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An Integrated approach to energy efficiency in automotive manufacturing systems: quantitative analysis and optimisation

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ABSTRACT
Automotive manufacturing industries are facing new challenges in the multi-faceted context of economy, technology and environment. Increasing energy prices and environmental issues mean that energy is now one of major costs in automotive manufacturing industries and also responsible for a significant proportion of Green House Gas emissions. The development of energy efficient techniques in automotive manufacturing operations is crucial to reduce energy consumption, Green House Gas emissions and also production costs. This paper presents a simulation-based methodology and the associated software development for the modelling of thermal and energy management across the automotive manufacturing plant and its application to the effective energy management of the manufacturing systems on shopfloor through an energy smart production management (e-ProMan). After current laboratory/workshop trials, the system will undergo validation trials at a number of manufacturing SMEs.

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Energy efficiency; manufacturing systems; simulation

1. Introduction

Concerns about energy consumption have increased in the manufacturing industry due to a rise in energy cost and ecological adverse outcomes of production (American Council for an Energy Efficient Economy [ACEEE], 2009; Cheng & Bateman, 2008). Energy efficiency is the key driver in today's manufacturing industry as it leads manufacturing to deliver economic and environmental performance (Lovins, 2004). Consequently, energy efficiency policies have been set up to reduce energy consumption (World Energy Council, 2015). The amount of energy consumed in manufacturing systems accounts for a significant proportion of carbon emissions which has a major impact on climatic changes (International Energy Agency [IEA Statistics], 2015). More specifically, electricity is the major source of energy in manufacturing, and more than 60 per cent of all electricity is produced from fossil fuels (World Energy Council, 2015). For these reasons, carbon emissions are a crucial component of energy efficiency particularly in automotive industries. In U.S., it is estimated

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that $3.6 million is spent on energy cost in automotive manufacturing each year (Galitsky & Worrell, 2008). Machine processes and tools consume a significant amount of electrical energy. Thus, one solution is to improve the efficiency of machines and equipment such that carbon emissions can be reduced. This paper aims to present Energy-smart production management (e-ProMan) which is an application of efficient energy management system based on thermal and energy consumption.

2. Energy efficiency in automotive manufacturing systems

An energy efficiency system has a great potential in reducing energy consumption in the manufacturing (Fysikopoulos, Anagnostakis, Salonistis, & Chryssolouris, 2012). In automotive manufacturing, energy consumption can vary depending on various factors such as the size of the cars being produced. Clearly, the total energy assumption of a car manufacturing plant is determined by the operation system, energy efficiency management, HVAC system, etc. Recently, it has been estimated that the energy demand in manufacturing plant range between 1.39 and 3.42 with an average of 2.5 MWh per car (EuroEnergest, 2013). Optimisation of energy consumption is likely to reduce this rate.

Real-time control of production systems is becoming more critical in improving system efficiency and responsiveness and also in reducing breakdown period (Li, Blumenfeld, Huang, & Alden, 2009). For instance, General Motors greatly profited from real-time methodologies in its decision support system. Nonetheless, much effort has been given to individual processes of energy efficiency improvement (National Association of Manufacturers [NAM], 2005). Among these is a study by Mouzon, Yildirim, and Twomey (2007) who proposed a multi-objective mathematical programming model. It was found that a large amount of energy is consumed when non-bottleneck machines are idle; this can be greatly reduced when machines are not bottlenecks. Start-up and idling of machines in manufacturing thus require significant quantities of energy. Taking Toyota as an example, 85% of energy is consumed when machines are 'idling', and only 15% of energy is accounted for machining functions (Gutowski et al., 2005). Importantly, energy efficiency can be divided into four levels by which process is defined at the lowest level, followed by machine, line and factory, respectively (Fysikopoulos, Alexios, Georgios, Panagiotis, & George, 2013). The experimental part of this research particularly focuses on process and machine levels.

2.1. *Temperature control in manufacturing*

In order to provide suitable and comfortable environment for machines and workers, Health, Safety and Welfare regulation 1992 stated,

> The temperature of indoor workplaces should be reasonable. The approved code of practice defines a reasonable temperature indoors as being normally at least 16 °C unless the work involves severe physical work in which case the temperature should be at least 13 °C. (Health & Safety Executive, 2013)

Previous research claimed that the controllers must set a region of 4–5 °C between heating and cooling thermostat set points to establish a comfortable 'dead band' as shown in Figure 1. This would provide a cost reduction and appropriate working condition. The ideal comfort temperature in heavy manufacturing (automotive industries) and light factories

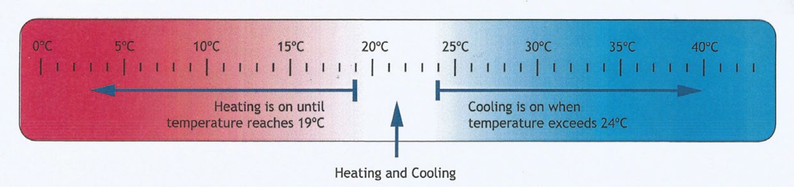


Figure 1. Diagram of 'Dead Band' control indication.

