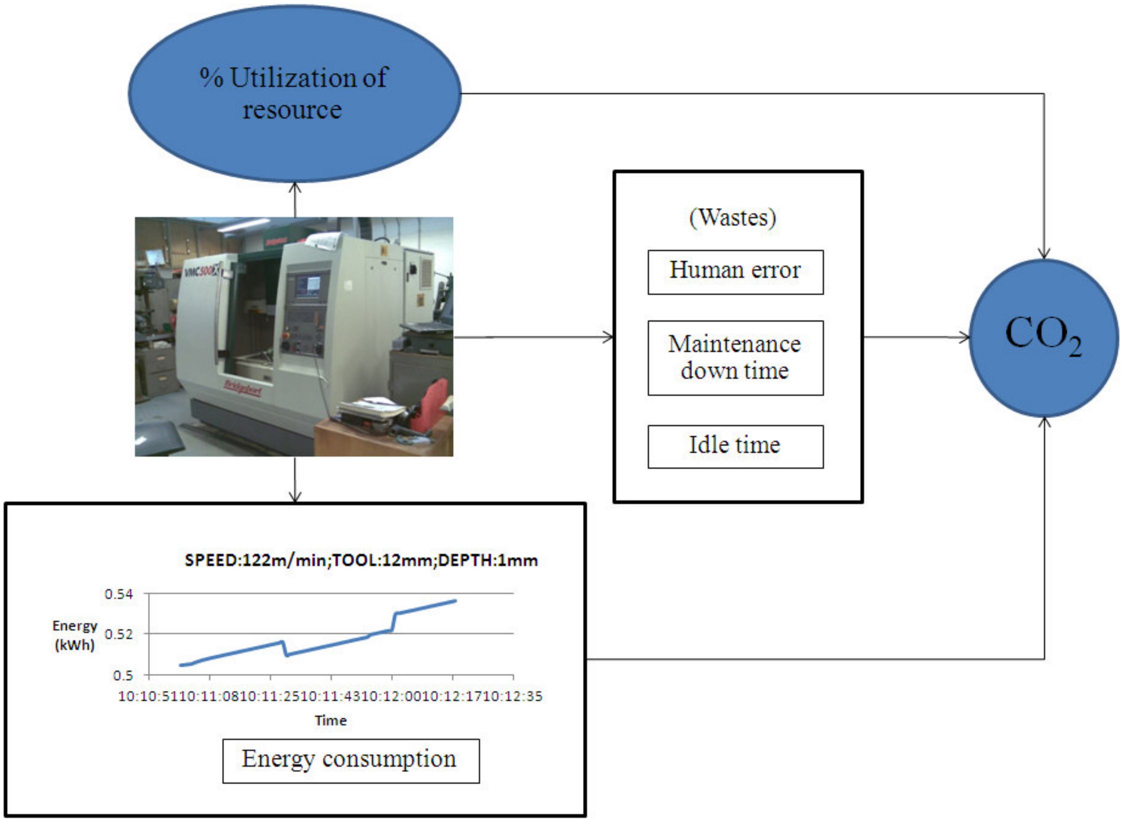


Fig. 5.1 The causes of carbon footprint in FMS

5.3 The conceptual model for EREE-based low carbon manufacturing

According to the concept of Axiomatic Design, the design process for EREE-based low carbon manufacturing begins with the transformation of the customer needs into functional requirements (FR) and defines design parameters (DP) as a solution for each functional requirement. This is for the first layer of the conceptual model. The set of functional requirements and design parameters for this layer are presented as follows:

FR_1 = Energy Efficiency, FR_2 = Resource Utilization, FR_3 = Waste Minimization

DP_1 = Using energy with efficiency, DP_2 = Using the resource corresponding DP_1, DP_3 = Eliminating waste corresponding DP_1 and DP_2

$$\begin{bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{bmatrix} = \begin{bmatrix} X & 0 & 0 \\ X & X & 0 \\ X & X & X \end{bmatrix} \begin{bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{bmatrix} \tag{5.2}$$

To select and use a proper resource, it must be accompanied with the use of using energy efficiency so as to find out the optimal solution while waste minimization can be performed after the optimal solution is determined. On the other hand, it could be implied that waste minimization must rely on DP_1 and DP_2. Hence, the mathematical relationship between functional requirements can be expressed as a triangular matrix which is decoupled and the independence axiom is satisfied.

Second level decomposition: FR_1 – Energy Efficiency

In this stage, it is very important to go back to the functional domain from the physical domain when the design parameters cannot be achieved without further details. The decomposition of FR_1 and DP_1 can be described as;

FR_{11} = Compatible with critical operation, FR_{12} = Relying on real process/data, FR_{13} = Evaluating the amount of energy consumption

DP_{11} = Clarifying process parameter, DP_{12} = Design of data collection, DP_{13} = Developing energy modelling

$$\begin{bmatrix} FR_{11} \\ FR_{12} \\ FR_{13} \end{bmatrix} = \begin{bmatrix} X & 0 & 0 \\ X & X & 0 \\ X & X & X \end{bmatrix} \begin{bmatrix} DP_{11} \\ DP_{12} \\ DP_{13} \end{bmatrix} \tag{5.3}$$

As the characterization of low carbon manufacturing, the use of energy with efficiency is required to reduce the source of carbon emissions. If the evaluation of the carbon footprint from the machining process is possible, the decision maker can, therefore, select the optimal machining operation with energy efficiency. In order to implement at this stage, the ability to predict the value of energy consumption from the combination of machine set-up is necessary. Hence, the critical machining parameters have to be clarified firstly because different machine parameters affect different levels of energy consumption. The cutting trials (experiments) for the chosen system/machine must be performed to collect the primary base data which can be used for identifying a functional trend. Finally, energy modelling is established based on FR_{11} and FR_{12}. Therefore, the design matrix is formulated in the form of a triangular matrix and it is decoupled. The matrix is presented in Equation 5.3.

Second level decomposition: FR_2 – Resource Utilization

FR_{21} = Use available resource, FR_{22} = Compromise with all other objective, FR_{33} = Select resource at the right time

DP_{21} = Clarify resource constraints, DP_{22} = Optimization method, DP_{23} = Resource planning/scheduling

$$\begin{bmatrix} FR_{21} \\ FR_{22} \\ FR_{23} \end{bmatrix} = \begin{bmatrix} X & 0 & 0 \\ X & X & 0 \\ X & X & X \end{bmatrix} \begin{bmatrix} DP_{21} \\ DP_{22} \\ DP_{23} \end{bmatrix} \tag{5.4}$$

The resource utilization concept of LCM aims to maximize the utilization of resources in the considered system by planning to select and use proper resources for the activities. Resource constraints must be clarified firstly to provide available resource lists for the decision maker. The optimization process must be performed to ensure that the selected resource can compromise with all objectives as an optimal solution because there is normally more than one objective in the real world problem. This stage can be concluded with resource planning/scheduling to provide a work assignment for all resources. To complete this decomposition, it must conform logically. Hence, the mathematical relationship has to be established in the form of a triangular matrix with decouple. The matrix is presented in Equation 5.4.

Second level decomposition: Fr_3 – Waste Minimization

FR_{31} = Clarify source of waste, FR_{32} = Predict waste, FR_{33} = Prevent waste of energy and carbon footprint

DP_{31} = Defining task environment related to emission factor, DP_{32} = Analysis of waste occurrence, DP_{33} = Waste elimination plan

$$\begin{bmatrix} FR_{31} \\ FR_{32} \\ FR_{33} \end{bmatrix} = \begin{bmatrix} X & 0 & 0 \\ X & X & 0 \\ X & X & X \end{bmatrix} \begin{bmatrix} DP_{31} \\ DP_{32} \\ DP_{33} \end{bmatrix} \tag{5.5}$$

Low carbon manufacturing is not only designed to meet the use of energy with efficiency and the selection of proper resources but also eliminate and minimize the waste of energy consumption and carbon footprint in the manufacturing process. It is obvious to firstly clarify the sources of waste in the chosen system because these unexpected wastes can affect the total energy consumption and carbon footprint. The decision maker might take the wrong action from this unknown problem. The model for prediction, then, is necessary to be applied to cope with this stage. The model should have the ability to observe the cycle time of the machine/worker, maintenance down time of the machine and error occurrence of the worker, etc. Therefore, waste minimization must eventually result in a preventive plan which can be used with the operational plan. This decomposition is also logically performed. Therefore, the matrix design is a triangular matrix as presented in Equation 5.5.

5.4 Transformation of conceptual design into logical approach

In this section, the transformation of design parameters (DP) into a logical approach is demonstrated as step by a step procedure. According to the conceptual model, the achievement of EREE-based LCM requires the completion of three elements logically as depicted in Fig. 5.2. The energy model must be created before the optimization of resource allocation is performed. Then, the optimal solution from the second stage is simulated with discrete event simulation to minimize and eliminate the waste of energy consumption and unnecessary carbon emissions.

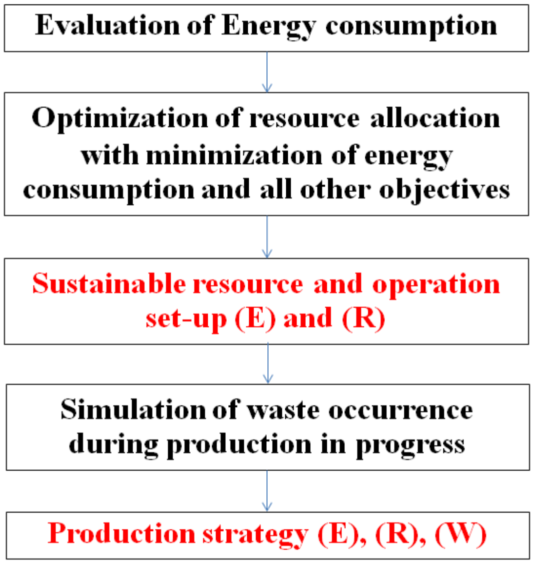


Fig. 5.2 Transformation of design parameters in a logical approach

5.4.1 Energy efficiency

Objective: evaluate energy consumption from process parameters and utilization of resource

Procedures at this stage

(1) Clarify factors (process parameters, resources) that affect the total energy consumption of the considered process
(2) Establish energy modelling based on related factors and their experimental results
(3) Model is established as energy based model
(4) Input parameters are process parameters and related resources
(5) Result from the energy modelling is primary energy consumption, e.g. electrical energy (kWh)
(6) Energy consumption is multiplied by related emission factor to gain carbon emissions

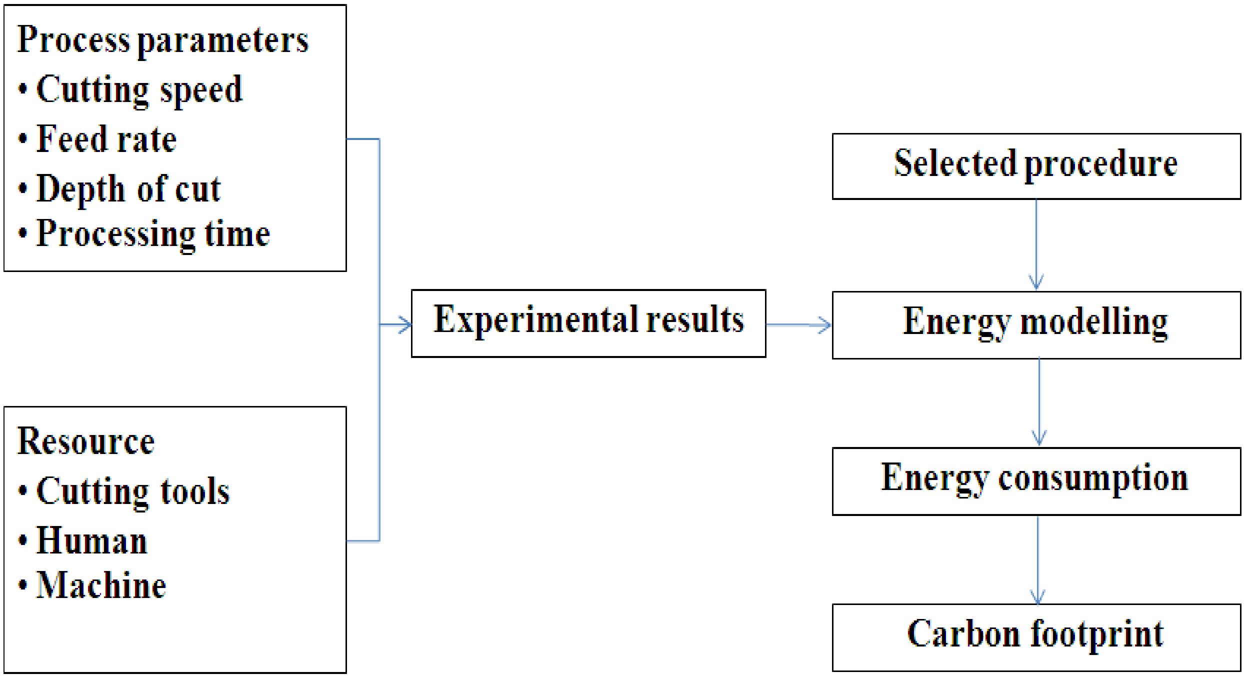


Fig. 5.3 Procedure at energy efficiency stage

Demonstration of energy modelling

In this section, the establishment of energy modelling based on experimental results is presented.

(1) The considered process is a cutting process on a CNC machine
(2) Process parameters are cutting speed and depth of cut and the resource is a cutting tool
(3) Range of cutting speed is 91 and 152 m/min. Range of depth of cut is 1 and 2 mm. Range of cutting tool is Ø12 and Ø16 mm. (clarify process parameters)

(4) Experimental results of differential process condition on aluminum cutting are presented in Table 5.1. (design data collection)

(5) The regression fit using interaction term is used in this demonstration (develop energy modelling)

(6) The energy modelling (equation) of this process is obtained from the statistical toolbox in MATLAB 7. It is expressed in equation 5.6.

(7) The model is fit with interaction term with $R^2 = 0.9$

Condition No.	Cutting speed (m/min)	Tool size (Ø mm)	Depth of cut (mm)	Energy consumption (kWh)
1	91	12	1	0.03
2	152	12	1	0.04
3	91	12	3	0.03
4	152	12	3	0.01
5	91	16	1	0.02
6	152	16	1	0.02
7	91	16	3	0.02
8	152	16	3	0.01

Table 5.1 Experimental results of cutting trials

$$Y = 0.0725 + 0.0001X_1 - 0.005X_2 - 0.0025X_3 - 0.0013X_2X_3 \tag{5.6}$$

where

Y = energy consumption (kWh)

X_1 = Cutting speed (m/min)

X_2 = Depth of cut (mm)

X_3 = Tool size (mm)

Numerical example

(1) Input parameters (process condition) are 91 m/min (X_1)/ 1 mm (X_2)/ Ø12 mm (X_3)
(2) Energy consumption from this process condition is 0.0325 kWh
(3) Emission factor for electricity is 0.49927 kg CO_2 per kWh (DECC 2009)

Carbon emissions from using this process condition is 0.01622 kg CO_2

5.4.2 Resource utilization

Objective: utilize/select resource with energy efficiency and minimization of carbon emissions

The proposed generic model

(1) Implementation of axiomatic model (resource utilization part)
(2) Arrangement of available process condition (process parameter, resource) in the form of matrix
(3) Optimize utilization of resource by transformation of the proposed model into the selected optimization method
(4) Constraints of the considered process are involved into the optimization procedure
(5) The model can be applied at both machine and shop-floor level
(6) The generic model is expressed in equation 5.7

$$\begin{bmatrix} PC_1 \\ PC_2 \\ PC_3 \\ . \\ . \\ . \\ PC_N \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \\ X_3 \\ . \\ . \\ . \\ X_n \end{bmatrix} \propto \begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ . \\ . \\ . \\ B_N \end{bmatrix} \tag{5.7}$$

where

PC_n = process condition = $f(PR_n, R_n)$

PR_n = process parameter e.g. cutting speed, depth of cut etc.

R_n = resource e.g. cutting tool, machine etc.

X_n = decision variable (activation of the related process condition n)

B_n = process/system constraint

Perspective of the generic model

(1) Process/system constraints define the size of decision matrix in both machine and shop-floor level.
(2) The left hand side matrix is the available process condition
(3) The second matrix is the decision variable matrix
(4) The third matrix is the constraint matrix
(5) Objective function of energy consumption can be established based on the evaluation model at the first stage.
(6) For example: $Ob = 0.01X_1 + 0.02X_2 + 0.003X_3$
(7) The constant values are obtained from the evaluation model presented in the first stage.
(8) For instance, the value of 0.01(kWh) is defined when 152 m/min, Ø12mm, 1mm are used as process condition.
(9) If process condition 1 and 2 (X_1, X_2) are activated (selected), the total energy consumption is 0.03 kWh.

(10) The arrangement of the decision matrix is dependent on the selected optimization model.

(11) The explanation of resource utilization is expressed in Fig. 5.4.

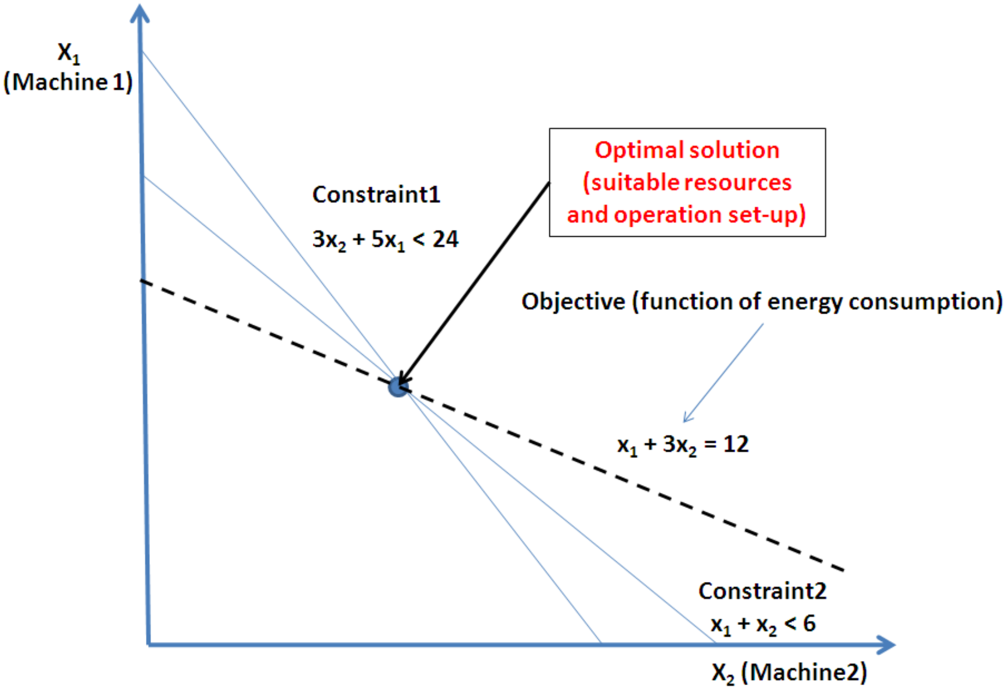


Fig. 5.4 The transformation of generic model into mathematical method

(1) All constraints have to be clarified (there are two constraints in this example)
(2) Objectives have to be clarified (objective function of energy consumption is obtained from the evaluation model)
(3) The optimal solution (utilization of resource with energy efficiency) can be determined in the range of constraint

At machine level

There is only one process condition selected to perform a process/machine. The optimization method is relied on the selected procedure. The expected result at this level is the utilization of resource in the considered system/boundary with energy efficiency while the constraints are satisfied. In this research, the fuzzy relation grade technique is used as the implementation method of resource utilization at machine level.

(1) If the constraints for machine cutting process are available process conditions such as range of cutting speed (91/122/152 m/min), range of depth of cut (1/1.5/2 mm) and tool size (Ø12/14/16 mm), the decision matrix of the process condition can be created as presented in Table 5.2. (clarify constraint and optimization method)

(2) In addition, the data of energy consumption of each process condition using the evaluation model is presented in Table 5.3.

(3) In the real world situation, there are multi objectives to be determined in the decision making not only minimization of energy consumption. For instance, the other objectives can be cost, production time and quality.

(4) If the cost of preparation of each process condition is presented in Table 5.3, the selected process condition (decision variable) is 152 m/min/Ø12 mm/2mm. It is obvious that the result is not concerned only with the minimization of energy consumption but also accomplished another objective (0.0231 kWh and 22.1 pounds). (resource planning with energy efficiency)

(5) Thus, the result at this stage covers two keys of EREE-based LCM: energy efficiency and resource utilization (cutting tools) to satisfy all considered objectives.

Scenario	Cutting Speed (m/min)	Tool Size (mm)	Depth of cut (mm)
1-1-1	91	12	1
1-2-2	91	14	1.5
1-3-3	91	16	2
2-1-2	122	12	1.5
2-2-3	122	14	2
2-3-1	122	16	1
3-1-3	152	12	2
3-2-1	152	14	1
3-3-2	152	16	1.5

Table 5.2 The decision matrix of process condition at machine level

Energy consumption (kWh)	Cost preparation (pounds)
0.03	20.45
0.0297	22.3
0.0244	21.23
0.0354	22.5
0.0246	30
0.032	21.8
0.0231	22.1
0.0347	20
0.0294	21.7

Table 5.3 The data of energy consumption and cost of preparation

At the shop-floor level

There can be more than one process condition chosen for the consideration at this level because there are many machines located at shop-floor level. However, the decision variables are still the same as at the machine level (activation of the process condition).

Typically, the constraints at the shop-floor level refer to the process sequence in the considered boundary. If there are two machines located in the shop-floor and there is only one machine that can perform at the considered period of time, this constraint then can be transformed into a linear equation as follow;

$$X_1 + X_2 = 1 \tag{5.8}$$

where $X_1, X_2 \in \{0,1\}$

In this research, the fuzzy integer linear programming for several objectives is used as the implementation method at the shop-floor level. Thus the transformation of the decision matrix is as follows:

$$\begin{bmatrix}1 & 1\\1 & 1\end{bmatrix}\begin{bmatrix}X_1\\X_2\end{bmatrix} = \begin{bmatrix}1\\1\end{bmatrix} \tag{5.9}$$

$$X_i = \begin{cases}1 & if\ X_i\ is\ selected\\0 & if\ X_i\ is\ not\ selected\end{cases}$$

The explanation of the decision matrix

(1) There are two machines located on the shop-floor (clarify constraint)
(2) There are two processes to be operated (clarify constraint)
(3) Each process can be performed by only one machine (clarify constraint)
(4) The first row of the left hand side of the matrix represents the first operation (optimization method)
(5) The second row of the left hand side matrix represents the second operation
(6) The constant value represents the process sequence and boundary
(7) The primary information used at this stage is obtained from the evaluation model
(8) The example of primary information is expressed in Table 5.4.
(9) If $X_1 = 1$ and $X_2 = 0$, it means machine 1 will be used in both process 1 and 2 while machine 2 will not be used.
(10) If the machine 1 is used for the process 1, it means process 1 will be performed with 152 m/min/ 1 mm depth of cut/ Ø 12 mm of cutting tool (resource) on machine 1 (resource).
(11) Resources can be well utilized with energy efficiency regarding to the optimal solution

Energy consumption	Resource		Machining parameter	
	Machine	Cutting tool (Ømm)	Cutting speed (m/min)	Depth of cut (mm)
0.01	Machine 1	12	152	1
0.02	Machine 2	16	91	2

Table 5.4 The primary information obtained from the evaluation model

5.4.3 Waste minimization

Objective: minimize and eliminate waste of energy consumption and carbon emissions

Procedure of converting waste into energy consumption and carbon emission

1. Clarify waste that can be a source of carbon emissions
2. Waste are converted into waste of energy consumption and multiplied by related emission factor to gain carbon emissions
3. Waste concerned in this research is energy and time based
4. Transformation of waste into carbon emissions are presented in Equation 5.10
5. Waste can be maintenance down time, idle time and human error etc.

$$WT_1 \text{ (min)} * CW_1 \text{ (Unit of used energy/ min)} * EW_1 = CO_2W_1 \tag{5.10}$$

$$WT_2 \text{ (min)} * CW_2 \text{ (Unit of used energy/ min)} * EW_2 = CO_2W_2$$

$$\cdot$$

$$WT_n \text{ (min)} * CW_n \text{ (Unit of used energy/ min)} * EW_n = CO_2W_n$$

$$\cdot$$

$$WT_N \text{ (min)} * CW_N \text{ (Unit of used energy/ min)} * EW_N = CO_2W_N$$

$$TCO_2 = CO_2W_1 + CO_2W_2 + \ldots + CO_2W_n + \ldots + CO_2W_N$$

where

WT_n = Total time of waste type n occurred (min)

CW_n = Consumed energy related to waste n (unit of used energy/ min)

EW_n = Emission factor of waste type n

TCO_2 = Total carbon emission from wastes at the considered system

Numerical example

1. (1) Wastes in CNC based manufacturing are maintenance down time, idle time and human error
2. (2) Time spent on maintenance down time is 1 hour and loss of energy for maintenance down time is 10 kWh
3. (3) Time spent on idle time is 1 hour and loss of energy for idle time is 5 kWh
4. (4) Time spent on human error is 1 hour and loss of energy for human error is 8 kWh
5. (5) Emission factor for electricity is 0.49927 kg CO_2 per kWh (DEFRA 2009)

$TCO_2 = (1)(10)(0.49927) + (1)(5)(0.49927) + (1)(8)(0.49927) = 11.32221\ kgCO_2$

Procedure for waste minimization

1. (1) Undesired wastes can occurr during the process
2. (2) Discrete event system simulation (time based) is used as a tool
3. (3) Record of failure such as previous maintenance down time is used to create data distribution of related waste
4. (4) Input for simulation model is optimal solution from the second stage (resource utilization)
5. (5) Output from the model is a preventive plan
6. (6) The proposed model for waste minimization is presented in Fig. 5.5

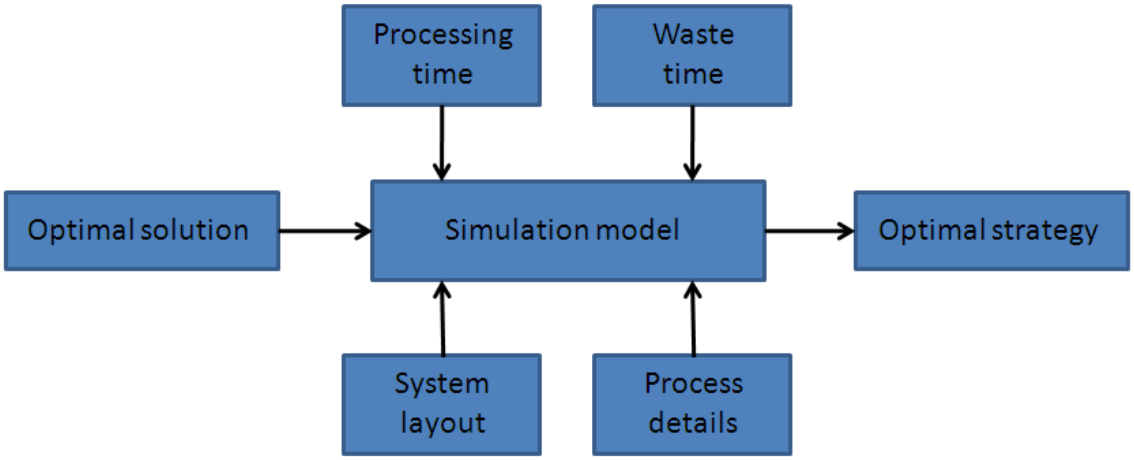


Fig. 5.5 Simulation model for waste minimization

Numerical example

(1) The input of the simulation model (process condition) is machine type A, cutting tool Ø12 mm, cutting speed 122m/min and depth of cut 1mm performed on aluminum cutting
(2) Simulation results are presented in Table 5.5
(3) Primary energy consumption is electricity
(4) Emission factor for electricity is 0.49927kgCO_2perkWh
(5) Loss of energy from idle time is 5kWh/hour
(6) Loss of energy from maintenance down time is 10 kWh/hour
(7) Carbon emission from waste = (3.83)(0.0435)(5)(0.49927) + (3.83)(0.5217)(10)(0.49927) = 10.4 kgCO_2
(8) If the carbon emission from performing this process condition is 0.016 kgCO_2 (obtained from the evaluation model), the total carbon emission is 10.4 + 0.016 = 10.42 kgCO_2
(9) To prevent unnecessary carbon emissions from waste, the preventive plan must be established
(10) The demonstration of the preventive plan will be discussed in machine and shop-floor modelling

Name	Scheduled Time (HR)	% Operation	% Setup	% Idle	% Waiting	% Blocked	% Down
Loc1	3.83	43.48	0	4.35	0	0	52.17

Table 5.5 Simulation of waste during the process using discrete event simulation

5.5 The systematic approach for applying the conceptual model to achieve sustainable manufacturing

This section presents the method of using the conceptual model for both machine and shop-floor levels as a systematic approach. It could be, on the other hand, implied that this model must be firstly applied to the lowest level of manufacturing structure (machine level) and then go through the next higher level in order to the minimize energy consumption and carbon footprint in every point of the system. In Fig. 5.6, the overall perspective of the systematic approach is presented. There are six steps for using the integrated model at machine and shop-floor level.

