The 6th International Conference on Manufacturing Research (ICMR08)
Brunel University, UK, 9-11th September 2008

LOW CARBON MANUFACTURING: CHARACTERIZATION, THEORITICAL MODELS AND IMPLEMENTATION

S. Tridech and K. Cheng

Advanced Manufacturing and Enterprise engineering (AMEE) Department, School of Engineering and Design, Brunel University, UK

Abstract

Today, the rising of carbon dioxide (CO_2) emissions is becoming the crucial factor for global warming especially in industrial sectors. Therefore, the research to reduce carbon intensity and enhance resources utilization in manufacturing industry is starting to be a timely topic. Low carbon manufacturing (LCM) can be referred to the manufacturing process that produces low carbon emissions intensity and uses energy and resources efficiently and effectively during the process as well.

In this paper, the concepts of LCM are discussed and the LCM associated theoretical models, characterization and implementation perspective explored. The paper is structured in four parts. Firstly, the conception of low carbon manufacturing is critically reviewed then the characterization of low carbon manufacturing is discussed and formulated. Third part, the theoretical models are developed with initial models by using the theory from supply chain modeling and linear programming solutions (LP). The models show the relationship of resource utilizations and related variables for LCM in two levels: shop-floor and extended supply chain. Finally, the pilot implementations of LCM are discussed with two approaches: desktop or micro machines and devolved manufacturing. The paper is concluded with further discussions on the potential and application of LCM for manufacturing industry.

Keywords: Low carbon manufacturing (LCM); Micro manufacturing system; Devolved manufacturing; Energy efficiency; CO_2 emissions

1.0 Introduction

Currently, global warming is extensively discussed as one of the most important global issues because of the rising of the amount of carbon and carbon dioxide contents emitted from industrial sectors. Many sectors have been trying to develop the solutions to solve and prevent this problem e.g. carbon emission analysis, software based prediction on economic factors and physical implementation using micro manufacturing system and microfactory. However, most of previous solutions does not mention about the configuration of the procedures to reduce carbon emission. Therefore, the effort to reduce carbon intensity and enhance resource utilizations is stated as a timely topic. The purpose of this paper is to develop an industrial feasible approach to implementing LCM including its theoretical models, methods and application perspectives.

2.0 Literature Review

2.1 Carbon Emissions Analysis

In the past decade, many countries have been conscious to develop the procedures for reducing carbon emissions. Fan et al. [1] have presented the model for prediction of carbon dioxide (CO_2) emissions based on the input of population, economy and urbanization. In 1996, Golove and Schipper [2] introduced the analysis of the tendency of energy consumption which can cause CO_2 emissions from manufacturing sectors based on the input of the gross domestic product (GDP) changed to economic output and process intensity. Although, these methods have been developed to deal with the global warming problem from carbon contents, the procedures to analyse is still focusing on the wide range and depending more on economic factors such as GDP. The procedures for reducing CO_2 emissions in manufacturing systems and the associated manufacturing processes have not been introduced yet.

2.2 Operational Model

In the area of production research, most of the research focuses on the objective such as cost minimization, quality assurance and the level of customer satisfaction as the objectives of the process optimization according to Gugor and Gupta (1999)[3]. Carbon emissions and energy efficiency have never been a critical factor in operation optimization. However, Mouzon et al. [4] have developed the operational model by using the theory of multi-objective mathematical programming in order to minimize energy consumption from equipments in manufacturing system. In the operational model, the constraints are focusing on completion time and total power per unit time. Even though, the production research for reducing total energy consumption has been introduced at this time, the operational model for reducing carbon contents from manufacturing processes need to be further developed.

2.3 Desktop and Micro Machine

The concepts of micro-factory and desktop machines for micro manufacturing purpose have been explored in the wide range. For the definition and concepts of the micro-factory and desktop machine, Yuichi [5] explain it as small scale manufacturing systems which can perform with higher throughput while resource utilization and energy consumption rate can be reduced simultaneously. In addition, Mishima [6] suggests that the concept of micro-factory and desktop machines should also concentrate on low heat generation and less energy consumptions of the systems. It is concluded that the innovation of desk-top and micro machine can be applied to the LCM by reducing the unnecessary carbon contents from manufacturing systems.

2.4 The Novell Approach: Devolved Manufacturing

The high proportion of carbon dioxide emissions not only comes from manufacturing systems and processes but also from the transportation while working on extended supply chains manufacturing. Bateman and Cheng [7] have introduced in a novel approach called Devolved Manufacturing (DM) which integrates main three elements together for future manufacturing systems: web based (e-manufacturing), mass customization (MC) and rapid manufacturing. The aim of this approach is to provide "factory-less" which customers can receive their products at the nearest location. In other words, this approach can be applied to minimize the transportation in associated with manufacturing systems set up. It is concluded that Devolved Manufacturing can be considered as an approach for reducing carbon contents emissions particularly for LCM in supply chain based manufacturing systems.