(laboratories) needs to be set at a range between 11–14 °C and 16–19 °C, respectively (Carbon Trust, 2011).

2.2. HVAC systems and their real-time management

Temperatures vary across different areas within a facility. For this reason, HVAC systems should be managed and controlled accordingly such that energy is consumed at a possibly lowest rate. More importantly, controllers for HVAC systems help regulate the environments within the comfortable parameters and also satisfy requirements set by local or national regulations (Haines & Wilson, 2003).

In spite of various methods in HVAC systems, the basic scheme of ON/OFF (also known as Bang Bang) control is the most common method and has contributed a significant impact on building automation (Wang & Ma, 2008). In this scheme, the controller is functioned in relation to the set point value. The inputs are turned on when the temperature has dropped below the lower set point, and when the temperature has risen above the upper set point value, the inputs are then turned off (Chinnakani, Krishnamurthy, & Moyne, 2011). The cycle continues in the same pattern. Therefore, a dead zone refers to the region between the upper and lower set point values in which the controller does not carry out any function.

A more accurate HVAC control system can benefit from real-time weather forecast data as real-time data are regularly updated. Numerical Weather Prediction or NWP model is a reliable predictive system that uses a computer simulation (Rodwell & Palmer, 2007). In this research, predictive weather data are obtained from Met Office. Met Office is selected as it is one of the meteorological specialists in UK and also uses NWP model in its system. Moreover, the present ON/OFF system in the HVAC controller does not only take into account the set point value but also use future weather forecast to maintain comfortable parameters and to minimise energy consumption.

2.3. Energy flow, work flow and information flow in a manufacturing systems

There is a correlation between energy flow, work flow and information flow. First, order forecasts and lot sizes establish a relationship between information flow and work flow. Consequently, the electricity is consumed during production processes which refer to the work flow. In terms of a correlation between work flow and energy flow, the different production rates cause different levels of energy consumption (Mori, Fujishima, Inamasu, & Oda, 2011). However, the results from the sum of individual parts or processes cannot directly provide the total energy consumption of the manufacturing system as individual processes can cause each other negatively or positively (Weinert, Chiotellis, & Seliger, 2011).

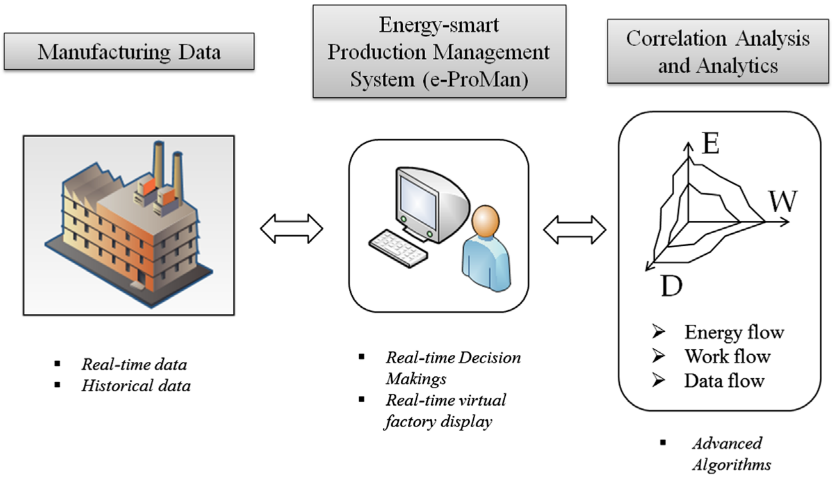


Figure 2. Development of energy-smart production management system (e-ProMan).

Hence, the investigation of energy management system should identify both positive and negative correlation between the three flows.