(1) Machining operations analysis: First of all at machine level, it is very important to understand operations/process of the considered machine in order to seek out what factors can affect the amount of energy consumption and carbon footprint. Some factors might make a different effect on the total energy consumption compared to the other factors. So, it is very useful in the preparation of preparing these details to use energy efficiency. Resources (such as a cutting tool) which are used in the operations are also concerned to increase the utilization of resource. The details of waste related to the total carbon footprint are also required to analyze how the waste of energy occurs during machining operations.

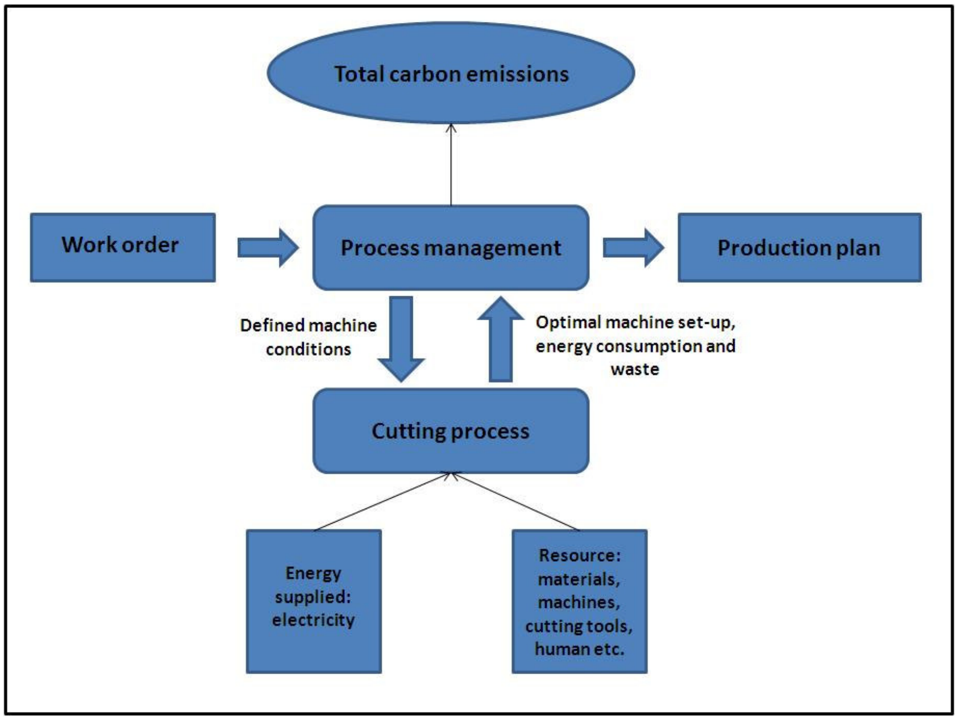


Fig. 5.6 Applied conceptual model for systematic approach

(2) Evaluation and optimization at machine level: After all relevant factors are clarified, the next step of using the integrated model is to evaluate the amount of energy consumption from the combination (scenario) of machining parameters and the selected resource. It can be a crucial factor for an effective plan if the decision maker can evaluate the amount of energy consumption from the machining process. However, there is not only one combination that can be selected for the machine and the decision maker cannot be concerned only with the minimization of energy consumption but with the other objectives such as production time and cost of production, etc. also need to be considered. It is not meaningful if the carbon footprint can be reduced but the other manufacturing performance cannot be maintained. Therefore, it is important to apply the optimization method with several objectives to the integrated model. The machining operation with energy efficiency and the proper resources can be provided as an optimal result after the optimization method is accomplished.

(3) Waste minimization at machine level: This is the final step at machine level regarding the conceptual model when energy efficiency and resource utilization are already determined respectively. All causes that can waste energy and the carbon footprint from the machine must be considered such as idle time, break down time, tool life and operator error etc. Therefore, the history or record of waste that relate to the optimal solution (scenario) from the previous section must be prepared. In order to complete at this stage, the author uses the discrete event simulation method to observe waste that occurs during the manufacturing process and calculate the total waste of the carbon footprint. From the simulation results, the preventive plan is possibly planed in advance to eliminate the waste of carbon footprint. Therefore, the decision maker can choose the optimal solution with a preventive plan which eventually refers to low carbon manufacturing machine level.

(4) Understanding the system flow of the considered shop-floor: This stage is going deeper in terms of complexity as it is a higher level of the manufacturing system. There is not only one machine to be considered like at machine level but there are many machines located in different places regarding to the shop-floor layout. In an everyday situation, there could be many types of workpiece or product that are required to be machined on the shop-floor. Some products can be machined with any machines while some products need a specific group of machines. In addition, different products have different process sequences. With these details, it is obvious that all information related to the considered shop-floor such as machine capacity, objective requirements, process chain details, lists of machines and products, cycle time, maintenance down time, shift assignment for worker and product arrival time etc. must be prepared for the decision maker.

(5) Optimization for energy efficiency and resource utilization at shop-floor level: According to the details from the previous section, the optimization model for the operation plan must be established at this stage. This step is similar to the second step when objectives and goals are concerned with the formulation of the optimization model. In the real world, there is normally more than one goal or objective that must be satisfied at the same time per planning. So, the establishment of a multi objective operational model which is subjected to all system constraints is very important at this step. For the evaluation of

energy consumption from the machining process, all machines in the system have used the methodologies in the second step of the machine level. So, the data of energy consumption can be prepared by this way. The work assignment plan and proper selected resource (machine, cutting tool and operator) with energy efficiency can be provided after the optimal solution is obtained. All machines can also be operated with optimal setting when the machine level was applied with the proposed model before. This is the advantage of allying the systematic approach.

(6) Waste minimization at shop-floor level: Even though, the optimal solution from the optimization method returns the used of energy efficiency regarding the results, the real energy consumption and carbon footprint might be higher than the level it should be. This is also similar to the case at machine level. However, the number of machines on the shop-floor is too many compared to the machine level (only one). This means the amount of waste energy consumption and carbon footprint must be much more as well and the optimal solution will not be meaningful. Hence, the process for waste minimization is also important at shop-floor level. The author uses the same technique as described in the third step. More numerical examples will be presented in the applications and discussion section.

5.6 EREE-based LCM at the machine level

5.6.1 The cutting force system

In the machining process, the relationship between the cutting force system and chip load is often mentioned. In Fig. 5.7, it depicts the conventional dynamic end milling cutting force prediction model and its relationship in the form of a feedback control diagram. The cutting force system can be expressed in the function of the contact area between the end mill and workpiece (chip load). A model for chip load determination is formulated as a function of process geometry.

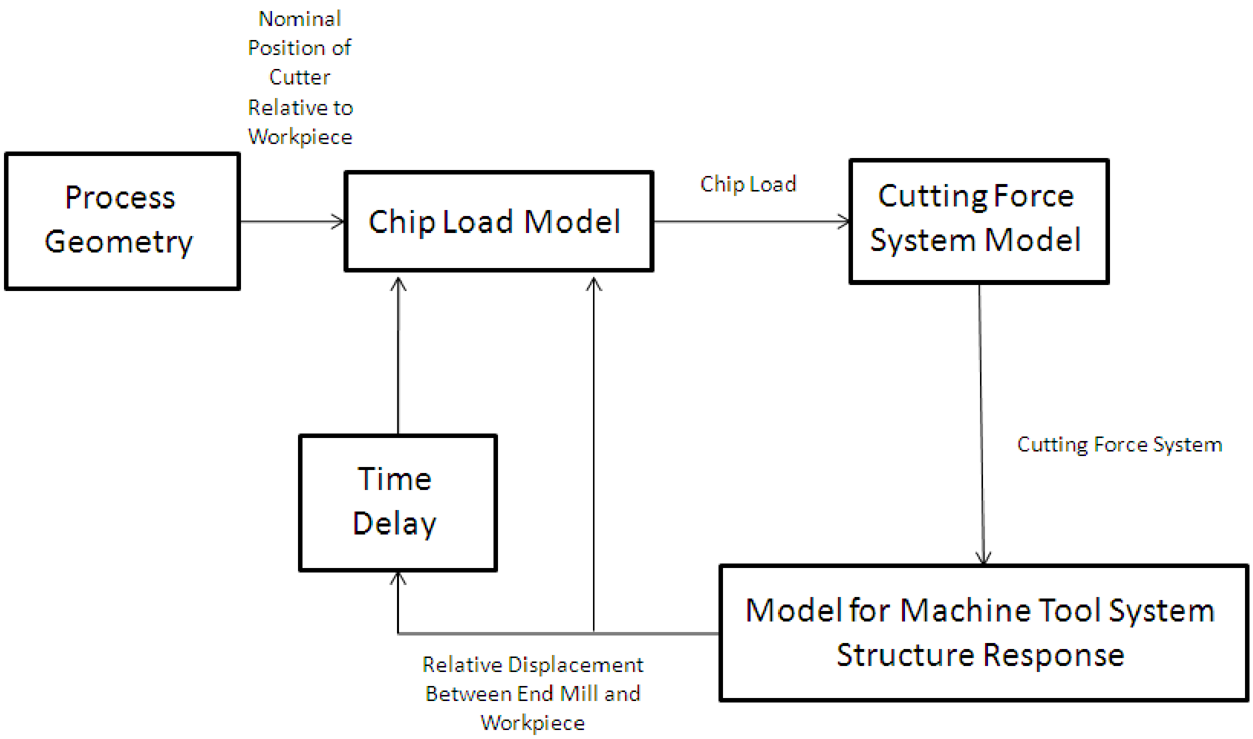


Fig. 5.7 The conventional dynamic end milling cutting force prediction model (Sutherland 1998)

5.6.1.1 Cutting force model

Many research works have investigated the nature of cutting forces in metal cutting operations. Fig. 5.8 represents the simple configuration of the cutting forces applied to a flute on the end mill. It is assumed that the cutting forces are proportional to the contact area between the flute and the workpiece according to (Kline 1982; Kline 1983; Sutherland 1998). With this assumption, the cutting forces at tangential and radial direction can be expressed in Equations 5.11 and 5.12 logically.

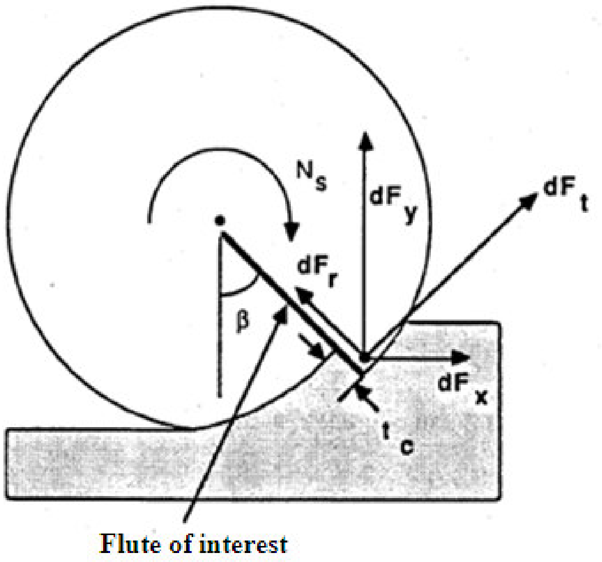


Fig. 5.8 The elemental cutting forces applied to a flute on the end mill (Sutherland 1998)

$$dF_t(i,j, k) = K_tA_c(i, j, k) \qquad (5.11)$$

$$dF_r(i, j,k) = K_rdF_t(i, j, k) \qquad (5.12)$$

where $dF_t(i, j, k)$ is the elemental tangential force

$dF_r(i, j, k)$ is the elemental radial force

$A_c(i, j, k) = t_c(i, j, k)\ dz$, is the contact area or chip load

$t_c(i, j, k)$ is the uncut chip thickness

K_t and K_r are empirically determined functions

5.6.1.2 Chip load model

Obviously, it is essential that knowledge of the contact area between the end mill and the workpiece is critical for the determination of cutting forces. For an axial element, the required knowledge can be referred to the uncut chip thickness, t_c. In order to examine the effect of the cutting process regarding cutter movement on the chip thickness, the formulation for chip thickness can be described as:

$$t_c(i, j, k) = f_t\sin\beta(i, j, k) \qquad (5.13)$$

where $f_t = V_f/(N_s\ N_f)$, is the feed per tooth

V_f = feed rate (inches/min or mm/min)

N_s = spindle speed (RPM)

N_f = number of teeth (inches/mm)

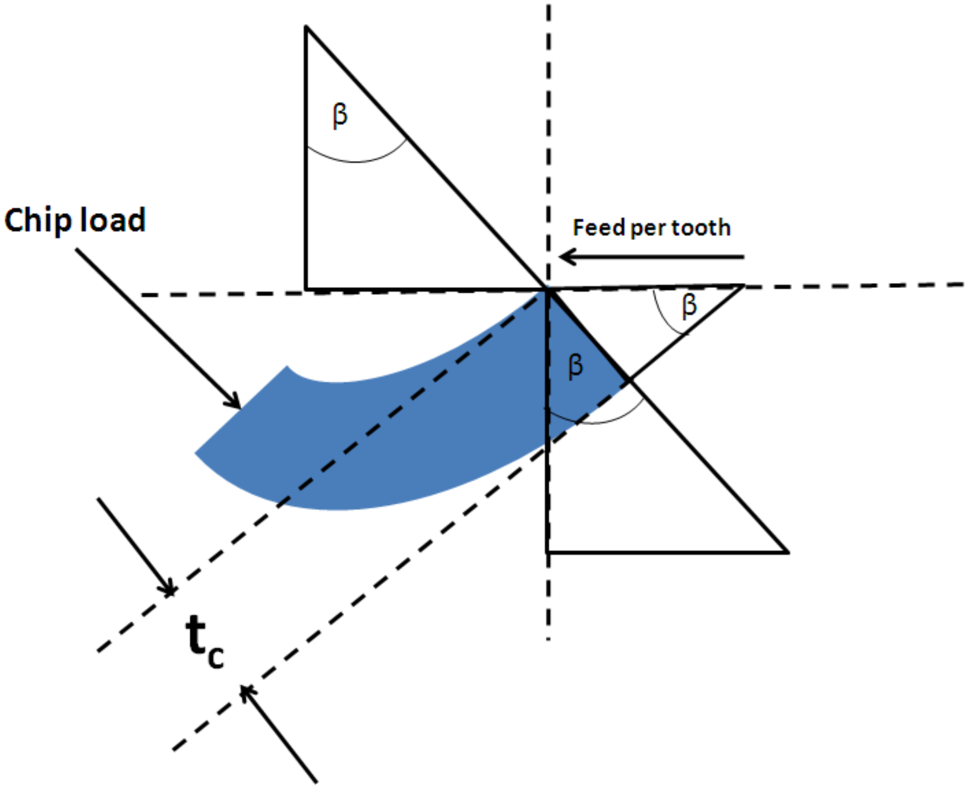


Fig. 5.9 The thickness of chip load formation

This chip model was developed by Martellotti (Martellotti 1945). The value of chip thickness can be found from Equation 5.8 under the conditions that the tooth path is spherical, no runout is present and the interested system is not interfered with.

5.6.2 Energy consumption model for the conventional motor

In a conventional electrical motor, the related power can be divided into input power and output power. The amount of electrical consumption (electrical power/input) is transformed into mechanical power (output). In Fig. 5.10, it represents the configuration of a conventional AC motor as described in previous details. The energy consumption or power input can be illustrated as a function of voltage (V) and current (I) in Equations 5.14 and 5.15. In addition, Equation 5.14 represents the simple form of electrical power formulation while Equation 5.15 depicts the real time formulation as referenced theory applied in a measurement device. It includes the term of wave form (angle) into the function.

$$P(t) = V(t) \cdot I(t) \tag{5.14}$$

$$P = \sum_{k=1}^{50} V_k \times I_k \cos(\varphi_k) \tag{5.15}$$

Where P = power (watt)

V = voltage (volt)

I = current (amp)

φ = angle of the wave form

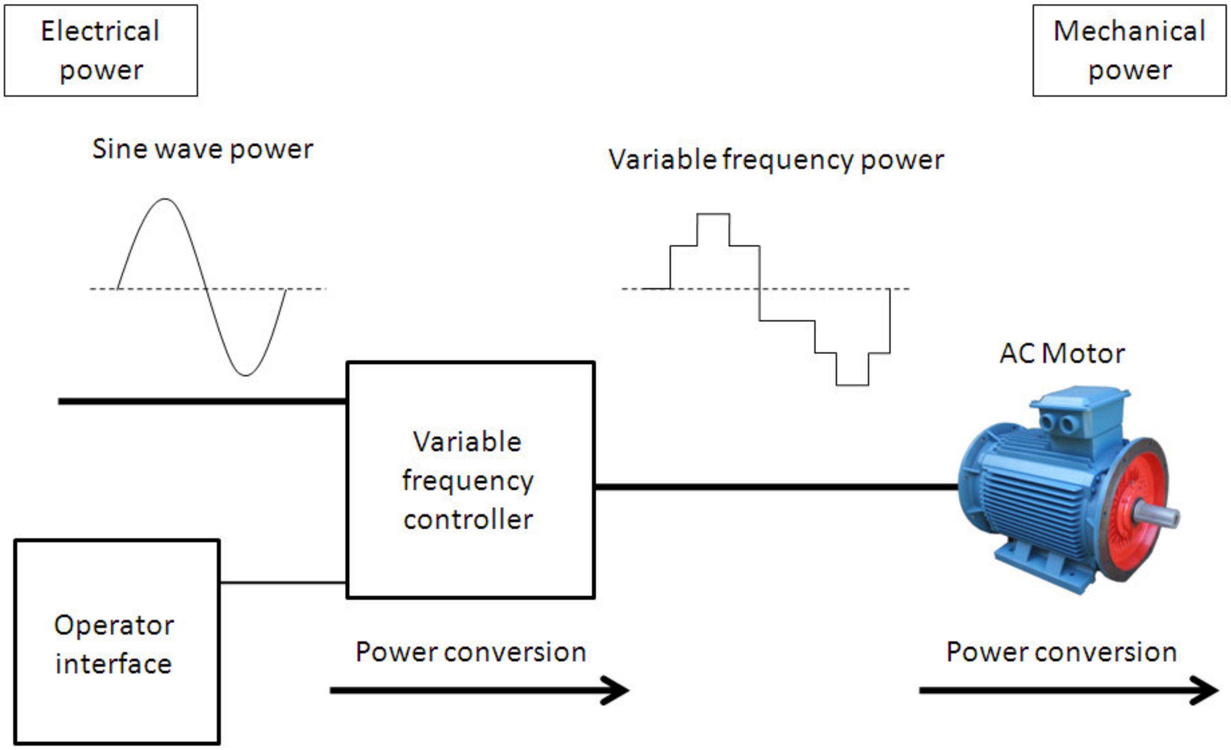


Fig. 5.10 The configuration of conventional AC motor

According to the term of mechanical power, it is related as a function of work performed during the period of time as described in Equation 5.16 or it can be decomposed into the function related to activated force in Equation 5.17. Due to the mechanical process of the conventional motor which is related to the rotational speed and the force performed on the axis, the function of mechanical power, therefore, can be expressed in terms of torque and rotational speed at the during of time as depicted in Equation 5.17.

$$P = \frac{W}{T} = \frac{F \times R}{T} \tag{5.16}$$

$$P = \frac{\left(\frac{\tau}{r}\right) \times (r \times \emptyset V \times t)}{t} = \tau \times 2\pi \times RPM \tag{5.17}$$

where P = power (W)

W = work (N·m)

F = force (N)

R = r = distance (m)

T = time (sec)

τ = torque (N·M)

$\emptyset V$ = angular speed (ω)

RPM = rotational speed (RPM)

From equations and theories derived in the previous section, the chip thickness is immediately increased when the feed rate is increased according to the function expressed in Equation 5.13. On the other hand, it can be implied from the cutting force model that the tangential force performed on the workpiece is also proportionally increased when the feed rate is increased because the tangential force proportionally varies to the chip area (t_c(i, j ,k)·dz) as discussed by (Lai 2000). This term can be expressed in Equation 5.18. From this relationship between the cutting force and feed rate, the energy output of the motor is also increased when the feed rate is increased. Hence, it can be concluded that the energy output of the motor can be varied due to the set-up of the feed rate and spindle speed as described in Equation 5.19.

$$dF_x(i,j,k) \propto V_f \tag{5.18}$$

$$P \propto (V_f, RPM) \tag{5.19}$$

In Fig. 5.11 and fig. 5.12, the energy consumption data from cutting trials using the commercial CNC turning machine are presented. It is obvious that the energy input (electrical energy) is increased when the machine parameters including spindle speed, feed rate and depth of cut are increased. In addition, it can be implied that the energy input is proportional with the energy output. Therefore, the relationship between machining parameters and the amount of energy consumption can be expressed in Equation 5.20.

$$P_{input} \propto P_{output} \propto (V_f, RPM) \tag{5.20}$$

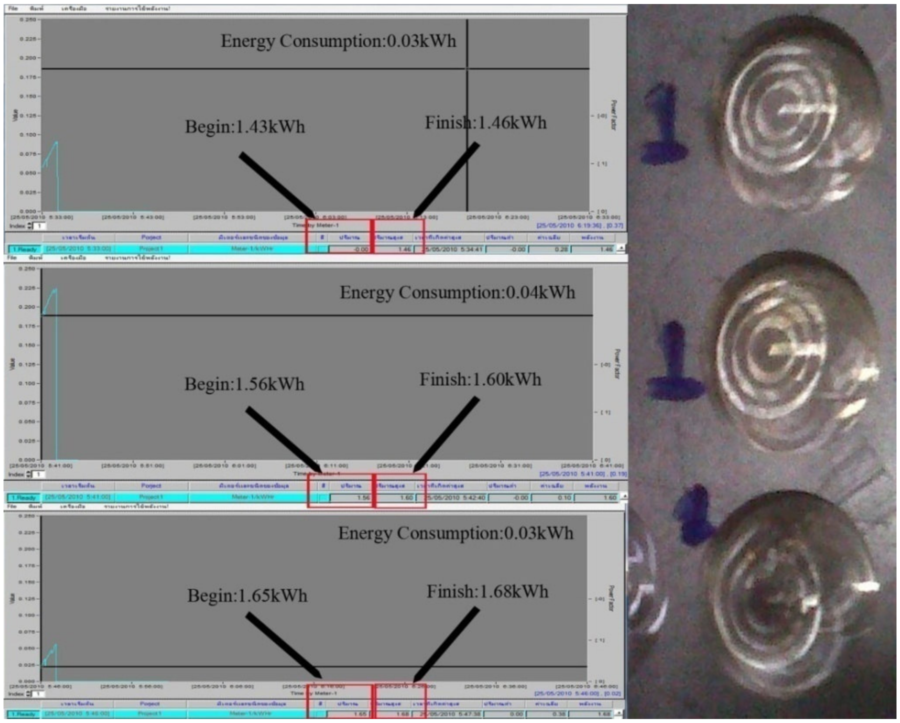


Fig. 5.11 Cutting trial under the conditions: 2500 rpm, 1000 mm/min and 1 mm

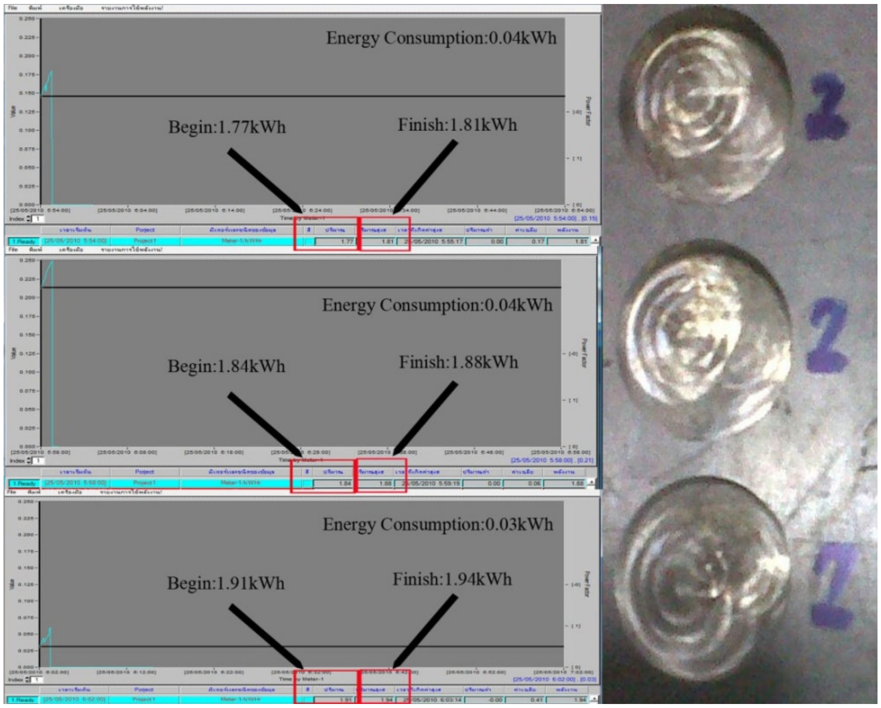


Fig. 5.12 Cutting trial under the conditions: 4166 rpm, 1666.4 mm/min and 1 mm

5.6.3 Modelling and application for machine level

In the experimental design, the Taguchi method is widely used because it can provide the level of factor on the response. This advantage can also provide the optimized factor (Taguchi 1987; Taguchi 2000; Taguchi 2005). However, schism arises when many researchers found that this technique can optimize with only one objective (Tarng 1998; Lin 2000; Antony 2001; Jeyapaul 2005; Gaitonde 2008). In 1989, Deng proposed the method called grey relational analysis which can cope with uncertain systematic problems (Deng 1989). This method was successfully applied to eliminate the conflict between objectives by Lin and Tang (Lin 1998). Lin then developed the new technique called grey-fuzzy logic base by integrating grey relation analysis with the fuzzy logic (Lin 2005). In addition, fuzzy logic is proven as the technique for dealing with uncertain information (Zadeh 1965). In the research concerned with energy criteria, Ahilan (2009) was successful in applying grey-fuzzy logic to optimize machining parameters (cutting speed, feed rate, depth of cut) on a turning machine when objectives are energy consumption at a specific point (kW/kJ per sec) and the material removal rate (MRR) (Ahilan 2009). Moreover, fuzzy logic is also successful in terms of forecasting and assessment aspects in manufacturing. For example, Lau (2008) applied fuzzy logic to forecast a manufacturing system while Deweiri

(2003) used fuzzy logic to generate surface roughness in the milling process (Dweiri 2003; Lau 2008).

Whilst the grey-fuzzy reasoning grade method is successful in different manufacturing processes (Lin 1998; Lin 2005), the ability to predict and optimize the input parameters which exclude from experimental results is limited. For example, the experiment runs with two levels of depth of cut (1mm and 3mm) on the cutting trial. The grey-fuzzy reasoning grade can only select these two values for the optimization process. Therefore, the development of the effective system which can also predict the total energy consumption together with the optimization process is necessary for flexible planning on CNC machining.

In this section, the developed model for EREE-based LCM for the machine level is proposed. The model aims to provide optimal machine operations with energy efficiency, proper resource utilization and waste minimization for the decision maker. The model is illustrated in Fig. 5.13. The model begins with the evaluation of energy consumption when cutter parameters and selected resources are prepared. Then, the optimization model seeks the optimal combinations of machine set-up that can compromise with all desired objectives based on the optimized rules. Finally, the related waste data is provided for the optimal machine set-up. The simulation can be used to prevent waste occurring after the selected machining set-up was used.

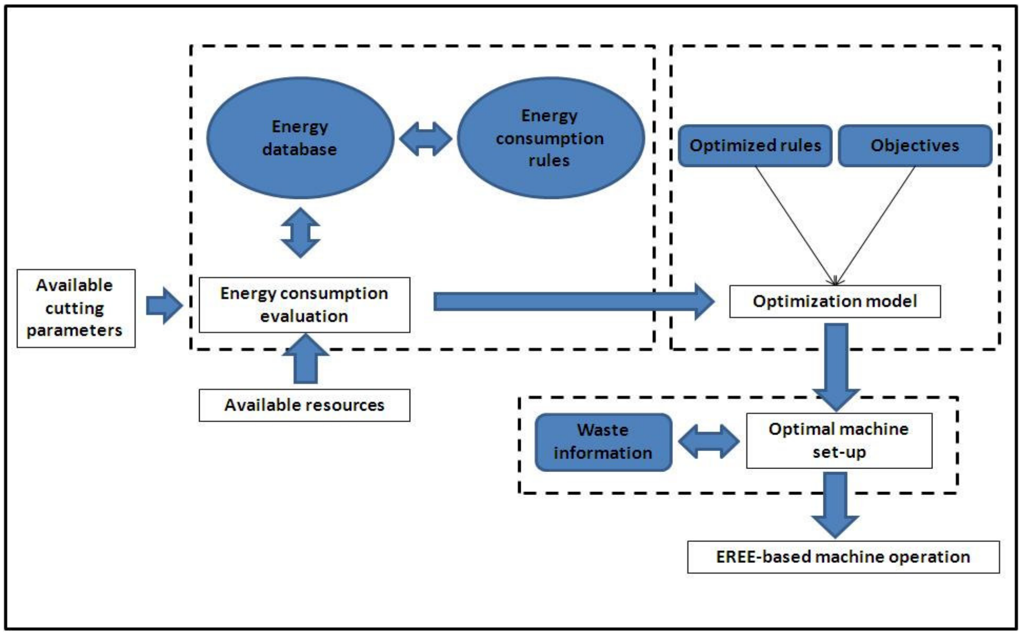


Fig. 5.13 EREE-based LCM for machine level

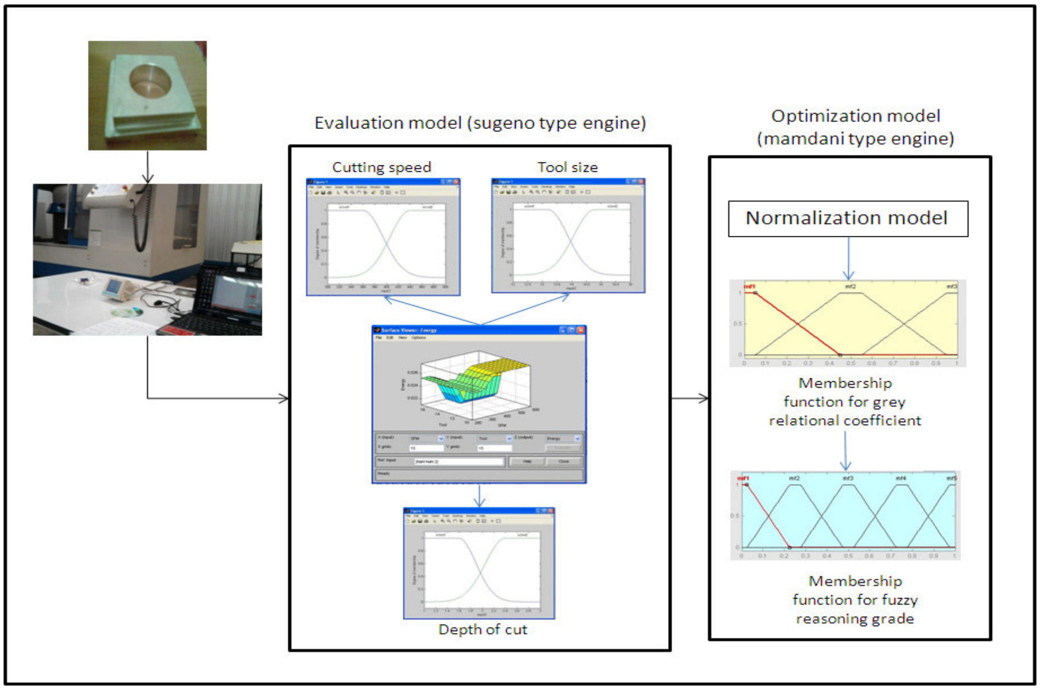


Fig. 5.14 EREE model at machine level performing in aluminum cutting trial

Fig. 5.14 presents the EREE based LCM at machine level applied to the milling process trials on aluminum. To determine the optimal machining strategy conducting the EREE concept, the evaluation system of energy consumption is established as the knowledge based system.

The fuzzy logic theory is applied by training with the experimental data (energy consumption). In addition, the experimental data is obtained from the data acquisition device (power logger) to create membership functions of the input variable and determination rules (fuzzy rules), while the optimization model is formulated using the grey reasoning based fuzzy logic technique. In this part, the theory of fuzzy logic is also used but the different type of processing engine is applied instead. The model is not only designed to minimize energy consumption from the cutting process but it has the ability to support multi objective problems. The prediction value from the first process is transformed by a normalization method before determining by fuzzy rules and fuzzy membership function. The normalization process is illustrated by equations 5.21, 5.22 and 5.23. The pre data processing values from the normalization stage, then, are evaluated for reasoning grade ranking by the final membership function. Finally, the optimization of machining strategy involving energy efficiency, resource optimization and other objectives satisfaction is clarified by using the taguchi method. The weights of each decision variable are provided.

Grey relational coefficient

The concept of grey relational coefficient is used to cope with the conflict between objectives when several objectives have to be resolved in the same situation. First of all, the data from each objective is normalized in the range between 0 to 1. In this research, the data linear preprocessing method is used to normalize the data (Haq 2008). The equation applied to the group of data is dependent on the characteristic of the data. The equations are illustrated as

The larger, the better

$$X_i(k) = \frac{N_{i(k)} - minN_i(k)}{maxN_i(k) - minN_i(k)} \tag{5.21}$$

The smaller, the better

$$X_i(k) = \frac{maxN_i(k) - N_i(k)}{maxN_i(k) - minN_i(k)} \tag{5.22}$$

where: $X_i(k)$ = value of the data preprocessing

After all data was normalized, theses values are calculated for grey the relational coefficient using the following equation

$$Y_{ij} = \frac{\Delta \min + \delta\Delta max}{\Delta_{oj}(k) + \delta\Delta max} \tag{5.23}$$

where; Y_{ij} = relational grade coefficient

$\Delta \min = \min_{\forall j \in i} \min_{\forall k} \left\| y_0(k) - y_j(k) \right\|$ is the minimum value of $Y_j(k)$

$\Delta \max = \max_{\forall j \in i} \max_{\forall k} \left\| y_0(k) - y_j(k) \right\|$ is the maximum value of $Y_j(k)$

$\Delta_{oj} = \left\| y_0(k) - y_j(k) \right\|$ is the absolute value between $Y_o(k) and\ Y_j(k)$

δ = the distinguishing coefficient (0 ≤ δ ≤ 1)

j = 1, 2,…, n: k = 1, 2,…, m n is the number of experimental data, m is the number of the response

The experiment is conducted on aluminum. The shape of the workpiece is designed as a circle with 10 mm diameter and 10 mm depth. Each cutting sequence is repeated three times in order to collect the total energy consumption (kWh) per cutting trial. Therefore, the total number of cutting trials is (8) × (3) = 24 workpieces. This set of experiments uses an aluminum plate (x: 210mm, y: 251mm) to take all cutting trials. Fig. 5.15 represents the cutting trials of one circle on the aluminum plate. In each cycle of the cutting process, the measurement device will record the data at the beginning and the end of the process from the user interface controller. In Fig. 5.16, the overall perspective of the software interface is expressed. The value of energy consumption, voltage and current from each phase used in the cutting process can be real time monitored and recorded (sec).

Fig. 5.15 The cutting trials of one circle on the aluminum plate

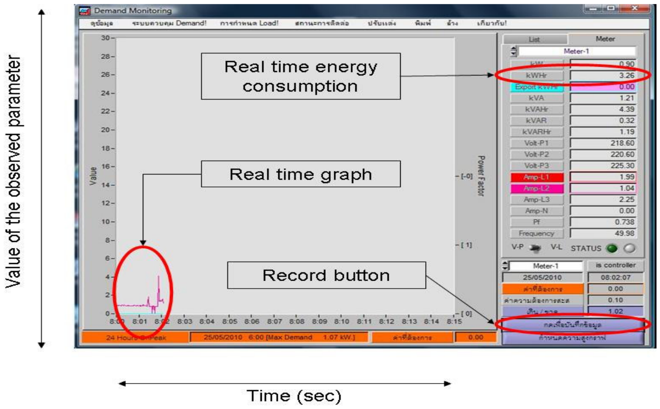


Fig. 5.16 The user interface for the measurement device

Cutting process	Milling
Workpiece material	Aluminum
Workpiece dimension	Ø 10 mm, depth 10 mm
Number of set-up combination	8
Cutting speed	91 m/min, 152 m/min
Tool size	Ø12 mm, Ø16 mm
Depth of cut	1mm, 3mm

Table 5.6 Parameters used in cutting trials for recording energy consumption

The advantages of combining the sugeno and mamdani type fuzzy logic in the context of EREE-based LCM at machine level are:

(1) The modelling and simulation can cover a flexible range of input variables including machining setup parameters (cutting speed and depth of cut) and resource allocation (tool size). The amount of process energy consumption as regards to input variables is simulated based on trained functions.

(2) The application of grey based fuzzy logic with the taguchi method within the system is able to eliminate the conflict between the minimization of energy consumption and all other objective functions as multi-objective optimization.

(3) The combination of sergeno and mamdani type fuzzy logic can integrate the automated function formulation and adjustable function based in the same system. On the other hand, it can be illustrated that the optimal machining strategy, as a final output of the system, is dependent on the experimental based modelling (sergino) and optimization of the normalization determination (mamdani).

The effect of considered machining parameters on the amount of energy consumption

Fig. 5.17 represents the energy consumption obtained from the first combination of the machining set-up (cutting speed: 122 m/min, tool size: Ø12 mm, depth of cut: 1 mm) while Fig. 5.18 shows the energy consumption from the second machining set-up using cutting speed: 152 m/min, tool size: Ø12 mm, depth of cut: 2mm). This data of the energy consumption during the cutting process is recorded in real time every second. The variation in energy consumption from the two different machining set-ups is presented in Table 5.7.

Machining set-up (cutting speed, tool size, depth of cut)	Recording periods (Hr/min/sec)	Energy consumption (kWh)	Differential energy consumption per second (kWh)
122 m/min, Ø12 mm, 1mm	10:11:00	0.505024	0.000219
	10:11:01	0.505243	
152 m/min, Ø12 mm, 2mm	10:34:00	0.854207	0.000221
	10:34:01	0.854428	

Table 5.7 The variation in energy consumption from different machining set-up

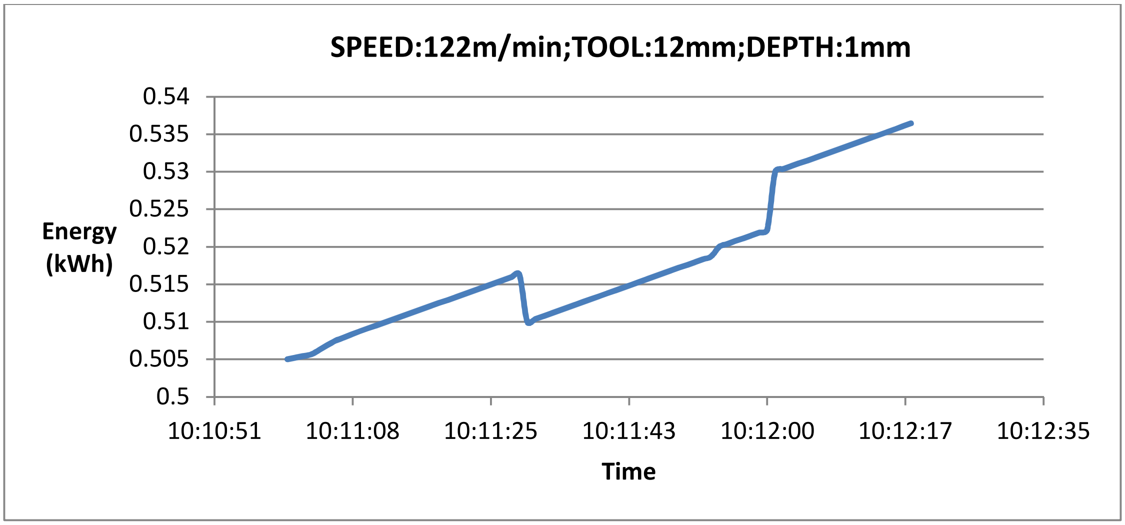


Fig. 5.17 Energy consumption under the cutting conditions: 122 m/min, Ø12 mm, 1mm

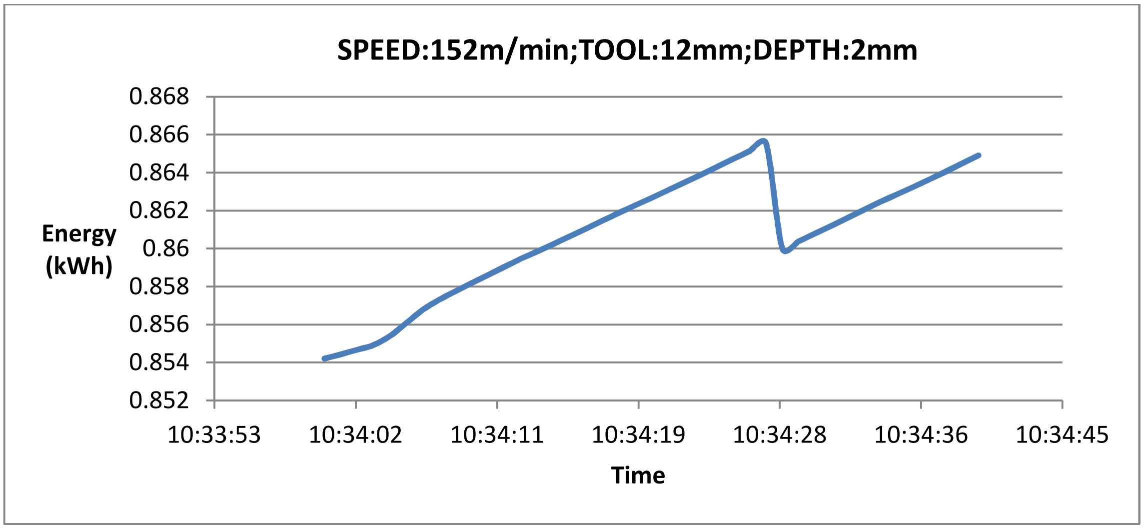


Fig. 5.18 Energy consumption under the cutting conditions: 152 m/min, Ø12 mm, 2mm

It can be seen that the amount of energy consumption used during the cutting process is increased when the input parameters are increased. The input energy per second is increased from 0.000219 kWh per second to 0.000221 kWh per second. From these experimental results, it can be found that the cutting trial results conform with the derived theory represented in Equation 5.20.

In Table 5.8, the simulation results of energy consumption using sergino type fuzzy logic and response surface methodology (RSM) are presented together with the experimental results. It is obvious that the simulation results from fuzzy logic have the same trend with experimental results while the outcome from RSM has error in some scenarios. The energy consumption from the first scenario must be less than the third scenario but MATLAB based RSM returns the same energy consumption. Therefore, it can be referred that the modelling of energy consumption evaluation based on machining set-up and resource allocation by applying sergeno type fuzzy logic is feasible. However, the precision of simulation results critically relies on the number of cutting trials according to the mechanism of trained function (more cutting trial results, more accurate).

Machining combination	Energy consumption from defuzzification (kWh)	Energy consumption from response surface (kWh)	Energy consumption from experiments (kWh)
152 m/min, Ø12 mm, 2mm	0.0231	0.025	0.010705
122 m/min, Ø16 mm, 1mm	0.032	0.03	0.022173
91 m/min, Ø16 mm, 2mm	0.0244	0.025	0.015664

Table 5.8 Simulation results from fuzzy logic and RSM comparing with experimental results

5.6.4 Environment of EREE-based LCM for energy efficiency and resource optimization

The architecture of the system constructed with two fuzzy inference engines: the role of the first is to evaluate total energy consumption (kWh) according to the machine parameter input while the second engine role can provide the grey-fuzzy reasoning grade between two objectives: energy consumption and cost preparation. With this method, the outcomes from this system are optimized machining parameters with energy efficiency and cost effectiveness. To provide the user with an effective and user-friendly interface for energy efficiency and optimization on the CNC milling machine, MATLAB graphic user interface (GUI) is used to receive the input data from the user which is then passed to the fuzzy inference engine.

In the system, the user can define machining parameters including cutting speed (m/min), tool size and depth of cut with three differential levels. The user can also edit the cost preparation for the cutting process based on the L9 orthogonal array. The system then provides the analysis of energy consumption from a combination of parameters and optimized machining.

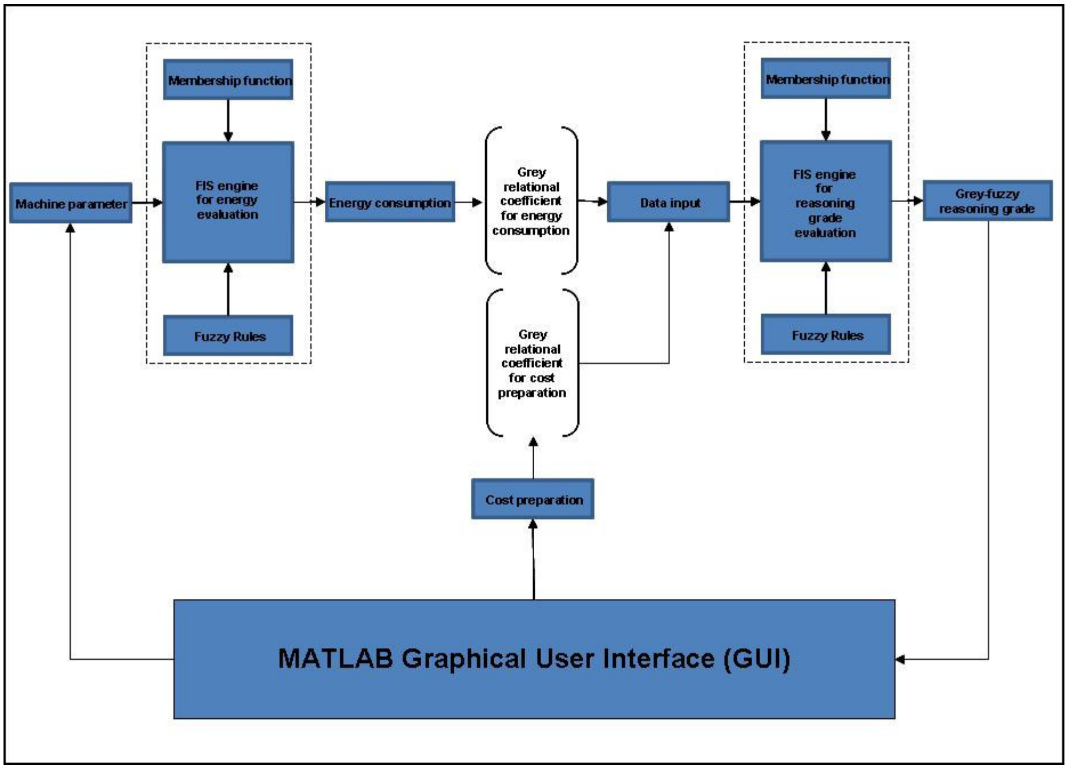


Fig. 5.19 Architecture of the optimization system

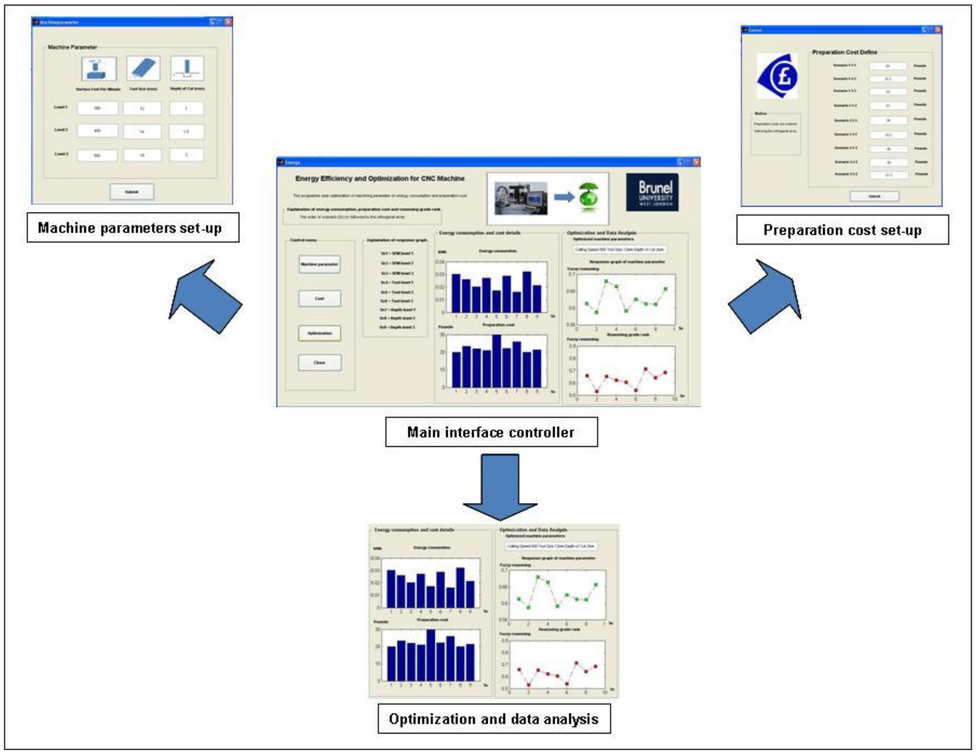
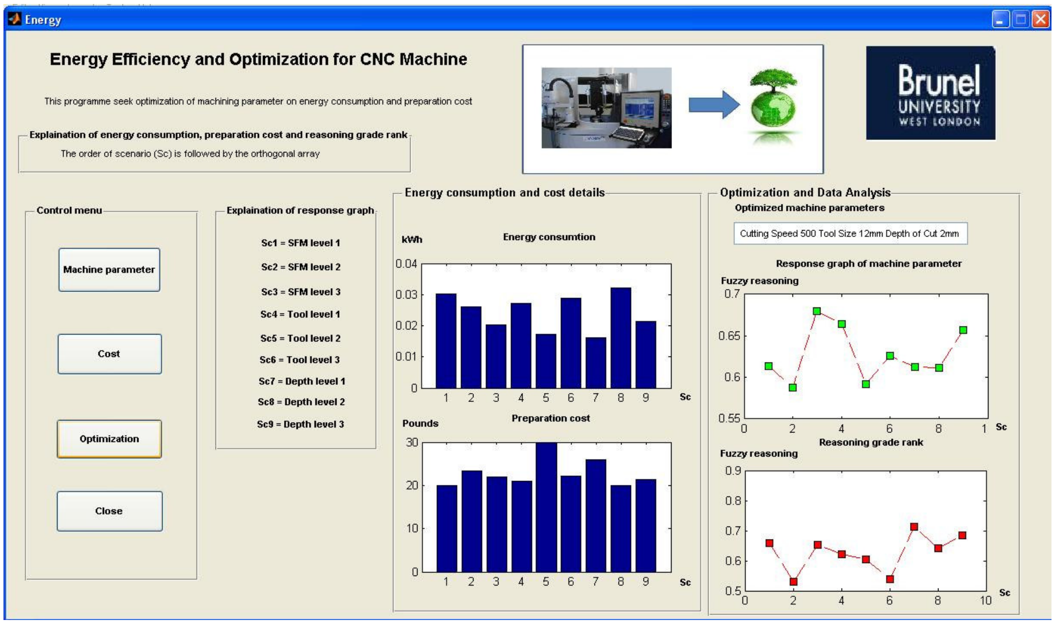


Fig. 5.20 The overall system perspective

The architecture of the energy efficiency and optimization system is illustrated in Fig. 5.19. In addition, the overall system perspective is illustrated in Fig.5.20. The machining parameters and cost preparation are passed from the user interface to the system. Machining parameters are used as input data at the first inference engine while the costs preparation data will be used only at the second engine. The first inference engine runs the defuzzification process with the membership function of machining parameters (cutting speed, tool, depth of cut and energy consumption) together with 8 fuzzy rules. The energy consumption from the first engine and costs preparation data are then transformed to grey relational coefficient in the form of a matrix. These matrixes are used as the input at the second inference engine. The environments of this engine are membership functions for reasoning grade (grey relational coefficient of energy consumption and costs preparation) and 27 fuzzy rules. The data analysis and optimized results can be obtained from the analysis section of the user interface.

The screen copy of the system main interface is illustrated in Fig. 5.21. It provides the user with the interactive set of functions to the system. These functions (buttons) are ordered as machine parameters, costs, optimization and close the system.

In the machine parameters set-up interface illustrated in Fig. 5.22, the user can define three different values of machining parameters including cutting speed, tool size and depth of cut. After the user submission (push submit button) these values are ordered into the array for energy consumption evaluation.



Energy

Energy Efficiency and Optimization for CNC Machine

This programme seek optimization of machining parameter on energy consumption and preparation cost

Explaination of energy consumption, preparation cost and reasoning grade rank

The order of scenario (Sc) is followed by the orthogonal array

Explaination of response graph

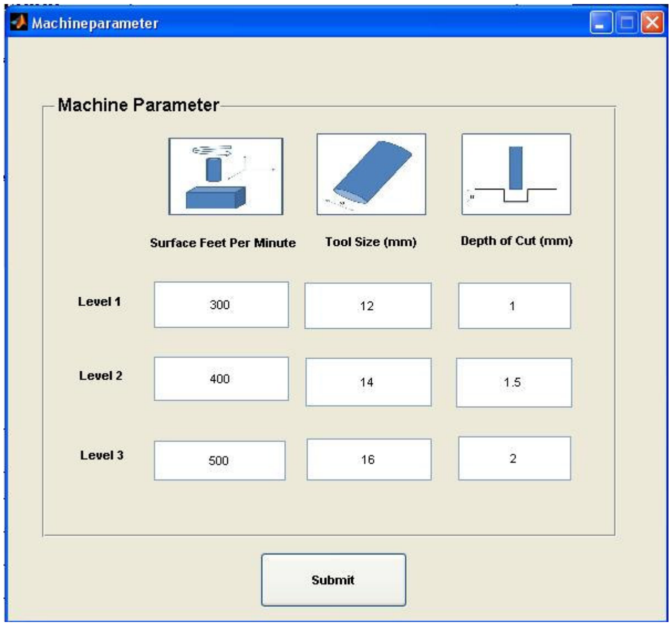
Sc1 = SFM level 1
Sc2 = SFM level 2
Sc3 = SFM level 3
Sc4 = Tool level 1
Sc5 = Tool level 2
Sc6 = Tool level 3
Sc7 = Depth level 1
Sc8 = Depth level 2
Sc9 = Depth level 3

Optimization and Data Analysis

Optimized machine parameters

Cutting Speed 500 Tool Size 12mm Depth of Cut 2mm

Fig. 5.21 The main interface of the energy efficiency and optimization system



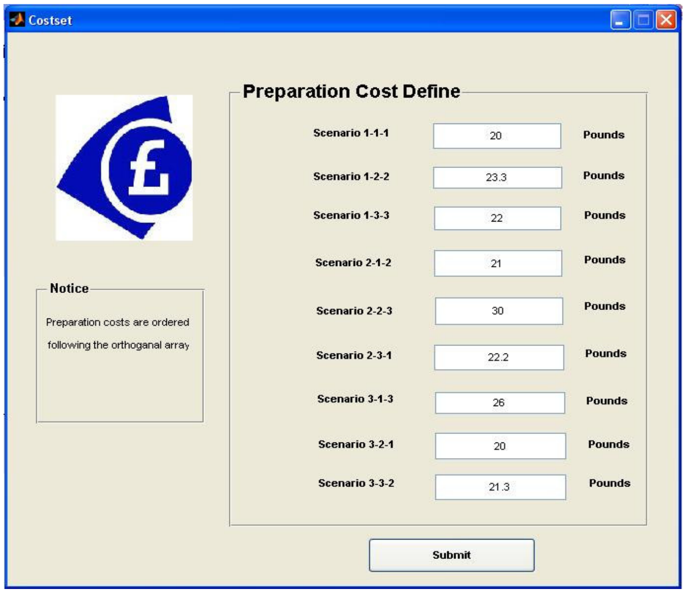
Machineparameter

Machine Parameter

	Surface Feet Per Minute	Tool Size (mm)	Depth of Cut (mm)
Level 1	300	12	1
Level 2	400	14	1.5
Level 3	500	16	2

Fig. 5.22 Machining parameters input interface

The costs preparation interface illustrated in Fig. 5.23 enables the user to edit the operation cost for each machining scenario ordered by the orthogonal array. To complete this part, its procedure is operated as the same as machine parameter set-up by clicking on the submit button. All values are then prepared into the array for calculating predata processing.