2.4. Development of simulation control for automotive manufacturing

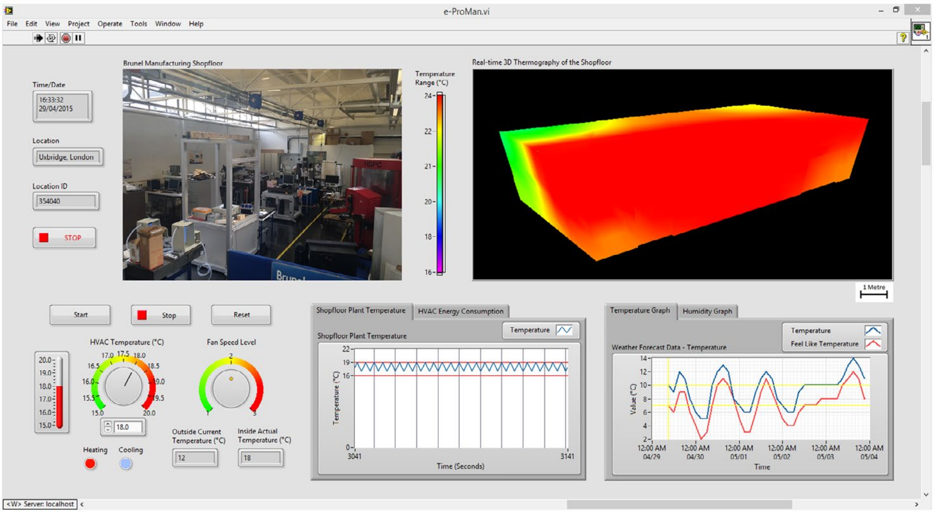
In an automotive industry, the manufacturing system operates in highly complex and dynamic environments. Especially, production processes are consisted of various machines serving different functions, consuming different amounts of energy and also generating different amounts of heat. As energy consumption in automotive industrial is affected by different variables, it is important to develop systematic energy efficiency methodically novel approach of energy consumption based on sustainable and low carbon manufacturing at machine, cell and shop-floor level. Figure 2 demonstrates a development of Energy-smart production management system (e-ProMan).

2.5. Manufacturing data

Manufacturing data consist of shopfloor temperature, climate forecast, production processes and production schedules, and energy consumption of CNC machines and HVAC system which include both historical and real-time data. LabVIEW and Arena Simulation programmes are used as data acquisition and implementation tools.

2.6. Energy-smart production management simulation

The e-ProMan simulation creates real-time virtual factory displays by using CAD models proceeding by using manufacturing data and analysing the correlation of energy flow, work flow and information flow. This system would create an accurate real-time decision-making. The system acquires data from three main sources: (1) temperature in manufacturing facility with temperature sensors, (2) weather forecast from the website and (3) energy consumption, production process and production schedule data via Arena Simulation programme



Time/Date 16:33:32 29/04/2015

Location Uxbridge, London

Location ID 354040

HVAC Temperature (°C) 18.0

Outside Current Temperature (°C) 12

Inside Actual Temperature (°C) 18

Figure 3. e-ProMan- forecastive control of HVAC systems.

including historical and real-time data. This programme runs continuously and displays the results over the period of time.

2.7. In-process correlation analysis and analytics

The process of correlation analysis is to provide a clear understanding of the relationship between energy flow, work flow and information flow in automotive industry. The development of this simulation will progress from this understanding.

3. Implementation and application perspectives

In this paper, the e-ProMan system is simulated in the Brunel Advanced Manufacturing shopfloor. The experiment partially provides manufacturing system environment compared to the actual manufacturing system. The experimental shopfloor system including one operating CNC machine, one ideal machine and measurement equipment. On the other hand, in the automotive manufacturing system, there are a variety of machines and processes operating simultaneously.

LabVIEW is used to combine all data and provide simulation control in manufacturing system. As shown in Figure 3, the HVAC controller acquires real-time temperature in Brunel manufacturing shopfloor using 10 temperature sensors and climate prediction data from Met office online database. The system controls the workshop temperature by comparing between actual and controlled temperatures. In this experiment, when the temperature in the shopfloor is lower than 16 °C and higher than 19 °C, the heating and the air conditioning system will automatically operate, respectively. In order to reduce the energy consumption, at the temperature range between 16 and 19 °C, the control system will turn off.

Energy consumption of a central air condition is typically 3000–5000 watts per hour operating about 3–7 months each year in the summer season depending on the outside weather. A water heater will use approximately 3000–4000 watts per hour to heat during

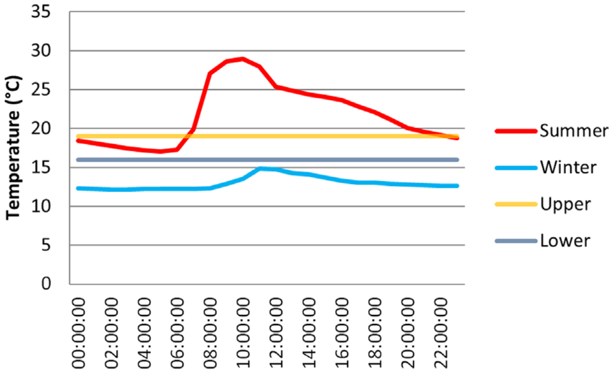


Figure 4. Brunel manufacturing shopfloor temperature.

the winter period. In addition, the HVAC controller also considers weather forecast in the near future to minimise the energy usage.