Preparation Cost Define

Scenario 1-1-1	20	Pounds
Scenario 1-2-2	23.3	Pounds
Scenario 1-3-3	22	Pounds
Scenario 2-1-2	21	Pounds
Scenario 2-2-3	30	Pounds
Scenario 2-3-1	22.2	Pounds
Scenario 3-1-3	26	Pounds
Scenario 3-2-1	20	Pounds
Scenario 3-3-2	21.3	Pounds

Notice

Preparation costs are ordered following the orthoganal array

Fig. 5.23 Costs preparation input interface

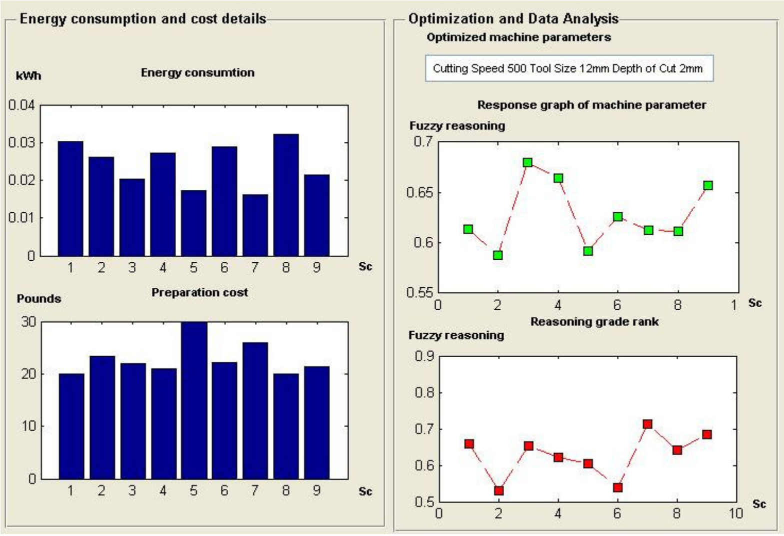
One example of the evaluation and optimization is illustrated in Fig. 5.24, in which the optimized machining parameters are calculated. The results are demonstrated in four steps as follows:

(1) The optimized machining parameters are presented in the first row of the optimization panel. This result corresponds to the response graph in this panel.

(2) The values of grey-fuzzy value of each cutting scenario ordering by the orthogonal array are displayed in the fuzzy reasoning graph at the bottom of the optimization panel.

(3) The values of total energy consumption for each cutting scenario are demonstrated in the energy consumption graph in the details panel.

The values of costs preparation for each scenario are displayed in the costs preparation graph in the details panel.



Cutting Speed 500 Tool Size 12mm Depth of Cut 2mm

Fig. 5.24 The evaluation and optimization results

5.7 Preparation of waste occurrence

After machine a machine combination was selected, the data of waste occurrence related to selected combination (previous breakdown/failure data and human error data) are required to prepare at this stage. As discussed in the first section of this chapter, there are many wastes that influence the total carbon emissions during the process. However, the data and record provided for the considered machine combination is not ready to be used as a preventive tool for waste elimination. In this research, the discrete event system simulation is used to cope with this problem. Thus, the transformation of the record of waste occurrence to data distribution form need to be done before the simulation process is applied (Harrell 2003). The procedure of preparation of waste occurrence is represented in Fig. 5.25.

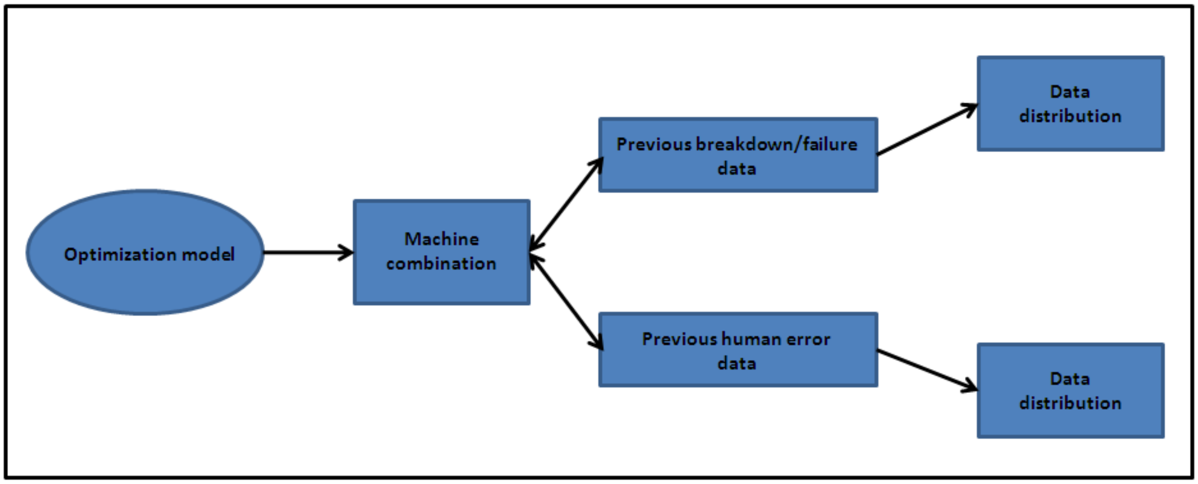


Fig. 5.25 Preparation of waste occurrence

To achieve data distribution of the relevant information, the pearson chi-square test, which is a statistical analysis technique, is used to determine the behavior of the data characteristics. The group of data is tested with the goodness of fit test by calculating chi-square distribution with expected distribution form and gain p-value. In 95% significant level, the null hypothesis is accepted when the p-value is higher than 0.05. In other word, the higher value of p-value, the more compatible with the expected distribution uniform. The application of preparation of waste occurrence will be presented in waste elimination and presentation of the shop-floor level. The equation used to gain chi-square distribution is expressed in Equation 5.24.

$$x^2 = \sum_{i=1}^{n} \frac{(O_i - E_i)^2}{E_i} \tag{5.24}$$

Where x^2 = Pearson’s cumulative test statistic

O_i = An observed frequency

E_i = An expected frequency

n = the number of cells (data) in the table

5.8 Implementation of waste minimization at the machine level

The implementation of discrete event simulation for waste minimization used in this research is performed by ProModel software. The uniform of data distribution presented in the previous section is entered into the machine. The simulation results can predict waste occurrences during the real time process. In this section, the simulation of machine break down at machine level is presented. The model layout presented in Fig. 5.26 consists of 3 elements: entity arrival location, machine and entity termination. Simulation parameters used as initial conditions are presented in Table 5.9. The simulation process finished after all entities were performed (20 entities). The simulation results expressed in Tables 5.10 and 5.11 depict that the percentage of down time is high because the production plan was performed without waste minimization (preventive plan). This clue can be referred to waste of energy consumption. In Fig. 5.27, the results in terms of time-weight value are presented. It is obvious that the appearances of failure are not constant regarding the selected form of data distribution. Thus, a preventive plan must be designed based on the prediction of waste occurrence in order to achieve low carbon emissions. The application of the preventive plan for waste minimization will be presented in the shop-floor level section because the main principle is the same.

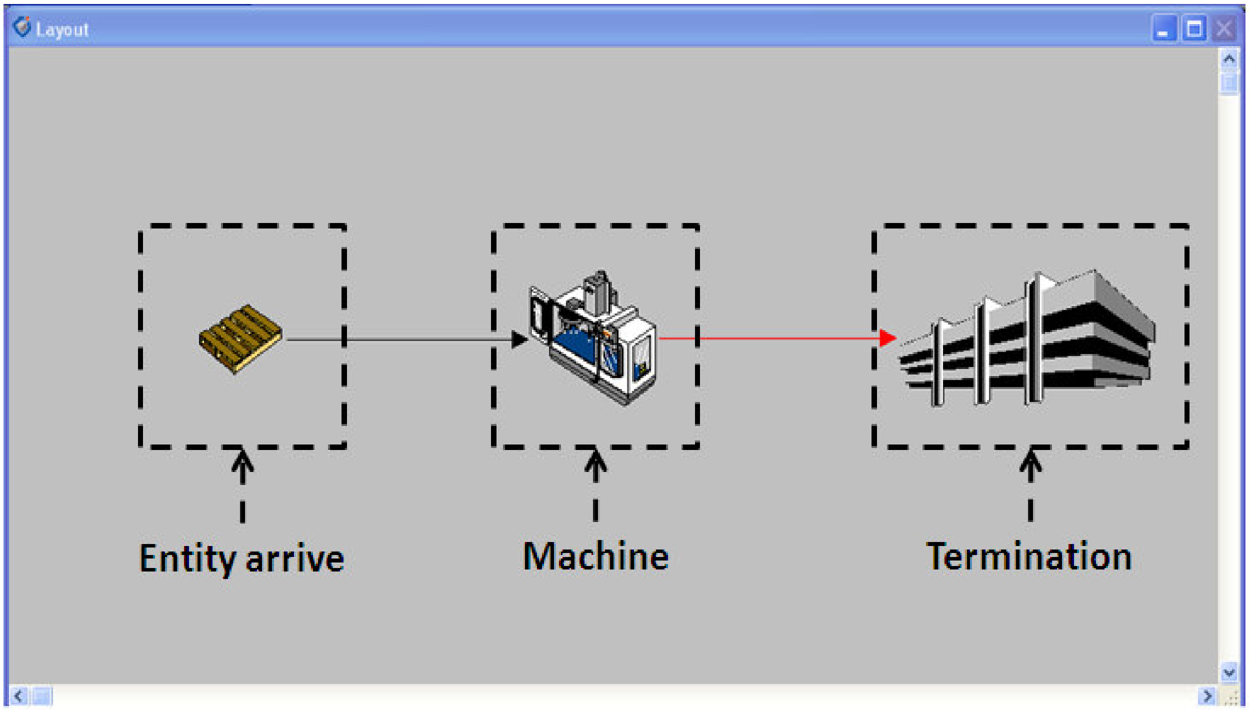


Fig.5.26 The model layout of waste minimization at machine level

Parameter setting	Value
Processing time	5 min
Distribution of down time	N(6,2)
Maintenance time	10 min
Inter arrival time of entity	10 min
Occurrence of entity	20

Table 5.9 Parameters for simulation set-up

Name	Scheduled Time (HR)	% Operation	% Setup	% Idle	% Waiting	% Blocked	% Down
Loc1	3.83	43.48	0	4.35	0	0	52.17

Table 5.10 Percentage of machine down time

Name	Scheduled Time (HR)	Capacity	Total Entries	Avg Time Per Entry (MIN)	Avg Contents	Maximum Contents	Current Contents	% Utilization
Loc1	3.83	1	20	5	0.434782609	1	0	43.47826087
Loc2	3.83	999999	20	12.5	1.086956522	3	0	1.09E-04
Loc3	3.83	999999	20	0	0	1	0	0

Table 5.11 Percentage of resource utilization

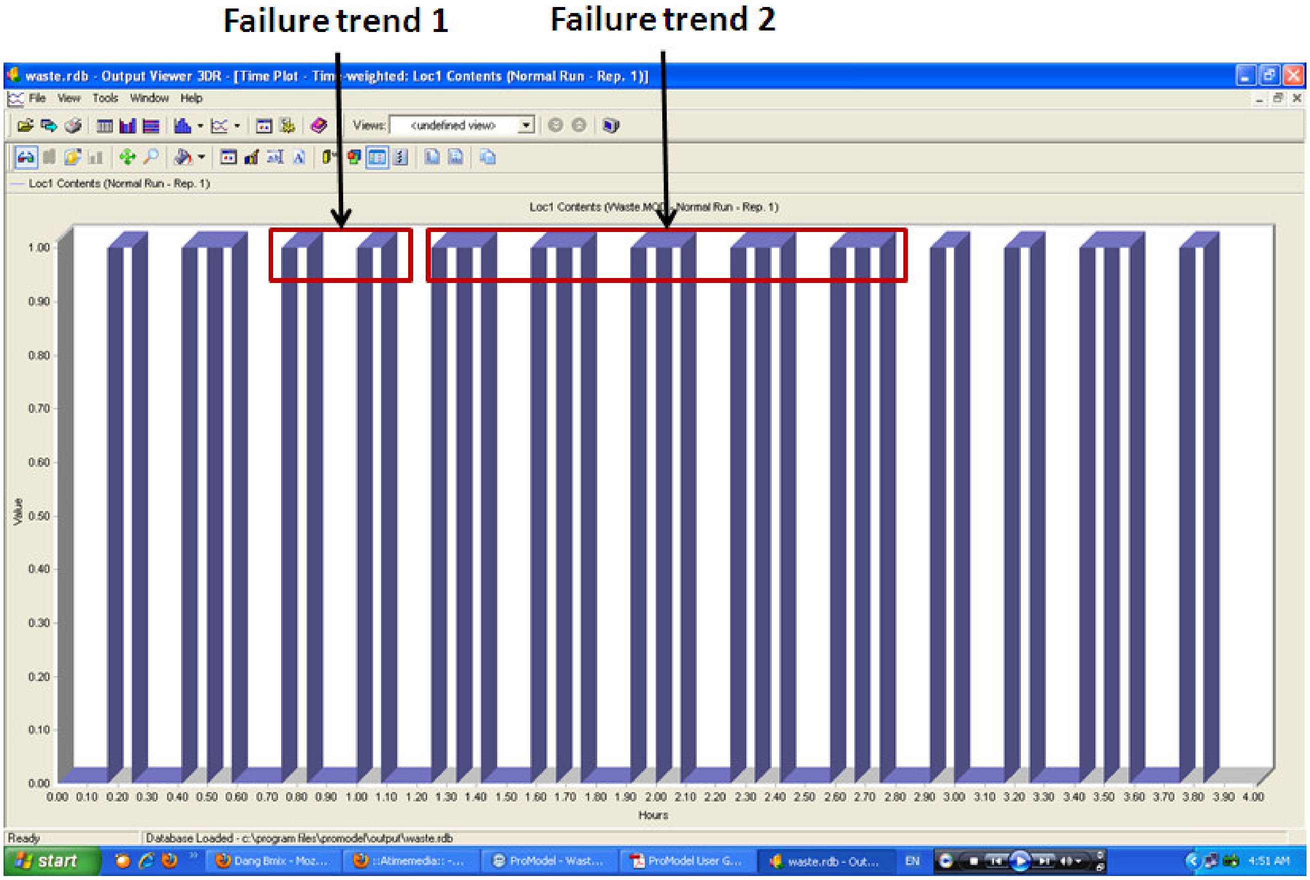


Fig. 5.27 Time weight value of machine down time

5.9 EREE-based LCM at shop-floor level

5.9.1 Modelling and application for shop-floor level

In conventional CNC manufacturing systems at shop-floor level, the determination of job-shop problem is a critical concern at this stage. The assignment of work order to machine and consideration of machine capacity are required to fulfill the conventional manufacturing performances. The different task assignment returns in different results regarding to objective functions of the considered system. From this reason, the selection of work scheduling which is integrated energy efficiency and resource utilization is obviously essential for EREE-based LCM at shop-floor level because different solutions also return in different total amount of energy consumption and carbon footprint.

In this section, the proposed model for the shop-floor level is applied to the conventional flexible manufacturing case study (CNC based manufacturing) to express the importance of optimization and simulation methods for low carbon manufacturing. Obviously, the value of profit, cost and production time are used as the key manufacturing performance. However, it is not enough for supporting the concept of sustainable manufacturing in the near future. Therefore, the key factor in the optimization method is to integrate the minimization of energy consumption as an objective. Here, the main goal is to determine the optimal of energy efficiency, resource utilization and waste minimization plan. Each machine can be provided work orders, turn on-off time, preventive maintenance required and operator analysis together with machining parameters and tools required. The model for shop-floor can be used after the model for machine level has been completed. The EREE-based LCM model for machine level is illustrated in Fig. 5.28.

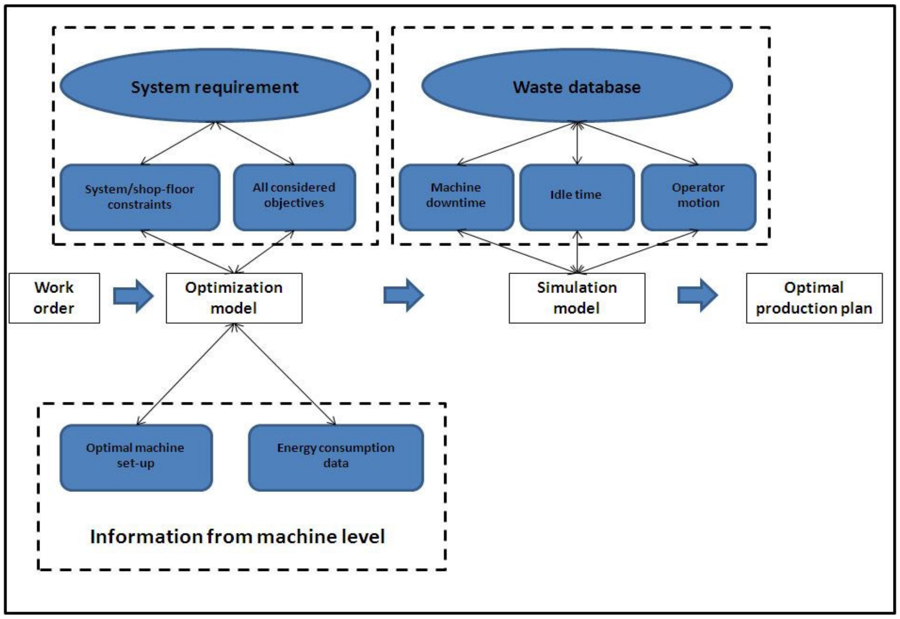


Fig. 5.28 EREE-based model for shop-floor level

5.9.2 The proposed concept for the development of optimization model at shop-floor level

As discussed in the previous section, a process can be performed by more than one machine and a machine may perform more than one task at a specific period in CNC based job-shop manufacturing. It can be implied that one process can be performed with alternative sets of machining combinations when more than one machine is available for a specific process. For instance, process 1 might be performed by a machining combination of cutting speed: 91 m/min, tool size: Ø12mm, depth of cut 1mm or cutting speed 152 m/min, tool size: Ø16mm, depth of cut: 3mm at machine A. Therefore, the determination of machining set-up and task assignment are crucially important for EREE-based LCM at shop-floor level because different machine set-ups require different amounts of energy consumption. The optimal machine set-up that a machine can provide for the relative process must be determined with the evaluation of energy consumption corresponding to the related machining set-up first. Then, the task assignment will be evaluated. In Table 5.12, the architecture of job-shop process is integrated with the proposed concept. The optimal machining set-up of product n performed on machine m ($COMB_{OPT/(n,m)}$) can be determined by the proposed modelling at machine level. The optimal set-up returns minimization of energy consumption and also satisfies all other objectives. Thus, task assignment in a job-shop system can be optimized when the best alternative solution is unveiled.

Machine Product	M_1	M_2	M_3	M_m	M_M
Product 1	$COMB_{(1,1)}$	$COMB_{(1,2)}$	$COMB_{(1,3)}$	$COMB_{(1,m)}$	$COMB_{(1,M)}$
Product 2	$COMB_{(2,1)}$	$COMB_{(2,2)}$	$COMB_{(2,3)}$	$COMB_{(2,m)}$	$COMB_{(2,M)}$
Product 3	$COMB_{(3,1)}$	$COMB_{(3,2)}$	$COMB_{(3,3)}$	$COMB_{(3,m)}$	$COMB_{(3,M)}$
Product n	$COMB_{(n,1)}$	$COMB_{(n,2)}$	$COMB_{(n,3)}$	$COMB_{(n,m)}$	$COMB_{(n,M)}$
Product N	$COMB_{(N,1)}$	$COMB_{(N,2)}$	$COMB_{(N,3)}$	$COMB_{(N,m)}$	$COMB_{(N,M)}$

Table 5.12 The conventional job-shop with machining optimization

$$\mathrm{COMB}_{/(n,m)} \propto \begin{bmatrix} COMB_{11} \\ COMB_{12} \\ COMB_{ij} \\ . \\ . \\ . \\ COMB_{IJ} \end{bmatrix} \tag{5.25}$$

$$\mathrm{COMB}_{nm} = f(r_{inm}, mc_{jnm}) \tag{5.26}$$

$$r_{inm} \epsilon R_{nm} \tag{5.27}$$

$$mc_{jnm} \epsilon M_{nm} \tag{5.28}$$

where

COMB_{nm} = selected machining combination for product n on machine m

r_{inm} = resource i used for product n on machine m

mc_{jnm} = machining condition j used for product n on machine m

$MC_{nm} = \{mc_{1nm}, mc_{2nm}, mc_{3nm},\ldots, mc_{jnm},\ldots, mc_{Jnm}\}$ = set of available machining conditions for performing product n on machine m

$R_{nm} = \{r_{1nm}, r_{2nm}, r_{3nm}, \ldots, r_{inm}, \ldots, r_{Inm}\}$ = set of available resource for performing product n on machine m

$P = \{1, 2, \ldots, n, \ldots, N\}$ = set of product $MA = \{1, 2, \ldots, m, \ldots, M\}$ = set of machine

$i \in \{1, 2, 3, \ldots, I\}, j \in \{1, 2, 3, \ldots, J\}$

On the other hand, the optimization of machining combination can be calculated from the vector of machining combination allocation as described in Equation 5.25. The size of the matrix (vector) depends on the number of alternative allocations while the machining combination can be illustrated in the form of the function between the machining conditions and resources as described in Equation 5.20. To define the pair-wise of machining combination, the same method applied for preparing an alternative solution at machine level is used (using taguchi method or response surface). It can be referred that the modelling of EREE-based at machine level is used to prepare information for product n performed on machine m. The example of initial information for EREE-based LCM at shop-floor level is illustrated in Tables 5.13 and 5.14.

Process / Machine	Workpiece									
	1			2		3			4	
	Process			Process		Process			Process	
	1	2	3	1	2	1	2	3	1	2
Machine: A	S:122 T:12 D:1	-	S:91 T:14 D:1.5	-	S:122 T:16 D:2	-	S:122 T:12 D:1	-	S:91 T:12 D:1	S:122 T:12 D:1
Machine: B	-	S:107 T:12 D:2	S:122 T:12 D:2	-	-	S:91 T:12 D:1	-	S:107 T:14 D:1.5	S:91 T:12 D:1.5	S:122 T:14 D:1.5
Machine: C	-	S:91 T:16 D:1	S:107 T:16 D:2	S:91 T:14 D:1.5	S:107 T:14 D:1.5	S:91 T:12 D:1	-	-	S:107 T:14 D:1.5	-
Machine: D	S:107 T:14 D:1.5	-	-	S:107 T:16 D:1	-	-	S:122 T:12 D:1.5	S:107 T:16 D:1.5	S:122 T:16 D:2	-

Table 5.13 Optimal machining set-up for shop-floor level provided by machine level modelling

Process	Workpiece									
	1			2		3			4	
	Process			Process		Process			Process	
Machine	1	2	3	1	2	1	2	3	1	2
Machine: A	2.2	-	2.5	-	3.2	-	2.8	-	2.3	2.5
Machine: B	-	4	3.8	-	-	4	-	3.9	3	3.3
Machine: C	-	1.8	2.9	2.8	3.5	3.1	-	-	2.7	-
Machine: D	3	-	-	1.7	-	-	2	2.5	1.9	-

Table 5.14 Energy consumption (kWh) for machining the workpiece

There are four machines and four workpieces in this job-shop process. Each workpiece has a different process and different machine that can perform on itself. It can be seen from Table 5.13 that workpiece 1 can be performed by machine A (using cutting speed: 122 m/min, tool size: Ø12 mm, depth of cut: 1mm, by consuming 2.2 kWh) and D (using cutting speed: 107 m/min, tool size: Ø14 mm, depth of cut: 1.5 mm by consuming 3 kWh). This information matrix can be established by using machine the level model.

5.9.3 Optimization method

According to the proposed concept in Chapter 4, it is obvious that the multi-objective optimization which is integrated minimization of energy consumption as an essential manufacturing performance is required to provide the optimal solution of manufacturing process. At machine level, the multi-objective can be completed by using grey based fuzzy logic with the taguchi method when normalization of primary data can be performed. However, the mechanism at shop-floor level is more complicated due to the considered operational process. For example, the details of the production process, machine allocation and availability (resource allocation), time limitation and maintenance conditions, etc. Thus, the modelling that has compatibility between objective functions and system constraints is crucially important for shop-floor level. Fuzzy linear programming with several objectives is an optimization method which is broadly used by many researchers to solve multi-objective problems. The fuzzy set theory is applied to transform the standard linear programming model (as illustrated in Equation 5.29) into fuzzy linear programming structure. To apply fuzzy set theory with linear programming, the terms of membership function described in Equations 5.30 and 5.31 are used. Critically, the elimination of conflict between objectives in fuzzy set theory is also an important part that must be mentioned in the modelling. The intersection between membership function values is applied as described in Equation 5.32. Finally, the final form of fuzzy linear programming is illustrated in Equation 5.33 (Zimmermann 1978).

$$OptZ = CX \tag{5.29}$$

$$s.t. AX \leq b$$

where: Z = vector of objective function

C, A and B = vector of constant value

X = vector of decision variable

Fuzzy maximization

$$V_1(f_1(x)) = \begin{cases} 1 & if\ f_1(x) > g_1 \\ \frac{f_1(x) - (g_1 - a_1^1)}{a_1^1} & if\ g_1 - a_1^1 \leq f_1(x) \leq g_1 \\ 0 & if\ f_1(x) < g_1 - a_1^1 \end{cases} \tag{5.30}$$

Fuzzy minimization

$$V_2(f_2(x)) = \begin{cases} 1 & if\ f_2(x) < g_2 \\ 1 - \frac{f_2(x) - g_2}{a_2^2} & if\ g_2 + a_2^2 \geq f_2(x) \geq g_2 \\ 0 & if\ f_2(x) > g_2 + a_2^2 \end{cases} \tag{5.31}$$

$$maxmin(V_1(f_1(x), V_2(f_2(x), \ldots.) \tag{5.32}$$

$$Max\ Min\ \lambda \tag{5.33}$$

$$s.t.\lambda \leq V_n(f_n(x))$$

$$h_i(x) \leq H_i(x)$$

$$0 \leq \lambda \leq 1$$

5.9.4 Optimization model

In the previous sections, the proposed concepts and supporting theory for achieving EREE-based LCM at shop-floor level are demonstrated. However, the optimization model in the real world problem depends on the details of the considered system/problem. Thus, problem descriptions or problem boundaries are required to be defined before generating the optimization model at shop-floor level. The model used in this research is based on the conventional model formulated by Mishra (2006).

Problem description

In the considered shop-floor layout, there is a cellular manufacturing layout (group technology) which has a group of non identical machines for machining part type or work pieces. The details and constraints are stated as follows:

(1) There are 4 types of product which have to be machined in each shift.

(2) There are 4 types of machine in the manufacturing cell.

(3) Each product has a different process sequence.

(4) Each process of a related product can be performed with only one machine.

(5) Each machine can perform more than one task in one shift.

(6) There are three objectives to be determined in this optimization problem: minimization of total production time, minimization of cost of production and minimization of total energy consumption.

Model formulation for optimization

Notation

w	workpiece type; $w \in \{1,2,\ldots,W\}$
m	machine type; $m \in \{1,2,\ldots,M\}$
o	operation for workpiece w; $o \in \{1,2,\ldots,O_W\}$
S_{wo}	set of machines that can perform operation o of workpiece w;
S_{mw}	set of workpieces that can perform on machine m;
S_{ow}	set of operations of workpieces that can perform on machine m;
X_{ijk}	operation j of workpiece i performed on machine k
C_{ijk}	set-up cost for operation j of workpiece i performed on machine k
T_{ijk}	production time used for operation j of workpiece i performed on machine k
E_{ijk}	energy consumption used for operation j of workpiece i performed on machine k
	function of total energy consumption
	function of total cost of operation
	function of total production time

Mathematical model

The optimization model is formulated into the form of fuzzy integer programming with several objectives. The details of system constraints and parameters described in the previous section are used in the mathematical model below:

Objective function

$$f_1(x) = \sum_{i=1}^{W}\sum_{j=1}^{O}\sum_{k=1}^{M} C_{ijk}\, x_{ijk} \tag{5.34}$$

$$f_2(x) = \sum_{i=1}^{W}\sum_{j=1}^{O}\sum_{k=1}^{M} T_{ijk}\, x_{ijk}$$

$$f_3(x) = \sum_{i=1}^{W}\sum_{j=1}^{O}\sum_{k=1}^{M} E_{ijk}\, x_{ijk}$$

Fuzzy integer programming for the case study

$$Max\ Min\ \lambda \tag{5.35}$$

s.t.

$$\lambda \leq V_1(f_1(x))$$

$$\lambda \leq V_2(f_2(x))$$

$$\lambda \leq V_3(f_3(x))$$

$$\sum_{k \in S_{wo}} x_{ijk} = 1 \quad , \forall\, i, j$$

$$\sum_{i \in S_{mw}} \sum_{j \in S_{ow}} x_{ijk} \geq 1 \quad , \forall k$$

$$0 \leq \lambda \leq 1$$

$$x_{ijk} \begin{cases} 1 \ if\ operation\ j\ of\ workpiece\ i\ perform\ on\ machine\ k \\ 0\ if\ else \end{cases}$$

5.9.5 Simulation model for waste elimination

As illustrated in Equation 5.14, it is obvious that the total energy consumption (input) can be illustrated in the function of time related to voltage (V) and current (A) input. Thus, it can be implied that the amount of total energy consumption is directly proportional to total production time as described in Equation 5.36. However, total production time in the real world situation not only includes production/processing time but also includes waste time which is referred to as an undesireable/unpredictable event such as idle time, maintenance down time and human error (as described in Equations 5.37-5.38). In other words, total energy consumption is not only proportional to production/processing time but also depends on waste time during the process. This relationship crucially affects the determination of optimal machining and production strategy because both the simulation and optimization of energy efficiency and resource utilization in both machine and shop-floor level are based on pure processing conditions which are not concerned with failure circumstances. Therefore, it is very important to prevent and eliminate waste in order to make the optimal solution more reliable. Discrete event system simulation which is normally used to simulate queuing systems can be used to cope with these requirements because it is a time based simulation. To establish a simulation model for waste elimination, the information of the processing time and waste time as data distribution is essential to integrate with system layout and process details. In Fig. 5.29, the input of the simulation model is the optimal solution from the optimization model while output is the optimal production strategy including a preventive plan.

$$E_{TOT} \propto T_{TOT} \tag{5.36}$$

$$T_{TOT} = f(T_p, T_w) \tag{5.37}$$

$$T_w = f(T_i, T_D, T_H) \tag{5.38}$$

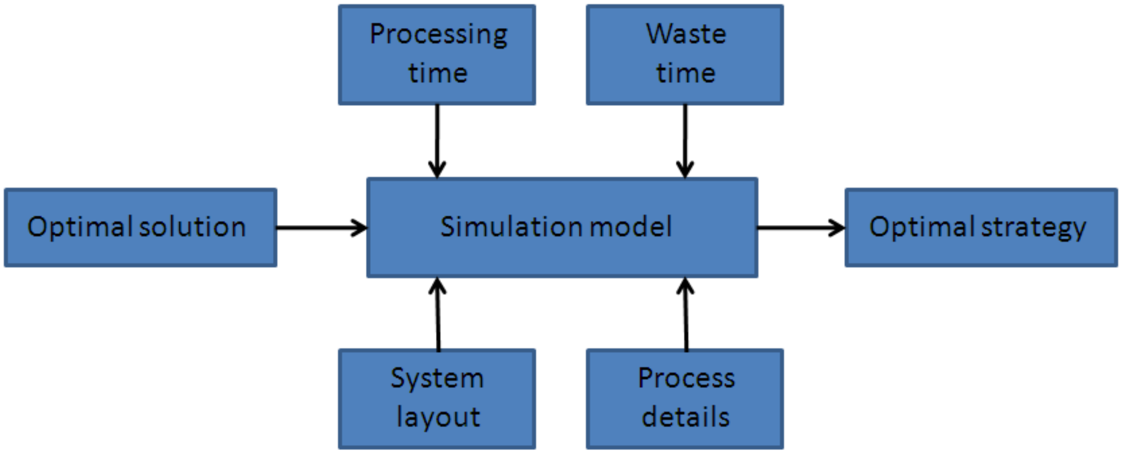
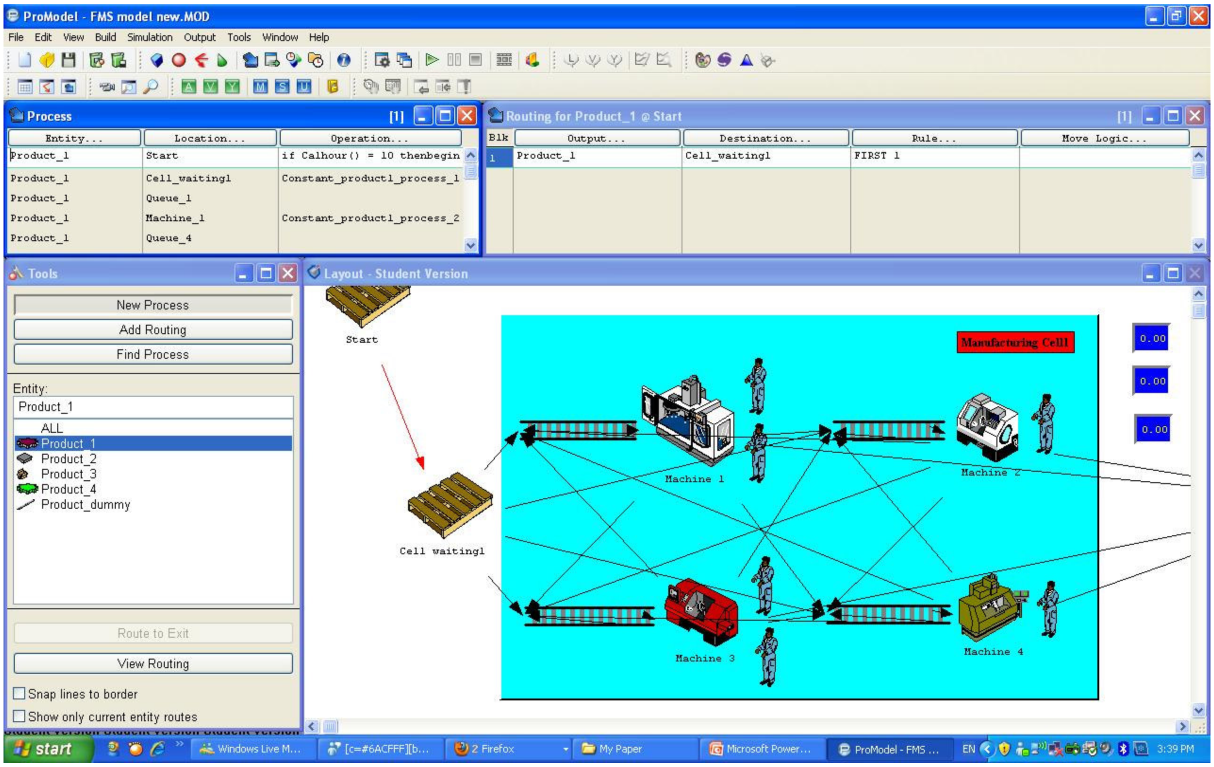


Fig. 5.29 Simulation model for waste energy elimination

5.9.5.1 The application of waste elimination model

Fig. 5.30 represents the simulation model constructed based on Equations 5.34 and 5.35. It is designed to simulate processing, idle, maintenance time and human error during the manufacturing process. In Table 5.15, the simulation results after running the model using optimization planning in Table 5.16 as an input are presented. It can be seen from the results that there is a large amount of waste energy which occurred from every machine in the system according to idle time, human error and maintenance down time. From this effect, the total carbon footprint during the manufacturing process becomes 20.512 kg CO_2 while the optimization result expects 13.18 kg CO_2 from the manufacturing process (optimization method is not concerned with a failure event). On the other hand, it can be depicted that the optimization result can't be relied on without confirmation with simulation method. To eliminate waste energy, the simulation results are transformed into a preventive plan as illustrated in Table 5.17. Each machine can be properly assigned turn on-off schedule time, a number of operators requirement and preventive maintenance. After applying preventive plan for waste elimination into the optimization result, the problem form undesired energy is resolved as described in Table 5.18. All percentages from idle time, human error and maintenance down time are vastly improved. This conclusion implies that optimization result from optimization model is reliable with preventive plan and simulation model for waste elimination is feasible.



Entity...	Location...	Operation...
Product_1	Start	if Calhour() = 10 thenbegin
Product_1	Cell_waiting1	Constant_product1_process_1
Product_1	Queue_1	
Product_1	Machine_1	Constant_product1_process_2
Product_1	Queue_4	

Blk	Output...	Destination...	Rule...	Move Logic...
1	Product_1	Cell_waiting1	FIRST 1	

Fig. 5.30 Simulation model for waste elimination

Name	Scheduled Time (HR)	% Operation	% Setup	% Idle	% Waiting	% Blocked	% Down
Machine 1	5.92	39.41	0	53.62	2.75	0	4.22
Machine 2	5.92	0	0	100	0	0	0
Machine 3	5.92	50.67	0	43.7	0	0	5.63
Machine 4	5.92	8.44	0	91.56	0	0	0

Table 5.15 Wastes occurred from the manufacturing process

Scenario specification					Optimized results			
Scenario No.	MC:A	MC:B	MC:C	MC:D	Energy consumption (kWh)	Production time (min)	Cost of production (£)	λ
1	(w1:1) (w1:3) (w3:2) (w4:1) (w4:2)	N/A	(w1:2) (w2:1) (w2:2) (w3:1)	(w3:3)	26	185	17	0.762

Table 5.16 Input parameters of the waste elimination model

Scenario NO.	Scheduling time (turn off)				Operator requirement	Maintenance
	MC:A	MC:B	MC:C	MC:D		
1	8.00 – 10.00 am 11.06 – 11.18 am 11.48 – 12.00 am 12.32 – 12.44 pm	N/A[a]	8.00 – 10.00 am 11.24 – 12.00 am 13.24 – 14.00 pm	8.00 – 10.44 am 11.02 – 13.00 pm 13.16 – 14.00 pm	2 for MC:A[b] 1 for MC:B 1 for MC:C 1 for MC:D	Preventive maintenance for MC:A and C

Table 5.17 Preventive plan obtaining from simulation results

Name	Scheduled Time (HR)	% Operation	% Setup	% Idle	% Waiting	% Blocked	% Down
Machine 1	3.2	93.69	0	3.2	0	0	3.12
Machine 2	5.75	0	0	100	0	0	0
Machine 3	2.85	93.57	0	1.9	0	0	4.53
Machine 4	0.58	85.71	0	14.29	0	0	0

Table 5.18 Simulation results using preventive plan

5.10 Summary

Fuzzy logic using mamdani and sugeno type techniques is used to develop EREE-based LCM modelling at the machine level. The architecture of the evaluation mechanism is constructed based on a cutting force model and experimental data. The experiment (cutting trial) has been made on aluminum material with a CNC milling machine. A MATLAB-based simulation system has been developed to facilitate and perform energy/resource simulation and optimization. From the simulation results, the following conclusions can be drawn:

(1) The simulation results from the modelling have the same trend with experimental data. It is also more reliable compared to results from a MATLAB-based response surface methodology.
(2) The result from the developed model provides the optimization of energy efficiency and resource utilization with the compromise between all other objectives.

This chapter has also presented a development of EREE-based LCM at shop-floor level. The developed systematic modelling includes two sub-models i.e. an optimization model cooperating with a machine level model and waste elimination model. The optimization model is formulated based on the information of the process sequence of the considered system. The input for this model uses a proposed matrix with optimal results from the machine level model while the optimization process uses fuzzy linear programming with several objectives. The output from this model provides an optimal production plan together with an optimal machining set-up in order to minimize the total carbon footprint and also satisfy all other objectives. For the waste elimination model, it is designed to eliminate waste energy during manufacturing processes by using discrete event system simulation theory to simulate failure events. ProModel software is used to establish the model related to the mathematical formulation used for the optimization model. The output from this model is a preventive plan used together with optimal production to eliminate waste energy. As part of the framework proposed for developing EREE-based LCM, the evaluation and validation of the developed models for machine and shop-floor level will be carried out in the next chapter.

Chapter 6 Application case studies

6.1 Introduction

This chapter presents the evaluation of the framework proposed for developing EREE-based LCM through two case studies. Since the framework includes a number of aspects, only partial evaluations are considered in this chapter.

The first case study is concerned with EREE-based LCM at machine level. The experimental data obtained from cutting trials is used to formulate learning rules. The prediction results from the proposed model are, then, compared with the conventional statistical methods.

The second case study is related to EREE-based LCM at shop-floor level. The numerical example is demonstrated with initial information (input data). The combination of an optimization model and a simulation model represents the integration of energy efficiency, resource utilization and waste minimization throughout the minimization of the carbon footprint.

6.2 EREE-based LCM case study one

In this case study, the investigation on energy consumption of the conventional CNC milling machine using aluminum as a material, is used. The objective of this case study is to determine the optimal machining set-up that can satisfy energy efficiency and even reduce the total carbon footprint.

6.2.1 Experimental set-up

To perform these experiments, the 5 axis CNC milling machine with 10 kW motor speeds corresponding with 6000 rpm maximum spindle speed and 35 m/min maximum feed rate is used to proceed all cutting trials. The flexible AC power quality tester (PRIMUS PC-02) is connected to the main power supply using the three phase electrical system of the machine in order to measure the total energy consumption (kWh) per cutting trial. To connect the power quality tester with the CNC machine, the first voltage test lead is connected to the phase no.1 and the second voltage test lead is connected to the phase no.3. The flexible loop is connected to the phase no.2. In Fig. 6.1, the connection of the measurement device and the 3-phase main power supply is illustrated. The full experimental set-up is depicted in Fig. 6.2. The measurement device can be controlled by using the compatible software on the PC. The material used for all cutting trials is aluminum. The shape of the workpiece is designed as a circle with Ø10 mm diameter and 10 mm depth.

Fig. 6.1 The connection of the measurement device with the CNC machine

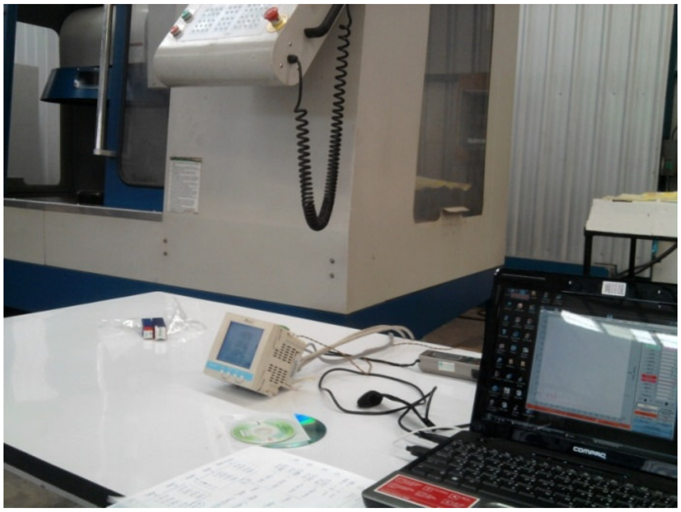


Fig. 6.2 The full experiment set-up

6.2.2 Design of experiments

In order to prepare the experimental design, three cutting parameters are selected as observed parameters and each parameter has two levels of parameter values. The selected cutting parameters are cutting speed/surface feet per minute, tool size and depth of cut. Table 6.1 provides the matrix of cutting parameters used in this experiment corresponding to their lower limit and upper limit level. In addition, all cutting trials in these experiments use carbide end mills tools (diameter: Ø12mm and Ø16mm) which have four teeth.

Variable	Level1	Level2
Cutting speeds	91 m/min	152 m/min
Tool size	Ø12 mm	Ø16 mm
Depth of cut	1 mm	3 mm

Table 6.1 The selected cutting parameters associated with their levels

To determine the sequence of cutting trials, the 2^k factorial design methodology is used due to the level of all parameters equal to two. There are three parameters and each parameter has two levels then the combination of cutting trial sequences are: $2^3 = 8$. In Table 6.2, the combinations of parameters for each cutting trial are presented.

	Cutting speed	TOOL	DEPTH
No.1	Low (91)	Low (12)	Low (1)
No.2	Hi (152)	Low (12)	Low (1)
No.3	Low (91)	Low (12)	Hi (3)
No.4	Hi (152)	Low (12)	Hi (3)
No.5	Low (91)	Hi (16)	Low (1)
No.6	Hi (152)	Hi (16)	Low (1)
No.7	Low (91)	Hi (16)	Hi (3)
No.8	Hi (152)	Hi (16)	Hi (3)

Table 6.2 The combination of selected parameters for each cutting trial

Based on the matrix in Table 6.2, each combination of parameter is transformed into conventional machining parameters (spindle speed (rpm), feed rate (mm/min) and depth of cut) by using the two equations as follow:

Spindle speeds

$$RPM = \frac{S}{C} \tag{6.1}$$

Where

RPM	spindle speed in rev/min
S	cutting speeds in m/min
C	Circumference in feet or mm

Feed rate

$$FR = RPM \times T \times CL \tag{6.2}$$

Where

FR	feed rate in or millimeters per minute
T	the number of teeth on the cutter
CL	size of chip that each tooth of the cutter takes

Regarding the above equations, the set-up of machining parameters for all sequences of cutting trial are summarized in Table 6.3. The spindle speeds are 2500 rpm and 4166 rpm when the Ø12 mm cutting tool is used and the spindle speeds are 1875 rpm and 3100 rpm when the Ø16 mm cutting tools are used. Chip load values are available from Harvey Tool (2011).

Workpiece No.	Cutting Parameters		
	Sp(rpm)	Fr(mm/min)	D(mm)
1	2500	1000	1
2	4166	1666.4	1
3	2500	1000	3
4	4166	1666.4	3
5	1900	937.5	1
6	3100	1562.5	1
7	1900	937.5	3
8	3100	1562.5	3

Table 6.3 The conventional machining parameters for all cutting sequences

6.2.3 Experiments and results

After the cutting process was finished, the recorded data is transferred to the logging reporter. In the recording time period, the energy consumption corresponding to a specific time can be observed. In addition, the maximum and minimum value using through the whole process can also be monitored. Figs. 6.3 and 6.4 represent the example of using the logging reporter after finishing the cutting trial no.1 (2500 rpm, 1000 mm/min, 1mm) and no.2 (4166 rpm, 1666.4 mm/min, 1mm) in order.

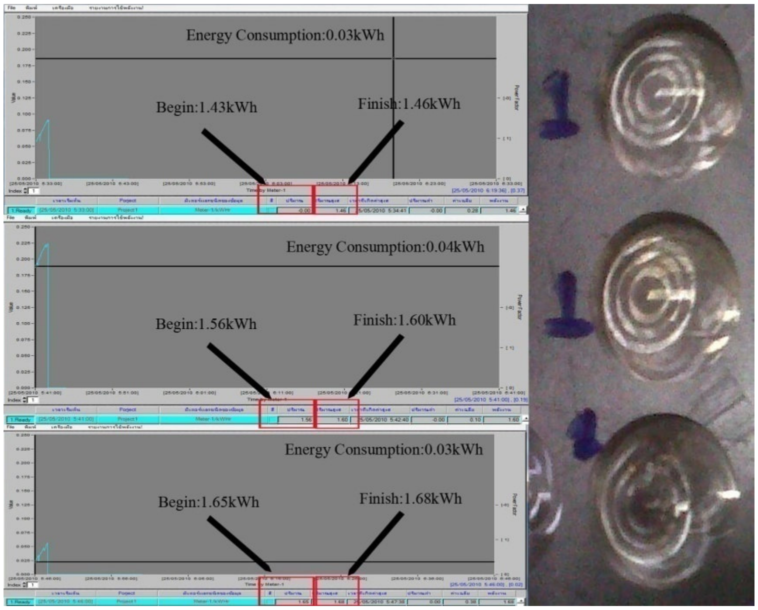


Fig. 6.3 workpiece(1) under the conditions: 2500rpm:1000mm/min:1mm

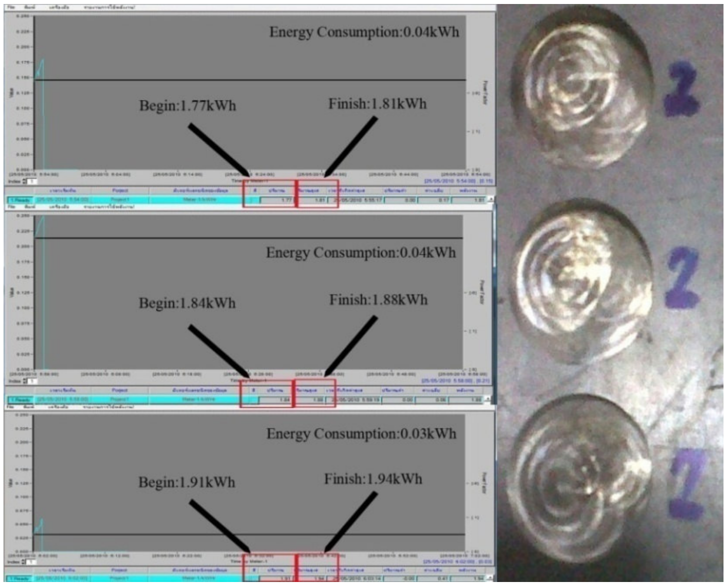


Fig. 6.4 workpiece(2) under the conditions: 4166rpm:1666.4mm/min:1mm

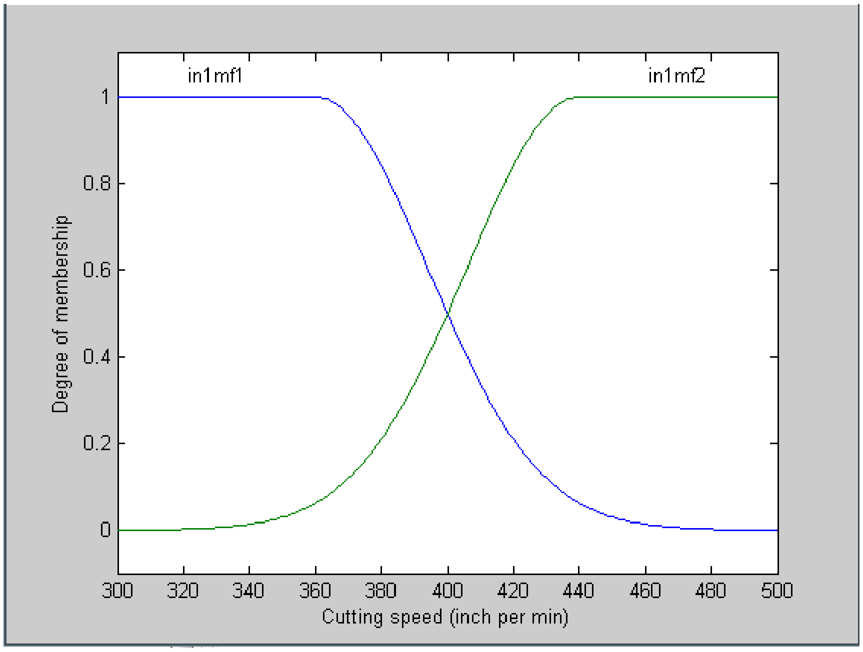
The experimental results are summarized in Table 6.4. The number order of the workpieces in Table 6.4 is related to the number order in Table 6.3.

Workpiece number	Energy consumption (kWh)		
	Repeat 1	Repeat 2	Repeat 3
1	0.03	0.04	0.03
2	0.04	0.04	0.03
3	0.03	0.02	0.04
4	0.01	0.02	0.01
5	0.02	0.04	0.03
6	0.02	0.04	0.03
7	0.02	0.02	0.01
8	0.01	0.01	0.02

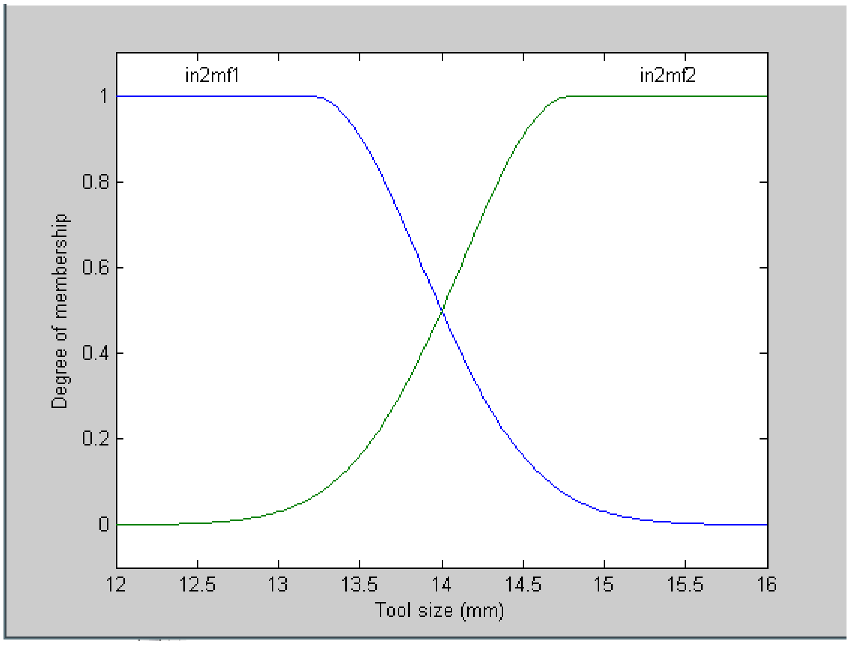
Table 6.4 The energy consumption results from 24 cutting trials

6.2.4 Establishment of energy prediction model

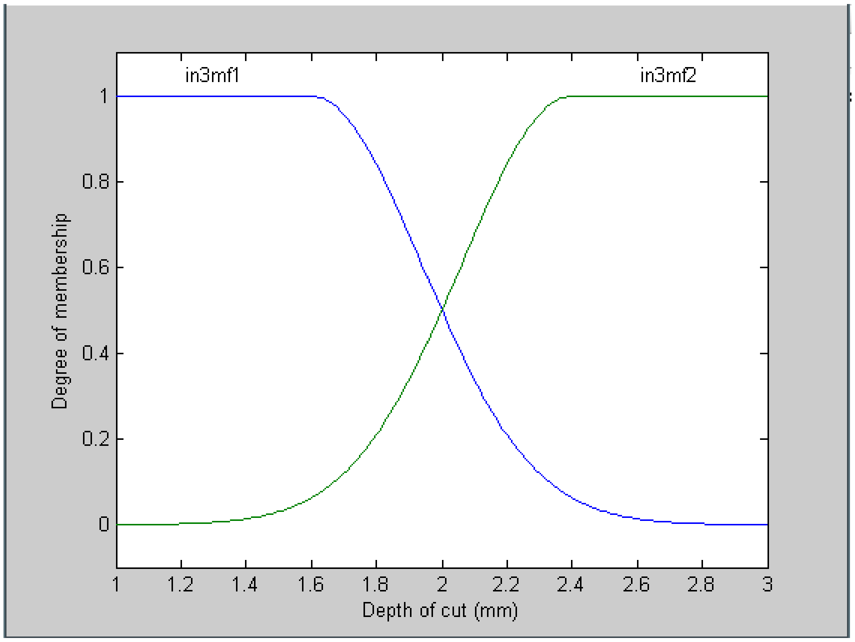
To develop the predicable energy modelling, the Sugeno Type-fuzzy inference engine in MATLAB is used. The neuro-adaptive learning method which has the procedure similar to neural networks is used to learn the set of data input/output in order to evaluate the most appropriate membership function. In this research, the set of data is divided into two groups: training data and checking data. The final energy modelling is based on the FIS structure whose parameters are set according to a minimum checking error criterion. The initial membership function for three input parameters (cutting speed, tool size, depth of cut) is a Gaussian combination membership function. The new membership functions trained by the neuro-adaptive learning method are illustrated in Fig. 6.5.