Generally, the HVAC systems are used to maintain the ambient temperature in buildings and also in manufacturing plants by using a difference of the temperature values between a current temperature and an ambient temperature (ΔT). This paper implemented an e-ProMan HVAC system which takes into account of the real-time weather forecast data. The simulation controller acquires and operates one hour in advance by considering (1) the current ambient temperature measures by the temperature sensors and (2) the weather temperature in the near future obtains from predictive weather forecast database in order to reduce energy usage consumed by the operation of the HVAC system. For instance, if the weather database predicts that the weather is going to drop by 5 °C in the next hour, the HVAC system would stop the air conditioning system and prepare to start the heating system.

4. Results and discussion

This research was conducted at two different periods of time which were Summer and Winter seasons at Brunel laboratory in London. The Summer experiment ran between 1 and 31 August 2014, and the Winter test ran from 1 to 31 January 2015.

Figure 5 illustrates the average temperature during the day in Summer 2014 and Winter 2015. Overall, in the Summer, the graph shows the fluctuation of the temperature over time. There was a sharp increase between 6am and 11am. It reached the peak at about 28 °C. In contrast, the Winter temperature slightly changed at around 13 °C over the period of time. According to the Health and Safety policies, manufacturing temperature needs to be maintained at a range between 16 and 19 °C. Hence, the air conditioning system should be operating frequently in the Summer season, especially in the morning. Additionally, the heating system will be running most of the time in the Winter period.

This paper proposes two different systems. The first is the ON/OFF system which is a basic HVAC system, and the second is the e-ProMan system which is a more advanced HVAC system concerning weather forecast. Generally, the total energy consumption of both HVAC systems in the Summer are lower than the ones in the Winter as shown in

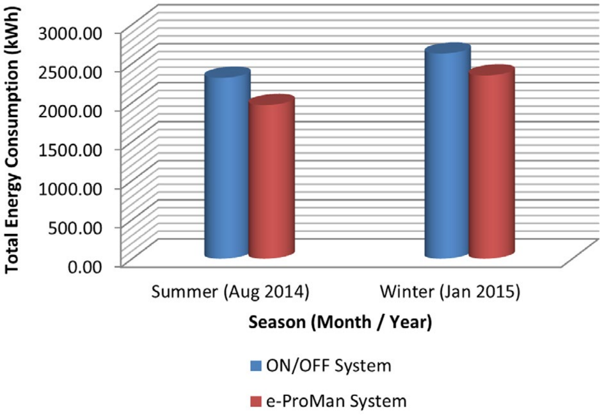


Figure 5. Results of total HVAC energy consumption.

Table 1. Results of total HVAC energy consumption comparison.

	Summer (Aug 2014)	Winter (Jan 2015)
On/Off system (kWh)	2317.50	2628.00
e-ProMan system (kWh)	1968.50	2347.00
Energy saving (%)	15.06	10.69

Figure 5. Importantly, the e-ProMan system can save energy usage in both Summer and Winter periods.

The results of the Summer and Winter experiments are compared in Table 1. In August 2014, e-ProMan reduced the energy consumption from 2317.50 to 1968.50 kWh which is about 15% deduction compared to the ON/OFF system. Also, more than 10% of energy usage was saved in January 2015 which is 281 kWh in comparison.

Interestingly, the percentage of energy saving in Summer season is greater than the Winter one because the Summer temperature is more fluctuate over the period of time. Hence, the weather forecast would significantly affect to the energy consumption in the Summer season.

5. Conclusions

In this paper, a prototype e-ProMan system is presented, which has a great potential to enhance efficiency of HVAC system by using real-time measurement and analysis. By including weather forecast data, the results show evidence of HVAC energy consumption reduction, thus minimising the overall energy usage in an automotive manufacturing system. The e-ProMan highlights the importance of taking temperature forecast data into account. In the future, machine processes will be included in the experiment in order to simulate precise factory environment. Also, the system will add the PID (Proportional-integral-derivative) controller to increase result accuracy. This research will further focus on work flow in the manufacturing process and provide the quantitative relationships between the information, work and energy flows in order to develop more complex and real manufacturing environment-based models for validation purposes.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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