(a) Cutting speed



(b) Tool size



(c) Depth of cut

Fig. 6.5 The final membership function of cutting speed, tool size and depth of cut

6.2.5 Optimization of machining parameters for energy efficiency and cost effectiveness

In this section, the comparison between the developed system and the response surface methodology based system (using the response surface for prediction of energy consumption) is investigated. There are three inputs for this case study (cutting speed, tool size, and depth of cut) and two responses to be observed (energy consumption and costs preparation). The values of input parameters are illustrated in Table 6.5. Thus, the L9 orthogonal array from taguchi method is used to optimize the prediction value from fuzzy inference system based and response surface methodology based. The structure of the L9 orthogonal array is expressed in Table 6.6.

	Level 1	Level 2	Level 3
Cutting speed (m/min)	91	122	152
Tool size (mm)	12	14	16
Depth of cut (mm)	1	1.5	2

Table 6.5 Input parameters for both systems

Experiment (scenario)	Parameter 1 (Cutting speed)	Parameter 2 (Tool size)	Parameter 3 (Depth of cut)
1	1 (91)	1 (12)	1(1)
2	1 (91)	2 (14)	2 (1.5)
3	1 (91)	3 (16)	3 (2)
4	2 (122)	1 (12)	2 (1.5)
5	2 (122)	2 (14)	3 (2)
6	2 (122)	3 (16)	1 (1)
7	3 (152)	1 (12)	3 (2)
8	3 (152)	2 (14)	1 (1)
9	3 (152)	3 (16)	2 (1.5)

Table 6.6 the L9 orthogonal array of taguchi method

The values of total energy consumption (kWh) from the defuzzification method and response surface methodology (prediction processes) are illustrated in Table 6.7. These values are ordered by the orthogonal array. In addition, the values of cost preparation used in this case study are also illustrated in Table 6.7.

Scenario	Cutting speeds (m/min)	Tool size (mm)	Depth of cut (mm)	Energy consumption from defuzzification (kWh)	Energy consumption from response surface (kWh)	Cost preparation (pounds)
1-1-1	91	12	1	0.03	0.03125	20.45
1-2-2	91	14	1.5	0.0297	0.0275	22.3
1-3-3	91	16	2	0.0244	0.025	21.23
2-1-2	122	12	1.5	0.0354	0.03	22.5
2-2-3	122	14	2	0.0246	0.02375	30
2-3-1	122	16	1	0.032	0.03	21.8
3-1-3	152	12	2	0.0231	0.025	22.1
3-2-1	152	14	1	0.0347	0.035	20
3-3-2	152	16	1.5	0.0294	0.026	21.7

Table 6.7 Evaluated results using defuzzification and response surface

After all values of energy consumption and cost preparation are ready, they are normalized by the linear data processing method using equation 5.22 (the smaller the better). Then, pre data processing of the two objectives are calculated in order to gain grey relational coefficient values. The value of pre data processing and grey relational coefficients for the two objectives are presented in Table 6.8.

Scenario	Data preprocessing			Grey relational coefficient		
	Energy from FIS	Energy from RSM	Cost preparation	Energy from FIS	Energy from RSM	Cost preparation
1-1-1	0.4397	0.33	0.955	0.4716	0.428	0.917
1-2-2	0.4657	0.67	0.77	0.4834	0.6	0.684
1-3-3	0.8980	0.89	0.877	0.8305	0.818	0.803
2-1-2	0	0.44	0.75	0.3333	0.473	0.667
2-2-3	0.8823	1	0	0.8095	1	0.333
2-3-1	0.2779	0.44	0.82	0.4091	0.473	0.735
3-1-3	1	0.89	0.79	1	0.818	0.704
3-2-1	0.0553	0	1	0.3461	0.333	1
3-3-2	0.4917	0.8	0.83	0.4959	0.714	0.746

Table 6.8 Data preprocessing and grey relational coefficient from fuzzy inference system and response surface methodology

6.2.6 Optimization of machining parameters using grey-fuzzy logic based

To optimize machining parameters with the grey-fuzzy logic technique, the mamdani type fuzzy inference engine is used to evaluate the fuzzy reasoning grade for each machining scenario. The membership function for energy consumption and costs preparation is Trapezoidal-shaped and has three fuzzy sets. For the membership function of the output (fuzzy reasoning grade), it is Trapezoidal-shaped built and has five fuzzy sets. The construction of fuzzy sets is based on the investigation of Lin (2005) and Chang Ching-Kao (2007) (Lin 2005; Chang Ching-Kao 2007). The fuzzy rules used to control the defuzzification process have nine rules. In order to determine the value of the fuzzy reasoning grade, Grey relational coefficient values from Table 6.8 are used as input values. The results for FIS and RSM based are illustrated in Table 6.9 with scenario ranking. In addition, the membership functions using in the mamdani type fuzzy inference engine are demonstrated in Fig. 6.6 and 6.7 while the screen copy of fuzzy rules copying from fuzzy logic graphical user interface in MATLAB 2007 is illustrated in Fig 6.8.

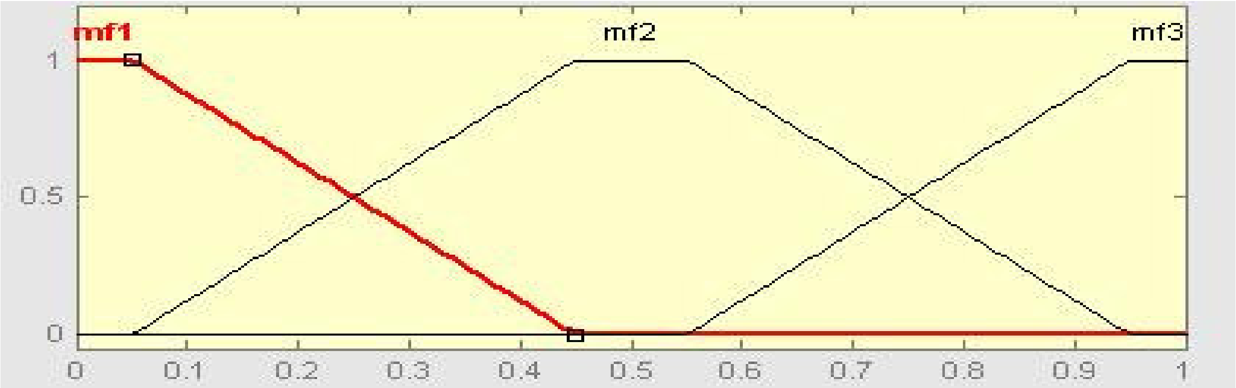


Fig. 6.6 Membership function for grey relational coefficient of energy consumption and costs preparation

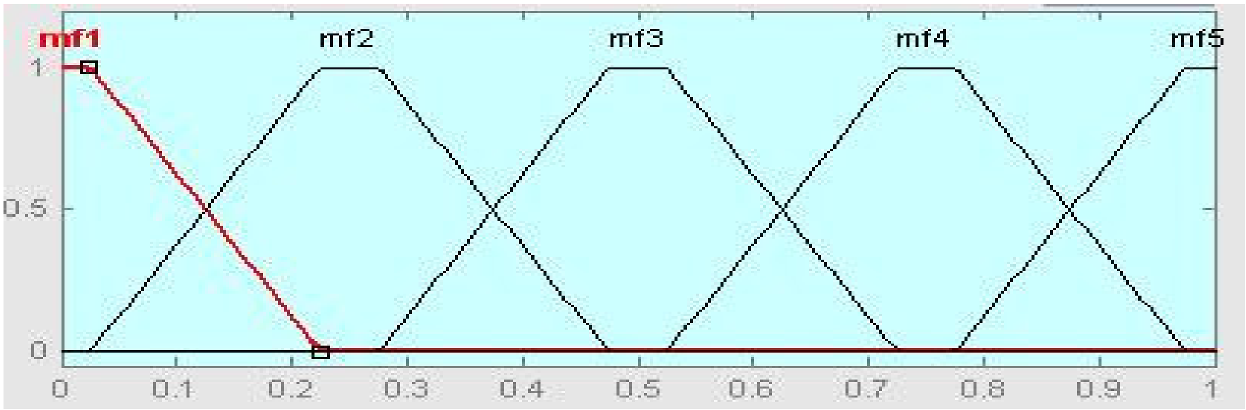


Fig. 6.7 Membership function for evaluating fuzzy reasoning grade

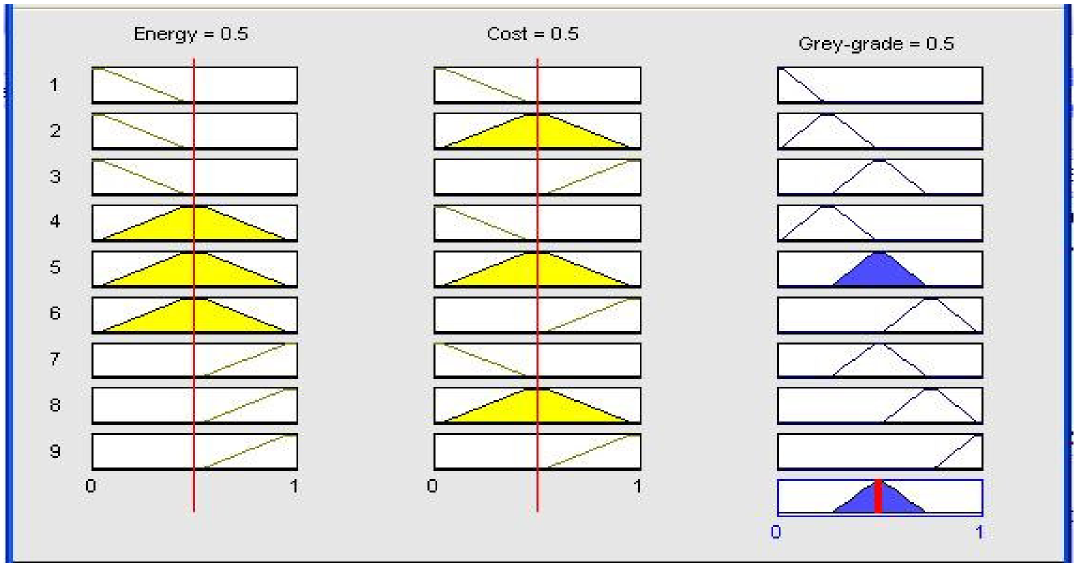


Fig. 6.8 Fuzzy rules used in the mamdani type FIS

Scenario	Optimization using FIS based		Optimization using RSM based	
	Grey-fuzzy reasoning grade	Rank	Grey-fuzzy reasoning grade	Rank
1-1-1	0.7237	2	0.7	1*
1-2-2	0.5905	6	0.6	6
1-3-3	0.7056	3	0.7	1*
2-1-2	0.5000	9	0.58	7
2-2-3	0.5620	8	0.67	3*
2-3-1	0.5814	7	0.617	5
3-1-3	0.7752	1	0.68	2
3-2-1	0.6770	4	0.67	3*
3-3-2	0.6231	5	0.649	4

Table 6.9 The grey-fuzzy reasoning grade from FIS and RSM

According to the grey-fuzzy reasoning grade in table 6.9, the mean grey-fuzzy reasoning grade refers to the effect of each level of machining parameters on the reasoning grade can be calculated. The effect of each parameter on minimization of total energy consumption and cost preparation using fuzzy inference based system is calculated and presented in Table 6.10. Table 6.11 and Fig. 6.9 summarize the effect of machining parameter on total energy consumption and cost of preparation.

Parameter	Effect on considered objective
Cutting speed level 1	$= \frac{(0.7237+0.5905+0.7056)}{3} = 0.6733$
Cutting speed level 2	$= \frac{(0.5+0.562+0.5814)}{3} = 0.5478$
Cutting speed level 3	$= \frac{(0.7752+0.677+0.6231)}{3} = 0.6918$
Tool size level 1	$= \frac{(0.7237+0.5+0.7752)}{3} = 0.6663$
Tool size level 2	$= \frac{(0.5905+0.562+0.677)}{3} = 0.6098$
Tool size level 3	$= \frac{(0.7056+0.5814+0.6231)}{3} = 0.6367$
Depth of cut level 1	$= \frac{(0.7237+0.5814+0.677)}{3} = 0.6607$
Depth of cut level 2	$= \frac{(0.5905+0.5+0.677)}{3} = 0.5712$
Depth of cut level 3	$= \frac{(0.7056+0.562+0.7752)}{3} = 0.6809$

Table 6.10 Calculation of effect from machining parameters using FIS based

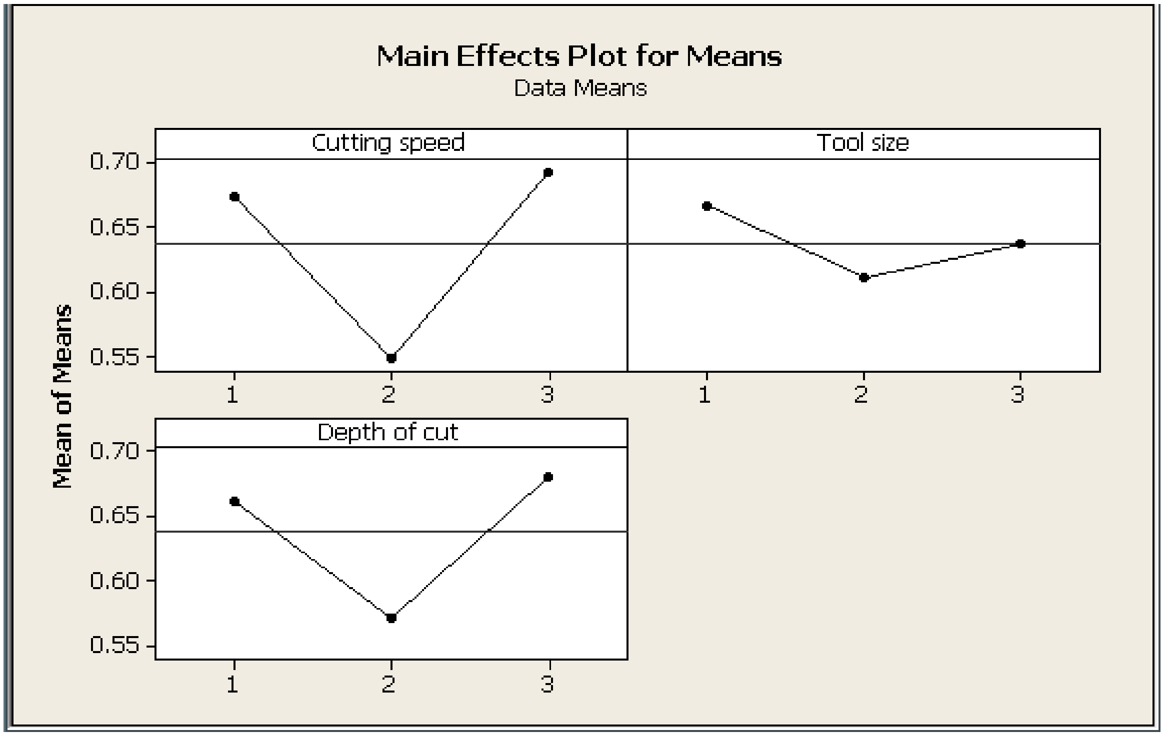


Fig 6.9 The effect of machine parameters on considered response using FIS based

Machine parameter	Grey-fuzzy reasoning grade using FIS based		
	Level 1	Level 2	Level 3
Cutting speed	0.6733	0.5478	0.6918
Tool size	0.6663	0.6098	0.6367
Depth of cut	0.6607	0.5712	0.6809

Table 6.11 Response table for the grey-fuzzy reasoning grade using FIS based

Hence, it is obvious that the optimized machining parameters from FIS based are 152meter per min/12mm tool size/2mm depth of cut. The effect of each parameter on minimization of total energy consumption and cost preparation using response surface methodology based system is calculated and presented in Table 6.12. Table 6.13 and Fig. 6.10 summarize the effect of machining parameter using response surface methodology on total energy consumption and cost of preparation.

Parameter	Effect on considered objective
Cutting speed level 1	$=\frac{(0.7+0.6+0.7)}{3}=0.666667$
Cutting speed level 2	$=\frac{(0.56+0.67+0.617)}{3}=0.622333$
Cutting speed level 3	$=\frac{(0.68+0.67+0.649)}{3}=0.666333$
Tool size level 1	$=\frac{(0.7+0.58+0.68)}{3}=0.653333$
Tool size level 2	$=\frac{(0.6+0.67+0.67)}{3}=0.646667$
Tool size level 3	$=\frac{(0.7+0.617+0.649)}{3}=0.655333$
Depth of cut level 1	$=\frac{(0.7+0.617+0.67)}{3}=0.662333$
Depth of cut level 2	$=\frac{(0.6+0.58+0.649)}{3}=0.609667$
Depth of cut level 3	$=\frac{(0.7+0.67+0.68)}{3}=0.683333$

Table 6.12 Calculation of effect from machining parameters using RSM based

Hence, it is obvious that the optimized machining parameters from RSM based method selects 91 meter per min/16mm tool size/2mm depth of cut.

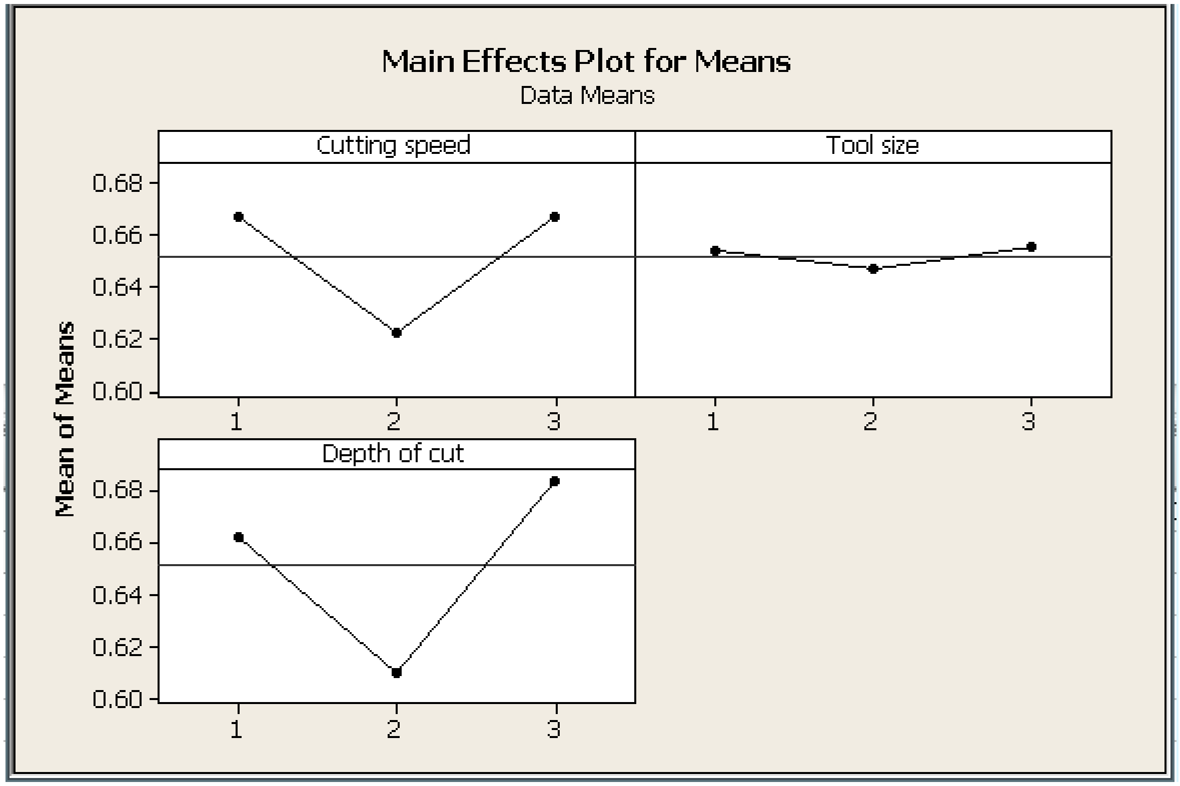


Fig 6.10 The effect of machine parameters on considered response using RSM based

Machine parameter	Grey-fuzzy reasoning grade using RSM based		
	Level 1	Level 2	Level 3
Cutting speed	0.666667	0.622333	0.666333
Tool size	0.653333	0.646667	0.655333
Depth of cut	0.662333	0.609667	0.683333

Table 6.13 Response table for the grey-fuzzy reasoning grade using RSM based

6.2.7 Analysis of energy efficiency and carbon footprint

To analyze the effect on energy efficiency and the carbon footprint from different two different scenarios: 152 meter per min/12mm tool size/2mm depth of cut (scenario 1) and 91 meter per min/16mm tool size/2mm depth of cut (scenario 2), the case of performing workpiece cutting for one year is provided with experimental data (energy consumption). The results are illustrated in Table 6.14 and the details of the cutting trial cases are:

1) Scenario 1 uses 40 sec/cut, scenario 2 uses 43 sec/cut
2) Working hour = 8 hours/day
3) Working day = 365 days/year
4) The requirement is 670 cut/day
5) There are 20 machines on the shop-floor

Scenario	Energy consumption (kWh)
1	0.0107
2	0.01566

Table 6.14 The energy consumption for selected scenario

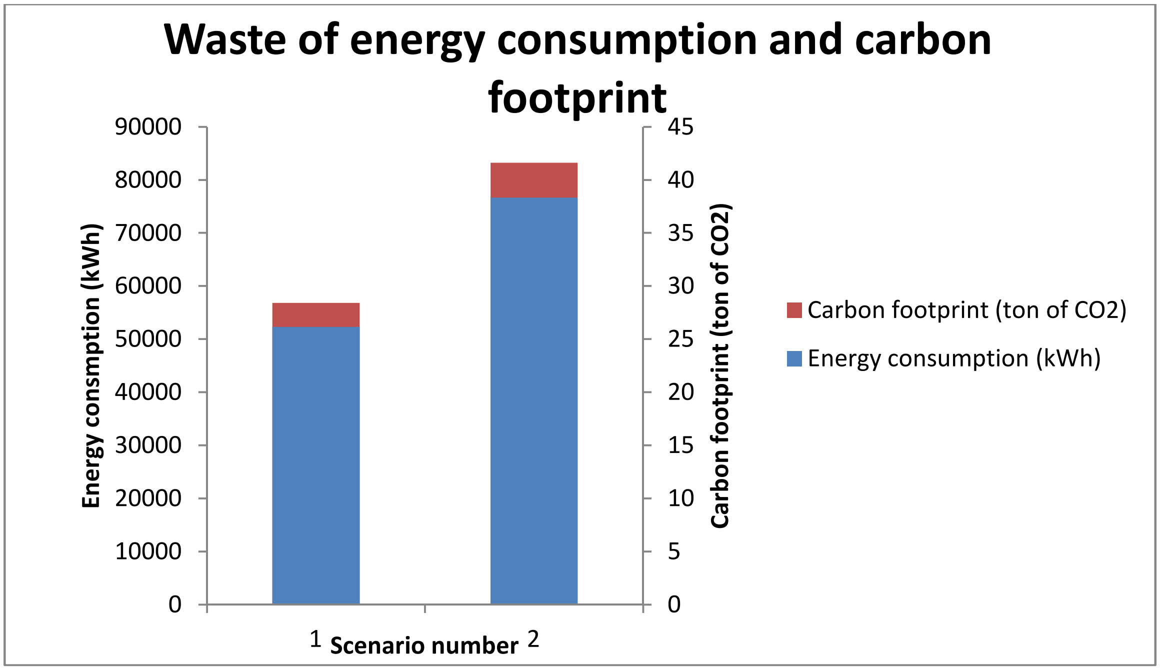


Fig. 6.14 Energy consumption and carbon footprint from each scenario

Based on the validation of the simulation results with experimental data, the main reason that RSM returns different results compared to fuzzy logic modelling is because RSM predicts that the combination of 152 m/min, Ø12 mm, and 2mm consumes energy equal to the combination of

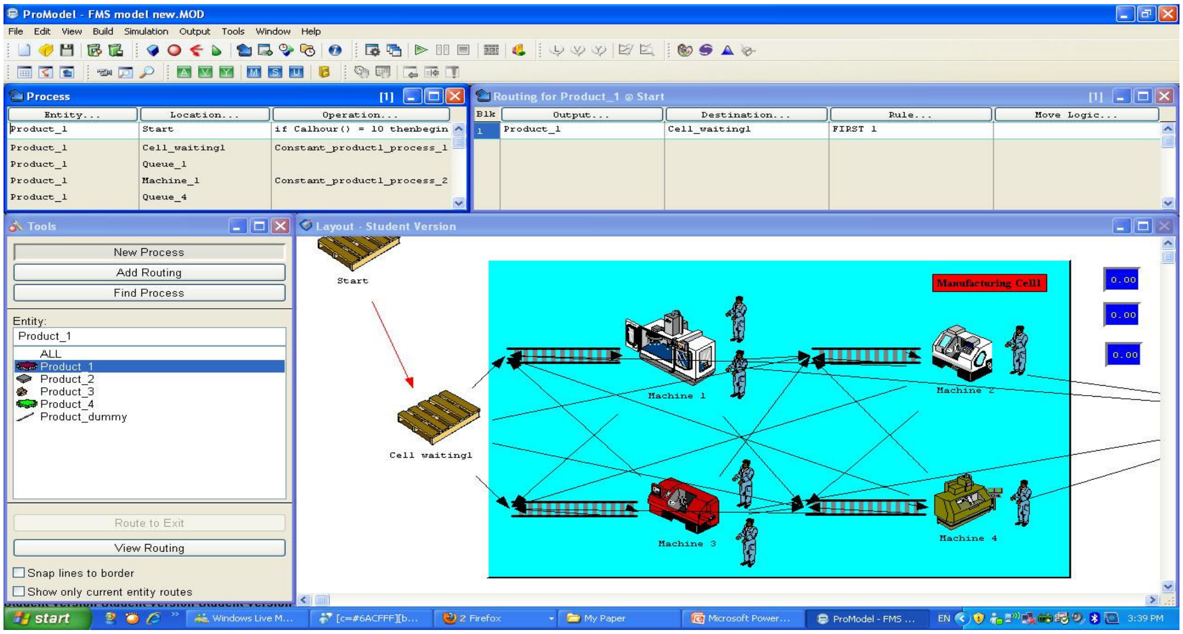
91 m/min, Ø16 mm, 2mm. These simulation results are not compromised with experimental data while the results from fuzzy logic can simulate the same trend results (the combination of 152 m/min, Ø12 mm, and 2mm consumes more energy than the combination of 91 m/min, Ø16 mm, 2mm). According to the analysis of carbon footprint, using the machining combination scenario 1 can save up to 24316.3 kWh and 13.205 ton of CO_2 comparing to machining combination 2. From this evaluation, it can be implied that the energy efficiency and resource utilization can be achieved by effective simulation and optimization modelling.

6.3 EREE-based LCM case study two

The modelling of EREE-based LCM at shop-floor level illustrated in Chapter 5 is demonstrated in this section. The numerical example is given with the optimization and simulation model described in Chapter 5. Initial information is provided as input of the modelling. The output represents the optimal production planning including machining set-up with a preventive plan, which eventually concludes with the minimization of the carbon footprint.

6.3.1 Simulation model for maximization of resource utilization and waste minimization

Figure 6.15 shows the simulation model which is established based on the details of the case study and related mathematical model stated above. To investigate the waste of energy consumption and carbon footprint which occurred from the process, the data of percentage of utilization including machine idle, machine down time and operator down time are used as a main impact factor. There are four machines in the model and each machine is assigned a break down time constraint using location down time in the function, whilst machine capacity is set to one. All resources in the model are also set the down time by using a shift editor function. Thus, it can be seen from the model's result after simulation where the waste appeared from the process. The example of the result is presented in Table 6.15. The simulation is conducted from 8.00am to 4.00pm (8 hours) using a weekly time set-up. The arrival time of the product (entity) is set to 2 hours. For the convenience of the scenario comparison, the array logic combined with Microsoft excel is used it is easier to change the sequence of work assignment otherwise all parameters would need to be changed in the algorithm every time before the simulation starts. The lists of simulation parameters are summarized in Table 6.16.



Entity...	Location...	Operation...
Product_1	Start	if Calhour() = 10 thenbegin
Product_1	Cell_waiting1	Constant_product1_process_1
Product_1	Queue_1	
Product_1	Machine_1	Constant_product1_process_2
Product_1	Queue_4	

Blk	Output...	Destination...	Rule...	Move Logic...
1	Product_1	Cell_waiting1	FIRST 1	

Fig. 6.15 FMS simulation model for waste minimization

Name	Scheduled Time (HR)	% Operation	% Setup	% Idle	% Waiting	% Blocked	% Down
Machine 1	5.92	39.41	0	53.62	2.75	0	4.22
Machine 2	5.92	0	0	100	0	0	0
Machine 3	5.92	50.67	0	43.7	0	0	5.63
Machine 4	5.92	8.44	0	91.56	0	0	0

Table 6.15 Type of waste occurred from each machine after simulation

Configuration	Parameter set-up
Number of location	12 locations
Number of entity	5 entities
Entity arrival time	2 hours
Simulation mode	Weekly time
Number of process	65 processes
Array logic	Activated

Table 6.16 Parameters used in the simulation model for the considered case study

6.3.2 Numerical example and results

The proposed model for shop-floor level is applied to the numerical problem in this section. The model will begin with optimization and end-up with simulation. Tables 6.17, 6.18, 6.19 and 6.20 provide the amount of energy consumption, production time, set-up costs and machine operation set-up used to machine operation j on workpiece i at machine k respectively. For example, operation 1 on workpiece 1 machined at machine A uses on energy consumption of 2.2 kWh, cost of production 1 (pounds), production time 1 (minute) and set-up with cutting speed 122 m/min, tool size Ø12 mm, depth of cut 1mm. All data in Tables 6.18, 6.19 and 6.20 are arranged in the same pattern of Table 6.17. In addition, there are sets of machine k that can machine operation j of workpiece i. For example, operation 1 on workpiece 1 can be machined by machines A and D. All sequences of each workpiece can be seen in Tables 6.17, 6.18, 6.19 and 6.20. From the proposed model, it can be seen that the data from Tables 6.17 and 6.20 are obtained from the machine level.

	Workpiece									
	1			2		3			4	
	Process			Process		Process			Process	
	1	2	3	1	2	1	2	3	1	2
Machine: A	2.2	-	2.5	-	3.2	-	2.8	-	2.3	2.5
Machine: B	-	4	3.8	-	-	4	-	3.9	3	3.3
Machine: C	-	1.8	2.9	2.8	3.5	3.1	-	-	2.7	-
Machine: D	3	-	-	1.7	-	-	2	2.5	1.9	-

Table 6.17 Energy consumption (kWh) for machining the workpiece

	Workpiece									
	1			2		3			4	
	Process			Process		Process			Process	
	1	2	3	1	2	1	2	3	1	2
Machine: A	1	-	1	-	3	-	2	-	2	2
Machine: B	-	3	2	-	-	1	-	4	3	3
Machine: C	-	1	3	4	2	1	-	-	4	-
Machine: D	2	-	-	4	-	-	3	1	1	-

Table 6.18 Costs of production (£) for machining the workpiece

	Workpiece									
	1			2		3			4	
	Process			Process		Process			Process	
	1	2	3	1	2	1	2	3	1	2
Machine: A	1	-	1	-	3	-	2	-	2	2
Machine: B	-	3	2	-	-	1	-	4	3	3
Machine: C	-	1	3	4	2	1	-	-	4	-
Machine: D	2	-	-	4	-	-	3	1	1	-

Table 6.19 Production time (min) for machining the workpiece

	Workpiece									
	1			2		3			4	
	Process			Process		Process			Process	
	1	2	3	1	2	1	2	3	1	2
Machine: A	S:122 T:12 D:1	-	S:91 T:14 D:1.5	-	S:122 T:16 D:2	-	S:122 T:12 D:1	-	S:91 T:12 D:1	S:122 T:12 D:1
Machine: B	-	S:107 T:12 D:2	S:122 T:12 D:2	-	-	S:91 T:12 D:1	-	S:107 T:14 D:1.5	S:91 T:12 D:1.5	S:122 T:14 D:1.5
Machine: C	-	S:91 T:16 D:1	S:107 T:16 D:2	S:91 T:14 D:1.5	S:107 T:14 D:1.5	S:91 T:12 D:1	-	-	S:107 T:14 D:1.5	-
Machine: D	S:107 T:14 D:1.5	-	-	S:107 T:16 D:1	-	-	S:122 T:12 D:1.5	S:107 T:16 D:1.5	S:122 T:16 D:2	-

Table 6.20 Optimal set-up for the machine operation

Scenario specification					Optimized results			
Scenario No.	MC:A	MC:B	MC:C	MC:D	Energy consumption (kWh)	Production time (min)	Cost of production (£)	λ
1	(w1:1) (w1:3) (w3:2) (w4:1) (w4:2)	N/A	(w1:2) (w2:1) (w2:2) (w3:1)	(w3:3)	26	185	17	0.762
2	(w1:1) (w1:3) (w3:2) (w4:2)	N/A	(w1:2) (w2:1) (w2:2) (w3:1) (w4:1)	(w3:3)	26.4	175	19	0.75
3	(w2:2) (w3:2) (w4:2)	(w1:3)	(w1:2) (w2:1) (w3:1)	(w1:1) (w3:3) (w4:1)	27.4	205	19	0.5714
4	(w1:1) (w1:3) (w2:2)	(w1:2) (w4:2)	(w2:1) (w3:1)	(w3:2) (w3:3) (w4:1)	27.5	215	21	0.4762
5	(w1:1) (w2:2) (w4:2)	(w1:3)	(w1:2) (w3:1) (w4:1)	(w2:1) (w3:2) (w3:3)	25.5	175	22	0.375

Table 6.21 Scenarios of optimized results

Table 6.21 illustrates the optimized results for the numerical example using a genetic algorithm on the MATLAB platform. Each scenario provides the work assignment sequence to each machine with the amount of energy consumption, total production time and costs of production for completing the scenario. For example, machine A is assigned to machine operations 1 and 3 on workpiece 1, operation 2 on workpiece 3, operations 1 and 2 on workpiece 4 while the machine B is idle for the whole shift in the scenario 1. From the result, it is obvious that there is conflict between three goals. The scenario 5 uses the lowest energy consumption but the amount of cost of production, on the other hand, is the highest value compared to the other scenario. The value of λ in each scenario depicts how the conflict of three goals can be compromised when the scenario was chosen. In this problem, scenario 1 ($\lambda = 0.762$) is the optimized scenario for energy efficiency, cost effectiveness and time. However, these results might not be reliable for the decision maker because the hidden waste which makes the total energy consumption and carbon footprint more than it should be can be appear in the process. Table 6.22 illustrates the hidden waste from each scenario after the optimized results from Table 6 are simulated using the proposed model on ProModel platform. For scenario 1, the amounts of carbon footprint from idle time, maintenance down time and operator error are 6.076, 1.243 and 0.089 kg CO_2 which make the total carbon footprint higher than it should be. Therefore, the process for low carbon manufacturings in the shop-floor level is not just only the optimization method but the simulation model is also needs to be applied. On the other hand, it could be implied that there should be an additional operation strategy plan used together with the optimized results in order to minimize all hidden waste.

Table 6.23 presents the additional operation strategy obtained from the simulation running. In each scenario, all machines are provided with a working shift (turn on-off time), an operator requirement and a predictive maintenance plan. For example, machine A of scenario 1 has to be shut down from 8.00-10.00am, 11.06-11.18am, 11.48-12.00pm and 12.32-12.44pm while machine B is shut down for the whole process (no work assignment). Preventive maintenance plans have to be applied to machine A and C of scenario 1 regarding the simulation results in Table 6.22.

With the proposed application, all core low carbon manufacturing performances for the considered problem, including energy efficiency, resource utilization, waste minimization and eventually the amount of carbon footprint are successfully improved. In Fig. 6.16, the comparison between only optimization method for low carbon manufacturing at shop-floor level and optimization combined with the simulation model is presented. The blue, red and green colour bar charts in Fig. 6.16 represent the total carbon footprint from using the proposed model, hidden carbon footprint and total carbon footprint when performing without the simulation respectively. The comparison is performed with every scenario. From the chart, it is obvious that there could be a large amount of carbon footprint from hidden waste when the effective plan was not applied to the utilization ratio, maintenance and operator plan. For example, scenario 3 should produce 13.68 kg CO_2 when the decision maker selected for the daily plan (the emission factor used for calculation is 0.49927 kg CO_2 per kWh with regards to electricity for emission factor 2008 according to Department of Environment Food and Rural Affairs 2009). However, the total carbon footprint can be up to 23.26 kg CO_2 when the 9.58 kg CO_2 of hidden waste occurred: 8.54 and 1.04 kg CO_2 appeared from the idle time and maintenance down time respectively. On the other hand, it could be implied that the decision maker can select scenario 3 and expect 13.68 kg CO_2 as the net carbon footprint if the additional plan from Table 6.23 is applied. Moreover, the improvement of resource utilization and waste minimization from the simulation is presented in Tables 6.24 and 6.25 by using the simulation results from scenario 1.

Environmental Status													Carbon footprint (kg CO_2)			
Scenario No.	%Utilization				%Down time				%Operator error				From idle	From mt	From err	Total
	MC:A	MC:B	MC:C	MC:D	MC:A	MC:B	MC:C	MC:D	MC:A	MC:B	MC:C	MC:D				
1	50.7	0	45.07	8.45	8.45	0	5.63	0	2.79	0	0	0	6.076	1.243	0.089	7.408
2	39.41	0	50.67	8.44	4.22	0	5.63	0	2.75	0	0	0	6.375	0.869	0.088	7.332
3	37.66	11.59	34.76	34.76	4.34	0	2.9	2.9	0	0	0	0	8.541	1.041	0	9.582
4	37.65	28.96	28.96	28.96	4.34	1.45	2.9	2.9	2.87	0	0	0	8.306	1.207	0.089	9.602
5	38.07	12.69	22.21	38.07	4.76	0	3.17	3.17	3.13	0	0	0	7.935	1.041	0.089	9.065

Table 6.22 Hidden waste (carbon footprint) of each scenario after simulation applied

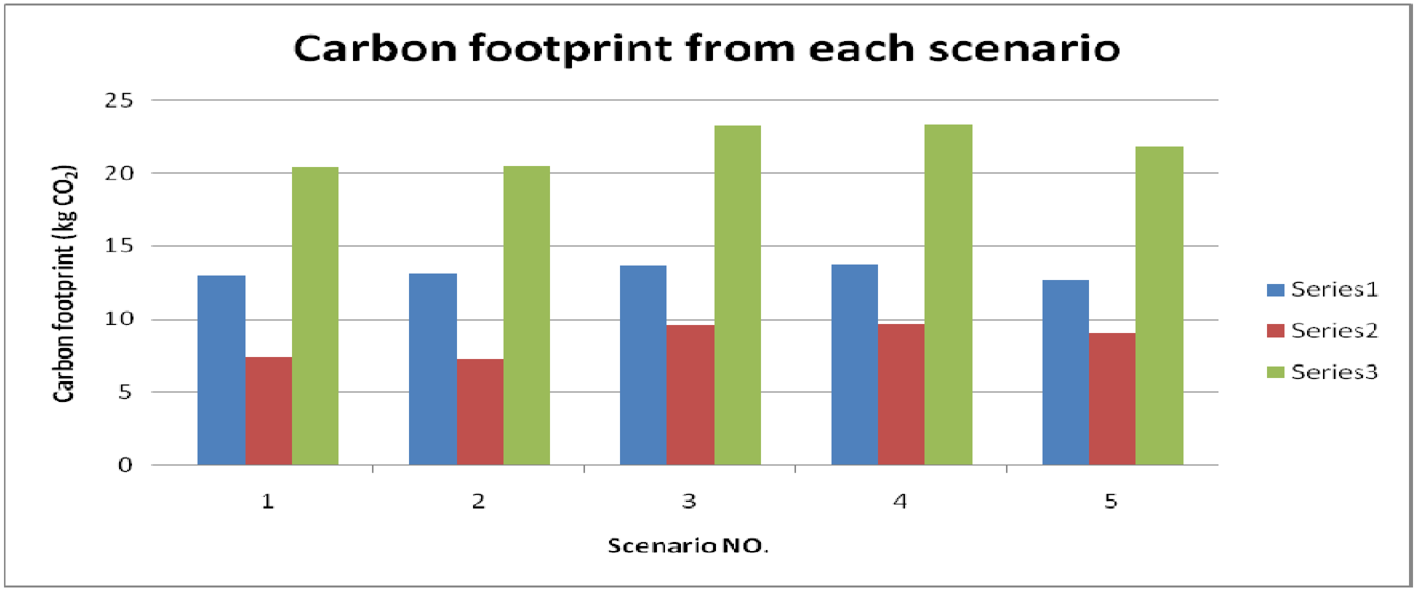


Fig. 6.16 Carbon footprint occurred of each scenario

Scenario NO.	Scheduling time (turn off)				Operator requirement	Maintenance
	MC:A	MC:B	MC:C	MC:D		
1	8.00 – 10.00 am 11.06 – 11.18 am 11.48 – 12.00 am 12.32 – 12.44 pm	N/A[a]	8.00 – 10.00 am 11.24 – 12.00 am 13.24 – 14.00 pm	8.00 – 10.44 am 11.02 – 13.00 pm 13.16 – 14.00 pm	2 for MC:A[b] 1 for MC:B 1 for MC:C 1 for MC:D	Preventive maintenance for MC:A and C
2	8.00 – 10.00 am 10.11 – 10.14 am 10.32 – 11.00 am 11.46 – 12.00 am 12.11 – 12.14 pm 12.32 – 13.06 pm	N/A	8.00 – 10.00 am 11.11 – 11.19 am 11.41 – 12.00 am 12.51 – 13.00 pm 13.41 – 14.00 pm	8.00 – 10.30 am 10.47 – 12.30 pm 12.47 – 14.00 pm	2 for MC:A 1 for MC:B 1 for MC:C 1 for MC:D	Preventive maintenance for MC:A and C
3	8.00 – 10.14 am 10.32 – 10.44 am 11.36 – 12.12 pm 12.32 – 12.54 pm	8.00 – 11.00 am 11.22 – 13.09 pm 13.31 – 14.00 pm	8.00 – 10.00 am 11.01 – 12.00 am 12.16 – 12.24 pm 13.12 – 14.00 pm	8.00 – 10.00 am 11.01 – 12.00 am 12.31 – 12.39 pm 13.11 – 14.00 pm	1 for MC:A 1 for MC:B 1 for MC:C 1 for MC:D	Preventive maintenance for MC:A, C and D
4	8.00 – 10.00 am 10.11 – 10.30 am 11.27 – 12.00 am 12.11 – 12.30 pm	8.00 – 10.09 am 11.01 – 12.09 pm 13.01 – 14.00 pm	8.00 – 10.00 am 10.51 – 12.00 am 12.51 – 14.00 pm	8.00 – 10.00 am 10.52 – 12.00 am 12.36 – 12.44 pm 13.01 – 14.00 pm	2 for MC:A 1 for MC:B 1 for MC:C 1 for MC:D	Preventive maintenance for MC:A, B, C and D
5	8.00 – 10.00 am 10.11 – 10.24 am 11.16 – 12.00 am 12.11 – 12.24 pm	8.00 – 10.34 am 10.57 – 12.34 pm 12.57 – 14.00 pm	8.00 – 10.00 am 10.36 – 12.00 am 12.36 – 14.00 pm	8.00 – 10.00 am 11.01 – 12.00 am 12.27 – 12.34 pm 13.11 – 14.00 pm	2 for MC:A 1 for MC:B 1 for MC:C 1 for MC:D	Preventive maintenance for MC:A, C and D

Table 6.23 The operational strategy applied to each scenario to reduce waste at shop-floor level

[a] Machine B must be turn off for the whole working period

[b] Machine A requires 2 operators for the whole working period

FMS model-normal.MOD (Normal Run - Rep. 1)							
Name	Scheduled Time (HR)	% Operation	% Setup	% Idle	% Waiting	% Blocked	% Down
Machine 1	5.92	50.7	0	38.06	2.79	0	8.45
Machine 2	5.92	0	0	100	0	0	0
Machine 3	5.92	45.07	0	49.3	0	0	5.63
Machine 4	5.92	8.45	0	91.55	0	0	0

Table 6.24 Simulation results without proposed model

FMS model optimal.MOD (Normal Run - Rep. 1)							
Name	Scheduled Time (HR)	% Operation	% Setup	% Idle	% Waiting	% Blocked	% Down
Machine 1	3.2	93.69	0	3.2	0	0	3.12
Machine 2	5.75	0	0	100	0	0	0
Machine 3	2.85	93.57	0	1.9	0	0	4.53
Machine 4	0.58	85.71	0	14.29	0	0	0

Table 6.25 Simulation results with proposed model

6.4 Summary

The feasibility of EREE-based LCM models has been demonstrated with two case studies, although there is still a long way to go to develop the comprehensive EREE-based LCM because there are enterprise and supply levels that are also required to develop the feasible modelling. The case studies have only validated the modelling for both the machine and shop-floor levels.

The case study one is validated using experimental results while the case study two is validated by using simulation results.

Chapter 7 Conclusions and recommendations for future work

This chapter draws important conclusions of the investigations, highlights the contributions to knowledge, and recommends the work for future studies.

7.1 Conclusions

Based upon the discussion in the previous chapters and results from the investigations, the following conclusions can be drawn:

1) Under the great impact of the new manufacturing platform which includes sustainable development as a manufacturing performance, the continuing development of systematic approaches for integrating carbon footprint reduction aspect with typical manufacturing performances has made it necessary and possible to develop "Energy Resource Efficiency and Effectiveness based Low Carbon Manufacturing (EREE-based LCM)". The development of EREE-based LCM demonstrates the potential to offer energy efficiency, resource utilization, waste minimization and even reduction of the carbon footprint for the different manufacturing levels such as machine and shop-floor level.
2) In order to scientifically organize and manage the complexities involved in EREE-based LCM, an integrated framework, theoretical model and characterizations have been proposed to support LCM development. In the proposed framework, the recommendations to achieve EREE-based LCM for each manufacturing level have been demonstrated.
3) To design a systematical approach, the axiomatic design is used to integrate characterizations of EREE-based LCM including energy efficiency, resource utilization and waste minimization to satisfy the main functional requirement (reduction of carbon footprint). It can be concluded that as conceptual design of the systematical approach can be applied to different manufacturing levels.
4) At machine level, the proposed modelling demonstrated its ability to provide a machining set-up that includes energy efficiency and resource utilization. The simulation of energy consumption affected by cutting parameters and selected resources has been implemented using sugeno-type fuzzy logic while the optimization of the machining set-up is implemented using a grey relational based fuzzy logic model (mamdani type fuzzy logic).

The user interface using MATLAB GUI is developed to control the two different types of fuzzy inference engine.

5) At the shop-floor level, the process of combining the mathematical optimization model with the results from the machine level has been introduced in the form of a profile matrix. Fuzzy integer linear programming with several objectives is used to formulate mathematical model for providing the optimal results of energy efficiency and resource utilization. To solve the problem, the genetic algorithm toolbox in MATLAB is used.
6) The waste elimination model used to reduce wastes that affect the amount of carbon footprint has been developed on the ProModel platform. Discrete event simulation theory is used to simulate wastes from machine idle time, human error and maintenance down time. The input of this model is the optimal results from the optimization model while the output is a preventive plan used together with the optimal results in order to eliminate an unnecessary carbon footprint and increase the reliability of the optimal result.

7.2 Contributions to knowledge

1) A novel energy resource efficiency and effectiveness based low carbon manufacturing (EREE-based LCM) has been proposed, and a framework and methodologies have been established, designed and demonstrated.
2) For the first time, the axiomatic design theory is applied to design a systematical approach for achieving low carbon emissions by integrating energy efficiency, resource utilization and waste minimization together.
3) An integrated tool box for the simulation of the energy consumption of a machining cutting process is developed using a sugeno-type fuzzy inference engine while the optimization process is conducted using a mamdani-type fuzzy inference engine. This support system includes user-friendly interface (MATLAB GUI), learning/rule base simulation and optimization with interpretation of results
4) The profile matrix is developed to synchronize results from the machine level with the optimization model of the shop-floor level. Thus, optimal results at shopfloor level can provide production plan with energy efficiency and optimized resource planning.
5) The waste elimination model is proposed using a time based simulation method via ProModel discrete event system simulation platform. The model can evaluate results

from the optimization model and eliminate the waste/unnecessary of energy consumption and the carbon footprint from manufacturing process.

7.3 Recommendations for future work

Since the research covers the range of aspects related to the development of EREE-based low carbon manufacturing, there are relevant contexts in the proposed concept which are incompletely investigated due to the limit of time and available facilities. The following areas are thus recommended for future investigations:

1) For the implementation of EREE-based LCM at shop-floor level, it is possible to develop the user interface such as Visulabasic based to control the optimization in MATLAB and the simulation model in ProModel together.
2) The mathematical model used for optimizing the resources and energy profile can be developed in terms of both mathematical function and seeking procedure. These additions can return the compatibility of complex system and the high potential of finding a global solution.
3) To improve the accuracy of the simulation model at shop-floor level, the validation of data distributions used in the model must be taken based on the comparison of simulation results and experimental data. The effectiveness of waste elimination can be, thus, improved.
4) More mathematical functions can be added into the learning process of Sugeno type fuzzy logic to provide more alternatives of membership function selection. The simulation results of energy consumption can be, thus, improved.
5) According to the model at machine level, the data from the commercial sector such as the machine provider can be added to the model as a reference base to compare with the formulated function created by fuzzy logic.

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Appendices I

A List of Publications Resulted from the Research

AppendicesI

Publications Resulted from the Research

1. S. Tridech and K. Cheng. (2011). Low carbon manufacturing: characterisation, theoretical models and implementation. International Journal of Manufacturing Research, Vol. 6, No. 2, pp. 110-121.

2. S. Tridech and K. Cheng. (2008). Low carbon manufacturing: characterization, theoretical models and implementation. Proceeding of The 6th International Conference on Manufacturing Research (ICMR08), 9-11 September 2008, pp.403-412.

3. S. Tridech and K. Cheng. (2010). An investigation on the framework for EREE-based low carbon manufacturing: Proceedings of the 5th International Conference on Responsive Manufacturing 'Green Manufacturing', 11-13 January, 2010.

4. S. Tridech and K. Cheng. (2010). An investigation of the EREE-based low carbon manufacturing on CNC machine. Proceedings of the 36th International MATADOR Conference 2010, pp. 395-399.

Appendices II

Parts of Programmes of Machining with Energy Efficiency

```
function varargout = Energy(varargin)
% ENERGY M-file for Energy.fig
%      ENERGY, by itself, creates a new ENERGY or raises the existing
%      singleton*.
%
%      H = ENERGY returns the handle to a new ENERGY or the handle to
%      the existing singleton*.
%
%      ENERGY('CALLBACK',hObject,eventData,handles,...) calls the local
%      function named CALLBACK in ENERGY.M with the given input arguments.
%
%      ENERGY('Property','Value',...) creates a new ENERGY or raises the
%      existing singleton*.  Starting from the left, property value pairs are
%      applied to the GUI before Energy_OpeningFunction gets called.  An
%      unrecognized property name or invalid value makes property application
%      stop.  All inputs are passed to Energy_OpeningFcn via varargin.
%
%      *See GUI Options on GUIDE's Tools menu.  Choose "GUI allows only one
%      instance to run (singleton)".
%
% See also: GUIDE, GUIDATA, GUIHANDLES

% Edit the above text to modify the response to help Energy

% Last Modified by GUIDE v2.5 05-Jul-2010 00:32:26

% Begin initialization code - DO NOT EDIT
gui_Singleton = 1;
gui_State = struct('gui_Name',       mfilename, ...
                   'gui_Singleton',  gui_Singleton, ...
                   'gui_OpeningFcn', @Energy_OpeningFcn, ...
                   'gui_OutputFcn',  @Energy_OutputFcn, ...
                   'gui_LayoutFcn',  [] , ...
                   'gui_Callback',   []);
if nargin && ischar(varargin{1})
    gui_State.gui_Callback = str2func(varargin{1});
end

if nargout
    [varargout{1:nargout}] = gui_mainfcn(gui_State, varargin{:});
else
    gui_mainfcn(gui_State, varargin{:});
end
% End initialization code - DO NOT EDIT
```

```
% --- Executes just before Energy is made visible.
function Energy_OpeningFcn(hObject, eventdata, handles, varargin)
% This function has no output args, see OutputFcn.
% hObject    handle to figure
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
% varargin   command line arguments to Energy (see VARARGIN)

backgroundimage = importdata('Energyeff.jpg');
axes(handles.axes5);
image(backgroundimage);
axis off

backgroundimage2 = importdata('Brunel.jpg');
axes(handles.axes6);
image(backgroundimage2);
axis off

% Choose default command line output for Energy
handles.output = hObject;

% Update handles structure
guidata(hObject, handles);

% UIWAIT makes Energy wait for user response (see UIRESUME)
% uiwait(handles.figure1);


% --- Outputs from this function are returned to the command line.
function varargout = Energy_OutputFcn(hObject, eventdata, handles)
% varargout  cell array for returning output args (see VARARGOUT);
% hObject    handle to figure
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Get default command line output from handles structure
varargout{1} = handles.output;


% --- Executes on button press in pushbutton1.
function pushbutton1_Callback(hObject, eventdata, handles)
% hObject    handle to pushbutton1 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

figure(Machineparameter);
```

```
uiwait;


% --- Executes on button press in pushbutton2.
function pushbutton2_Callback(hObject, eventdata, handles)
% hObject    handle to pushbutton2 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

figure(Costset);
uiwait;


% --- Executes on button press in pushbutton3.
function pushbutton3_Callback(hObject, eventdata, handles)
% hObject    handle to pushbutton3 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

global vvar1
global vvar2
global vvar3
global vvar4
global vvar5
global vvar6
global vvar7
global vvar8
global vvar9

global costv1
global costv2
global costv3
global costv4
global costv5
global costv6
global costv7
global costv8
global costv9

x = [vvar1; vvar2; vvar3];
y = [vvar4; vvar5; vvar6];
z = [vvar7; vvar8; vvar9];
cost = [costv1; costv2; costv3; costv4; costv5; costv6; costv7; costv8; costv9];
count = 1;
count2 = 1;
count3 = 1;
```

```
count4 = 1;
scenario = [1 2 3 4 5 6 7 8 9];
data = [300 12 1 0.03; 500 12 1 0.04; 300 12 3 0.02; 500 12 3 0.01; 300 16 1 0.03; 500 16 1 0.03;
300 16 3 0.02; 500 16 3 0.01];
ck = [ 500 12 2 0.0107; 300 16 2 0.01566];
nummf = [2 2 2];
mftype = str2mat('gauss2mf','gauss2mf','gauss2mf');
fismat = genfis1(data,nummf,mftype);
[fis,error,stepsize,chkFis,chkErr] = anfis(data,fismat,500,[],ck);


display(cost);
display(x);
display(y);
display(z);



relation = readfis('Relation');
   for i = 1:3
      for j = 1:3
         for k = 1:3

         dang(count,1) = evalfis([x(i,1) y(j,1) z(k,1)], chkFis);
         count = count + 1;
         end
      end
   end

   orthogonal = [dang(1,1); dang(5,1); dang(9,1); dang(11,1); dang(15,1); dang(16,1);
dang(21,1); dang(22,1); dang(26,1)];

   varmax = max(orthogonal);
   varmin = min(orthogonal);
   costmax = max(cost);
   costmin = min(cost);

   for a = 1:9
      predata(count2,1) = ((varmax - orthogonal(a,1))/(varmax - varmin));
      precost(count2,1) = ((costmax - cost(a,1))/(costmax - costmin));
      count2 = count2 + 1;
   end

   for b = 1:9
      coeffdata(count3,1) = (0.5/((1 - predata(b,1)) + 0.5));
      coeffcost(count3,1) = (0.5/((1 - precost(b,1)) + 0.5));
```

```
    count3 = count3 + 1;
end

for c = 1:9
    relationgrade(count4,1) = evalfis([coeffdata(c,1) coeffcost(c,1)], relation);
    count4 = count4 + 1;
end

vareff(1,1) = (relationgrade(1,1) + relationgrade(2,1) + relationgrade(3,1))/3;
vareff(2,1) = (relationgrade(4,1) + relationgrade(5,1) + relationgrade(6,1))/3;
vareff(3,1) = (relationgrade(7,1) + relationgrade(8,1) + relationgrade(9,1))/3;
vareff(4,1) = (relationgrade(1,1) + relationgrade(4,1) + relationgrade(7,1))/3;
vareff(5,1) = (relationgrade(2,1) + relationgrade(5,1) + relationgrade(8,1))/3;
vareff(6,1) = (relationgrade(3,1) + relationgrade(6,1) + relationgrade(9,1))/3;
vareff(7,1) = (relationgrade(1,1) + relationgrade(6,1) + relationgrade(8,1))/3;
vareff(8,1) = (relationgrade(2,1) + relationgrade(4,1) + relationgrade(9,1))/3;
vareff(9,1) = (relationgrade(3,1) + relationgrade(5,1) + relationgrade(7,1))/3;

parameter1 = [vareff(1,1) vareff(2,1) vareff(3,1)];
parameter2 = [vareff(4,1) vareff(5,1) vareff(6,1)];
parameter3 = [vareff(7,1) vareff(8,1) vareff(9,1)];

optimizedparameter1 = max(parameter1);
optimizedparameter2 = max(parameter2);
optimizedparameter3 = max(parameter3);

if optimizedparameter1 == vareff(1,1)

    factorA = 300;

elseif optimizedparameter1 == vareff(2,1)

    factorA = 400;

elseif optimizedparameter1 == vareff(3,1)

    factorA = 500;

end

if optimizedparameter2 == vareff(4,1)

    factorB = 12;

elseif optimizedparameter2 == vareff(5,1)
```

```
        factorB = 14;

    elseif optimizedparameter2 == vareff(6,1)

        factorB = 16;

    end

     if optimizedparameter3 == vareff(7,1)

        factorC = 1;

    elseif optimizedparameter3 == vareff(8,1)

        factorC = 1.5;

    elseif optimizedparameter3 == vareff(9,1)

        factorC = 2;

     end

    plot(handles.axes1,scenario,vareff,'--    rs','MarkerEdgeColor','k','MarkerFaceColor','g');
    set(handles.axes1,'XMinorTick','off');
    grid on

    resultstr = get(handles.edit1,'String');
    resultstr = {['Cutting Speed',' ',num2str(factorA),' ','Tool Size',' ',num2str(factorB),'mm','
','Depth of Cut',' ',num2str(factorC),'mm']};
    set(handles.edit1,'String',resultstr);

    plot(handles.axes2,scenario,relationgrade,'--rs','MarkerEdgeColor','k','MarkerFaceColor','r');
    set(handles.axes2,'XMinorTick','off');
    grid on

    bar(handles.axes3,orthogonal);
    bar(handles.axes4,cost);

    display(relationgrade);
    display(orthogonal);
    display(vareff);
    display(predata);
    display(coeffdata);


% --- Executes on button press in pushbutton4.
```

```
function pushbutton4_Callback(hObject, eventdata, handles)
% hObject    handle to pushbutton4 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

close(Energy);





function edit1_Callback(hObject, eventdata, handles)
% hObject    handle to edit1 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit1 as text
%        str2double(get(hObject,'String')) returns contents of edit1 as a double


% --- Executes during object creation, after setting all properties.
function edit1_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit1 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end
```

Appendices III

Parts of Programmes Using to Establish Model in ProModel

AppendicesIII

```
*******************************************************************************
*                                                                             *
*                      Formatted Listing of Model:                            *
* C:\Documents and Settings\compaq\Desktop\BU-work-2010\ProModel\FMS model new.MOD *
*                                                                             *
*******************************************************************************

Time Units:              Minutes
Distance Units:          Feet

*******************************************************************************
*                                Locations                                    *
*******************************************************************************

Name          Cap  Units  Stats        Rules         Cost
------------- --- ----- ----------- -------------- ----------------------
Machine_1      1     1    Time Series   Oldest, ,
Machine_2      1     1    Time Series   Oldest, ,
Machine_3      1     1    Time Series   Oldest, ,
Machine_4      1     1    Time Series   Oldest, ,
Queue_1       inf    1    Time Series   Oldest, FIFO,
Queue_2       inf    1    Time Series   Oldest, FIFO,
Queue_3       inf    1    Time Series   Oldest, FIFO,
Queue_4       inf    1    Time Series   Oldest, FIFO,
Start          inf    1    Time Series   Oldest, ,
Cell_waiting1 inf    1    Time Series   Oldest, ,
Warehouse     inf    1    Time Series   Oldest, ,
Signal          inf    1    Time Series    Oldest, ,
```

AppendicesIII

```
        ********************************************************************************
                    *                  Usage downtimes for Locations                *
        ********************************************************************************

Loc          Frequency    First Time   Priority       Logic
---------- ------------ ------------ ------------ ----------------------------
Machine_1       50                      99          wait 15 min
Machine_2       90                      99          wait 5 min
Machine_3       70                      99          wait 10 min
Machine_4       80                      99          wait 10 min

        ********************************************************************************
                    *                          Entities                          *
        ********************************************************************************

Name               Speed (fpm)       Stats       Cost
------------- ------------ ----------- -------------------------
Product_1              150         Time Series
Product_2             150          Time Series
Product_3             150          Time Series
Product_4             150          Time Series
Product_dummy     150           Time Series
```

AppendicesIII

```
        ******************************************************************************
                        *                  Resources                  *
        ******************************************************************************


                           Res   Ent
Name       Units   Stats   Search Search   Path    Motion               Cost
--------- ----- -------- ------ ------ ---------- ------------- -------------------------------------------
Operator1    1   By Unit   None  Oldest            Empty: 150 fpm
                                                   Full: 150 fpm


Operator2    1   By Unit   None  Oldest            Empty: 150 fpm
                                                   Full: 150 fpm


Operator3    1   By Unit   None  Oldest           Empty: 150 fpm
                                                   Full: 150 fpm


Operator4    1   By Unit   None  Oldest           Empty: 150 fpm
                                                  Full: 150 fpm


Operator5    1   By Unit   None  Oldest           Empty: 150 fpm
                                                  Full: 150 fpm


Operator6    1   By Unit   None  Oldest           Empty: 150 fpm
                                                  Full: 150 fpm
```

```
        ********************************************************************************
                          *                 Usage downtimes for Resources                   *
        ********************************************************************************


Res          Frequency    First     Time   Priority    Node      List      Logic
--------- ---------- ---------- ---------- -------- -------- ------------------------------------------
Operator1        60                                                        wait 5 min


        ********************************************************************************
                            *                        Processing                        *
        ********************************************************************************


                           Process                                             Routing


Entity            Location              Operation            Blk        Output          Destination       Rule     Move Logic
------------- ------------- ------------------   ---- ------------- ------------- -------  ---------------------------------------------
Product_1          Start         if Calhour() = 10 then
                                 begin
                                 Phase = 1
                                  end
                                  if Calhour() = 12 then
                                   begin
                                   Phase = 2
                                   end                             1          Product_1      Cell_waiting1     FIRST 1
Product_1     Cell_waiting1 Constant_product1_process_1 = Constant_product1_process_1 + 3
                                    Var1 = Array1[Constant_product1_process_1,1]


                                     if var1 = 1 then
```

		begin
		Route 1
		end
		if var1 = 2 then
		begin
		Route 2
		end
			1	Product_1	Queue_1	FIRST 1

			2	Product_1	Queue_4	FIRST 1
Product_1	Queue_1		1	Product_1	Machine_1	FIRST 1

Product_1	Machine_1	Constant_product1_process_2 = Constant_product1_process_2 + 3
		Var2 = Array1[Constant_product1_process_2,1]
		if Phase = 2 then
		begin
		use Operator5 for 10 min
		end
		if Phase = 1 then
		begin
		use Operator1 for 10 min
		end
		if Var2 = 1 then
		begin
		Route 1
		end
		if Var2 = 2 then
		begin
		Route 2
		end
			1	Product_1	Queue_2	FIRST 1

```
                                                 2      Product_1   Queue_3     FIRST 1
Product_1  Queue_4                               1      Product_1   Machine_4   FIRST 1
Product_1  Machine_4  Constant_product1_process_2 = Constant_product1_process_2 + 3
                       Var2 = Array1[Constant_product1_process_2,1]
                       use Operator4 for 30 min
                       if Var2 = 1 then
                       begin
                       Route 1
                       end
                       if Var2 = 2 then
                       begin
                       Route 2
                       end                        1      Product_1   Queue_2     FIRST 1
                                                  2      Product_1   Queue_3     FIRST 1
Product_1  Queue_2                                1      Product_1   Machine_2   FIRST 1
Product_1  Machine_2  Constant_product1_process_3 = Constant_product1_process_3 + 3
                       Var3 = Array1[Constant_product1_process_3,1]
                       use Operator2 for 20 min
                        if Var3 = 1 then
                        begin
                        Route 1
                        end
                        if Var3 = 2 then
                        begin
                        Route 2
                        end
                        if Var3 = 3 then
                         begin
```

```
                          Route 3
                          end                        1   Product_1   Queue_1     FIRST 1
                                                     2   Product_1   Queue_2     FIRST 1
                                                     3   Product_1   Queue_3     FIRST 1
Product_1   Queue_3                                  1   Product_1   Machine_3   FIRST 1
Product_1   Machine_3   Constant_product1_process_3 = Constant_product1_process_3 + 3
                        Var3 = Array1[Constant_product1_process_3,1]
                        if Phase = 2 then
                        begin
                        use Operator6 for 10 min
                        end
                        if Phase = 1 then
                        begin
                        use Operator3 for 10 min
                        end
                        if Var3 = 1 then
                        begin
                        Route 1
                        end
                        if Var3 = 2 then
                        begin
                        Route 2
                        end
                        if Var3 = 3 then
                        begin
                        Route 3

                         end                         1   Product_1   Queue_1     FIRST 1
```

AppendicesIII

```
                                                 2    Product_1   Queue_2    FIRST 1
                                                 3    Product_1   Queue_3    FIRST 1
Product_1   Queue_1                              1    Product_1   Machine_1  FIRST 1
Product_1   Machine_1   if Phase = 2 then
                        begin
                        use Operator5 for 25 min
                        end
                        if Phase = 1 then
                        begin
                        use Operator1 for 25 min
                        end

                                                 1    Product_1   Warehouse  FIRST 1
Product_1   Warehouse                            1    Product_1   EXIT       FIRST 1
Product_1   Queue_2                              1    Product_1   Machine_2  FIRST 1
Product_1   Machine_2   use Operator2 for 20 min
                                                 1    Product_1   Warehouse  FIRST 1
Product_1   Warehouse                            1    Product_1   EXIT       FIRST 1
Product_1   Queue_3                              1    Product_1   Machine_3  FIRST 1
Product_1   Machine_3
                        if Phase = 2 then
                        begin
                        use Operator6 for 40 min
                         end
                        if Phase = 1 then
                        begin
                        use Operator3 for 40 min
                          end
```

AppendicesIII

```
                                                  1    Product_1  Warehouse  FIRST 1
Product_1  Warehouse                              1    Product_1  EXIT       FIRST 1
Product_2  Start         if Calhour() = 10 then
                         begin
                         Phase = 1
                         end
                         if Calhour() = 12 then
                         begin
                         Phase = 2
                         end                      1    Product_2  Cell_waiting1 SEND 1
Product_2  Cell_waiting1 Constant_product2_process_1 = Constant_product2_process_1 + 2
                         Var4 = Array2[Constant_product2_process_1,1]
                         if var4 = 1 then
                         begin
                         Route 1
                         end
                         if var4 = 2 then
                         begin
                         Route 2
                         end                      1    Product_2  Queue_3    FIRST 1
                                                  2    Product_2  Queue_4    FIRST 1
Product_2  Queue_3                                1    Product_2  Machine_3  FIRST 1
Product_2  Machine_3     Constant_product2_process_2 = Constant_product2_process_2 + 2
                         Var5 = Array2[Constant_product2_process_2,1]
                         if Phase = 2 then
                         begin
                         use Operator6 for 35 min
                           end
```

```
                                  if Phase = 1 then
                                  begin
                                  use Operator3 for 35 min
                                  end
                                  if var5 = 1 then
                                  begin
                                  Route 1
                                  end
                                  if var5 = 2 then
                                  begin
                                  Route 2
                                  end                              1    Product_2   Queue_1    FIRST 1
                                                                   2    Product_2   Queue_3    FIRST 1
Product_2   Queue_4                                                1    Product_2  Machine_4   FIRST 1
Product_2   Machine_4   Constant_product2_process_2 = Constant_product2_process_2 + 2
                         Var5 = Array2[Constant_product2_process_2,1]
                         use Operator4 for 25 min
                         if var5 = 1 then
                         begin
                         Route 1
                          end
                         if var5 = 2 then
                         begin
                         Route 2
                         end                                       1    Product_2  Queue_1      FIRST 1
                                                                   2    Product_2  Queue_3      FIRST 1
Product_2   Queue_1                                                1    Product_2 Machine_1    FIRST 1
Product_2   Machine_1   if  Phase = 2 then
```

```
                              begin
                              use Operator5 for 30 min
                              end
                              if  Phase = 1 then
                              begin
                              use Operator1 for 30 min
                              end
                                                              1    Product_2  Warehouse   FIRST 1
Product_2   Warehouse                                         1    Product_2   EXIT       FIRST 1
Product_2   Queue_3                                           1    Product_2  Machine_3  FIRST 1
Product_2   Machine_3
                              if Phase = 2 then
                              begin
                              use Operator6 for 20 min
                              end
                              if Phase = 1 then
                              begin
                              use Operator3 for 20 min
                              end
                                                              1    Product_2  Warehouse  FIRST 1
Product_2   Warehouse                                         1    Product_2    EXIT      FIRST 1
Product_3   Start             if Calhour() = 10 then
                               begin
                              Phase = 1
                               end
                               if Calhour() = 12 then
                                begin
                                Phase = 2
```

```
                              end                                          1  Product_3  Cell_waiting1 FIRST 1
Product_3    Cell_waiting1 Constant_product3_process_1 = Constant_product3_process_1 + 3
                              Var6 = Array3[Constant_product3_process_1,1]
                               if var6 = 1 then
                               begin
                               Route 1
                               end
                               if var6 = 2 then
                               begin
                               Route 2
                               end                                          1    Product_3  Queue_2    FIRST 1
                                                                            2    Product_3  Queue_3    FIRST 1
Product_3    Queue_2                                                        1    Product_3 Machine_2  FIRST 1
Product_3    Machine_2
                              Var7 = Array3[Constant_product3_process_2,1]
                              use Operator2 for 10 min
                              if var7 = 1 then
                              begin
                              Route 1
                              end
                              if var7 = 2 then
                             begin
                             Route 2
                              end                                           1    Product_3  Queue_1   FIRST 1
                                                                            2    Product_3  Queue_4   FIRST 1
Product_3    Queue_3                                                        1    Product_3 Machine_3 FIRST 1
Product_3    Machine_3
                               Var7 = Array3[Constant_product3_process_2,1]
```

```
                          if Phase = 2 then
                          begin
                          use Operator6 for 15 min
                           end
                           if Phase = 1 then
                           begin
                           use Operator3 for 15 min
                           end
                           if var7 = 1 then
                           begin
                           Route 1
                           end
                           if var7 = 2 then
                           begin
                           Route 2
                           end                                1    Product_3  Queue_1   FIRST 1
                                                              2    Product_3  Queue_4   FIRST 1
Product_3   Queue_4                                           1    Product_3 Machine_4 FIRST 1
Product_3   Machine_4   Var8 = Array3[Constant_product3_process_3,1]
                         use Operator4 for 20 min
                          if var8 = 1 then
                          begin
                          Route 1
                          end
                          if var8 = 2 then
                          begin
                          Route 2
                           end                                1    Product_3  Queue_2    FIRST 1
```

```
                                                                 2   Product_3  Queue_4    FIRST 1
Product_3   Queue_1                                              1   Product_3 Machine_1 FIRST 1
Product_3   Machine_1
                              Var8 = Array3[Constant_product3_process_3,1]
                              if Phase = 2 then
                              begin
                              use Operator5 for 15 min
                              end
                              if Phase = 1 then
                              begin
                              use Operator1 for 15 min
                              end
                              if var8 = 1 then
                              begin
                              Route 1
                              end
                              if var8 = 2 then
                              begin
                              Route 2
                              end                                1   Product_3  Queue_2    FIRST 1
                                                                 2   Product_3  Queue_4    FIRST 1
Product_3   Queue_2                                              1   Product_3 Machine_2 FIRST 1
Product_3   Machine_2   use Operator2 for 20 min
                                                                 1   Product_3 Warehouse  FIRST 1
Product_3   Warehouse                                            1   Product_3    EXIT       FIRST 1
Product_3   Queue_4                                              1   Product_3  Machine_4 FIRST 1
Product_3   Machine_4   use Operator4 for 15 min
                                                                 1   Product_3 Warehouse  FIRST 1
```

```
Product_3   Warehouse                                          1   Product_3   EXIT        FIRST 1
Product_4   Start       if Calhour() = 10 then
                        begin
                        Phase = 1
                        end
                        if Calhour() = 12 then
                        begin
                        Phase = 2
                        end                                    1  Product_4 Cell_waiting1 SEND 1
Product_4   Cell_waiting1 Constant_product4_process_1 = Constant_product4_process_1 + 2
                            Var9 = Array4[Constant_product4_process_1,1]
                            if Var9 = 1 then
                            begin
                            Route 1
                            end
                            if Var9 = 2 then
                            begin
                           Route 2
                            end
                           if Var9 = 3 then
                           begin
                           Route 3
                            end
                            if Var9 = 4 then
                           begin
                           Route 4
                           end                                 1   Product_4    Queue_1      FIRST 1
                                                               2   Product_4    Queue_2      FIRST 1
```

```
                                                                   3  Product_4  Queue_3    FIRST 1

                                                                   4  Product_4  Queue_4    FIRST 1

Product_4  Queue_1                                                 1  Product_4  Machine_1  FIRST 1

Product_4  Machine_1  Constant_product4_process_2 = Constant_product4_process_2 + 2

                       Var10 = Array4[Constant_product4_process_2,1]

                       if Phase = 2 then

                       begin

                       use Operator5 for 20 min

                       end

                       if Phase = 1 then

                       begin

                       use Operator1 for 20 min

                       end

                       if Var10 = 1 then

                       begin

                       Route 1

                       end

                       if Var10 = 2 then

                       begin

                       Route 2

                       end                                         1  Product_4  Queue_1    FIRST 1

                                                                   2  Product_4  Queue_2    FIRST 1

Product_4  Queue_2                                                 1  Product_4  Machine_2  FIRST 1

Product_4  Machine_2  Constant_product4_process_2 = Constant_product4_process_2 + 2

                       Var10 = Array4[Constant_product4_process_2,1]

                       use Operator2 for 30 min

                       if Var10 = 1 then

                         begin
```

```
                                   Route 1
                                    end
                                    if Var10 = 2 then
                                    begin

                                Route 2

                         end                                              1    Product_4     Queue_1       FIRST 1
                                                                          2    Product_4     Queue_2       FIRST 1
Product_4     Queue_3                                                     1    Product_4   Machine_3     FIRST 1
Product_4     Machine_3     Constant_product4_process_2 = Constant_product4_process_2 + 2
                                  Var10 = Array4[Constant_product4_process_2,1]
                                  if Phase = 2 then
                                  begin
                                  use Operator6 for 10 min
                                  end
                                  if Phase = 1 then
                                  begin
                                  use Operator3 for 10 min
                                  end
                                  if Var10 = 1 then
                                  begin
                                  Route 1
                                  end
                                  if Var10 = 2 then
                                  begin
                                  Route 2
                                  end                                    1    Product_4     Queue_1       FIRST 1
```

```
                                                                          2   Product_4    Queue_2     FIRST 1
Product_4   Queue_4                                                       1   Product_4   Machine_4    FIRST 1
Product_4   Machine_4   Constant_product4_process_2 = Constant_product4_process_2 + 2
                         Var10 = Array4[Constant_product4_process_2,1]
                          use Operator4 for 15 min
                          if Var10 = 1 then
                          begin
                          Route 1
                          end
                          if Var10 = 2 then
                          begin
                          Route 2
                          end                                               1   Product_4   Queue_1      FIRST 1
                                                                            2   Product_4   Queue_2      FIRST 1
Product_4   Queue_1                                                         1   Product_4  Machine_1    FIRST 1
Product_4   Machine_1   if Phase = 2 then
                         begin
                         use Operator5 for 20 min
                         end
                         if Phase = 1 then
                         begin
                         use Operator1 for 20 min
                         end
                                                                          1   Product_4    Warehouse    FIRST 1
Product_4   Warehouse                                                     1   Product_4   EXIT          FIRST 1
Product_4   Queue_2                                                       1   Product_4    Machine_2    FIRST 1
Product_4   Machine_2   use Operator2 for 30 min
                                                                          1   Product_4    Warehouse    FIRST 1
```

```
Product_4     Warehouse                                          1    Product_4      EXIT         FIRST 1
Product_dummy Signal      Constant = Constant + 1
                          Constant_product3_process_2 = Constant_product3_process_2 + 3
                          Constant_product3_process_3 = Constant_product3_process_3 + 3
                          Var_dummy1 = Array_signal[Constant, 1]
                          Var_dummy2 = Array_signal[Constant, 2]
                          Var_dummy3 = Array_signal[Constant, 3]
                          Var_dummy4 = Array_signal[Constant, 4]
                           if Var_dummy1 > 0 then
                           begin
                           send 1 Product_1 to Cell_waiting1
                           end
                           if Var_dummy2 > 0 then
                           begin
                          send 1 Product_2 to Cell_waiting1
                           end
                           if Var_dummy4 > 0 then
                           begin
                           send 1 Product_4 to Cell_waiting1
                           end                                1    Product_dummy Warehouse    FIRST 1
Product_dummy Warehouse                                       1    Product_dummy    EXIT      FIRST 1
     ***************************************************************************
                 *                     Arrivals                      *
     ***************************************************************************


Entity          Location     Qty Each   First Time    Occurrences    Frequency     Logic
------------- -------- ---------- ---------- ----------- ---------- ---------------------------------------------------------
Product_1         Start         1                          2           120 min
```

```
Product_2       Start     1                        2         120 min

Product_3       Start     1                        2         120 min

Product_4       Start     1                        2         120 min

Product_dummy   Signal    1                        2         120 min


      ********************************************************************************
                     *                  Shift Assignments                  *
      ********************************************************************************


Locations...    Resources...      Shift Files...              Priorities...  Disable   Logic...
------------ ------------ ----------------------------- ------------- ------- ------------------------------------------------
Machine_1                      New Results and shift\Shift fo 99,99,99,99    No


Machine_4                      New Results and shift\Shift fo 99,99,99,99    No


Machine_2                      New Results and shift\Shift fo 99,99,99,99    Yes


Machine_3                      New Results and shift\Shift fo 99,99,99,99    No


                Operator1       Shift-for-operator1.sft       99,99,99,99    No


                Operator3       Shift-for-operator3.sft       99,99,99,99    No


                Operator5       Shift-for-operator5.sft       99,99,99,99    No


                Operator6       Shift-for-operator6.sft       99,99,99,99    No
```

AppendicesIII

```
*********************************************************************************
                    *                   Attributes                   *
*********************************************************************************

ID         Type         Classification
---------- ------------ --------------
Phase      Integer      Entity

*********************************************************************************
                    *               Variables (global)               *
*********************************************************************************

ID                                     Type            Initial value       Stats
------------------------- ------------ ------------ -----------------------------------------------------------------
Var1                                   Integer                 0           Time Series
Var2                                   Integer                 0           Time Series
Var3                                   Integer                 0           Time Series
Var4                                   Integer                 0           Time Series
Var5                                   Integer                 0           Time Series
Var6                                   Integer                 0           Time Series
Var7                                   Integer                 0           Time Series
Var8                                   Integer                 0           Time Series
Var9                                   Integer                 0           Time Series
Var10                                  Integer                 0           Time Series
Var_dummy1                             Integer                 0           Time Series
Var_dummy2                             Integer                 0           Time Series
Var_dummy3                             Integer                 0           Time Series
Var_dummy4                             Integer                 0           Time Series
```

```
Constant                              Integer          0          Time Series

Constant_product1_process_1           Real            -2          Time Series

Constant_product1_process_2           Real            -1          Time Series

Constant_product1_process_3           Real             0          Time Series

Constant_product2_process_1           Real            -1          Time Series

Constant_product2_process_2           Real             0          Time Series

Constant_product3_process_1           Real            -2          Time Series

Constant_product3_process_2           Real            -1          Time Series

Constant_product3_process_3           Real             0          Time Series

Constant_product4_process_1           Real            -1          Time Series

Constant_product4_process_2           Real             0          Time Series

      ****************************************************************************

                    *                    Arrays                    *

      ****************************************************************************


ID            Dimensions    Type      Import File    Export File    Disable    Persist

------------ ------------ ------------ ----------- ----------- -------------- ---------------------------------------

Array1             9,1      Integer    Trial_2.xls                   None       No

Array2             4,1      Integer    Trial_2.xls                   None       No

Array3             6,1      Integer    Trial_2.xls                   None       No

Array4             6,1      Integer    Trial_2.xls                   None       No

Array_signal       3,4      Integer    Trial_2.xls                   None       No
```

```
*********************************************************************************
*                              External Files                              *
*********************************************************************************


ID         Type              File Name                                        Prompt
---------- ----------------- ------------------------------------------ -------------------------------------------
(null)                      Trial_2.xls
(null)     Shift            Shift-for-operator3.sft
(null)     Shift            Shift-for-operator6.sft
(null)     Shift            Shift-for-operator1.sft
(null)     Shift            Shift-for-operator5.sft
(null)     Shift            New Results and shift\Shift for mc2 sc5.sft
(null)     Shift            New Results and shift\Shift for mc1 sc1.sft
(null)     Shift            New Results and shift\Shift for mc4 sc1.sft
(null)     Shift            New Results and shift\Shift for mc3 sc1.sft
```