3.0 Characterization of Low Carbon Manufacturing

Low carbon manufacturing (LCM) can be described as the process that emits low carbon dioxide (CO_2) intensity from the system sources and during the manufacturing process. In addition, the term of LCM can be broadly not only for environmental aspect but also the energy conservation and effective production because the process uses energy excess available capacity/constraint (low energy efficiency) simultaneously without optimal algorithm to run process or system can lead to the high volume of carbon dioxide intensity to atmosphere (Figure1). Therefore, the main characterization of LCM can be categorized into specific five terms as follows:

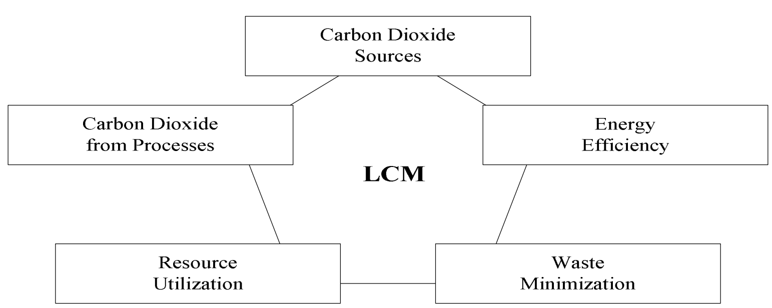


Fig. 1. Characterization of Low Carbon Manufacturing

1) Low carbon dioxide from source: currently, almost all equipment and machines in modern industry use electricity as a main energy to operate if machines or equipment can be adjusted or improved to use less energy, the carbon dioxide intensity from the machines and equipment sources will be reduced.
2) Energy efficiency: energy efficiency can be explained as a percentage of output of energy from process (in watt or joules) divided by the input of energy to the process [8]. Hence, this parameter in LCM concept should be higher than conventional industrial processes.
3) Waste minimization: This term can be meant as how waste can be dislodged or minimized according to the reference [9]. If the third criteria above are categorized into carbon dioxide emissions due to machines and equipment, it is emission from imperfect operation because waste can occur in the process. For example, many wastes can appear in the turbulent manufacturing process: idle time, waiting time and queuing time etc. Therefore, the optimal solution and algorithm (for example, optimal time to run machines and equipment which can conform to operational constraint) for the manufacturing process should be installed into LCM in order to minimize waste energy and thus carbon dioxide emissions.
4) Resource utilization: Sivasubramanian et al. [10] described that resource utilization in today industry can be typically observed from raw material usage and queue/waiting time in the process and priority rule in the process chain. These factors can become as constraints in problem formulation in order to create optimal production algorithm. The percent of carbon contents can be reduced when percent of resource utilizations are increased because unnecessary energy for CO_2 emissions is also reduced.

4.0 Implementation of LCM

Three implementations have been explored at Brunel University for LCM. The configuration of implementation of LCM is shown in Figure2.

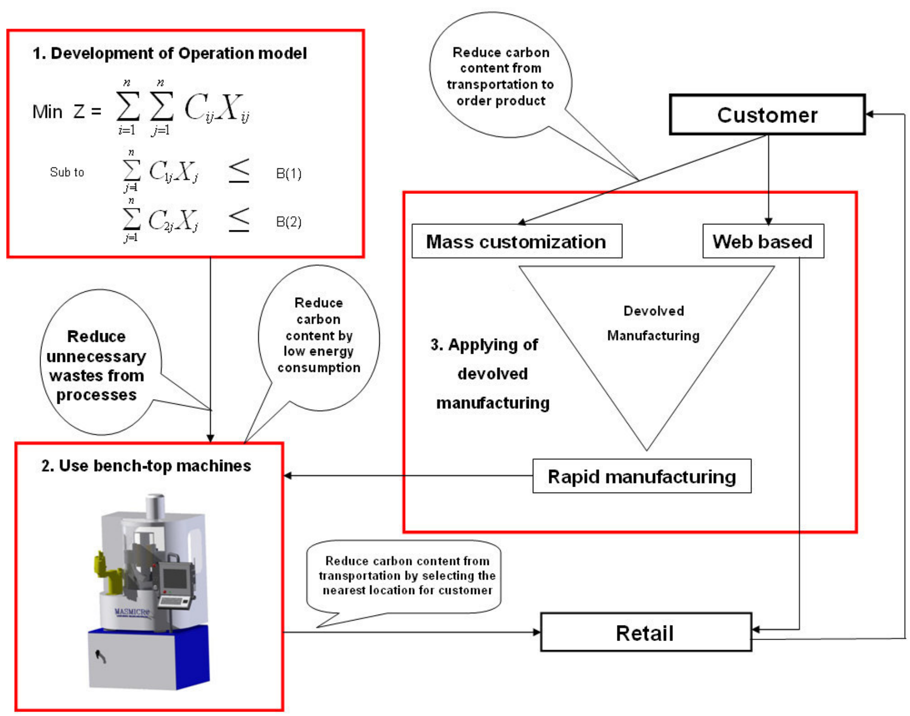


Fig. 2. Implemented Concepts for LCM

1) Development of operation models: this method is developed for establishing suitable objective function which can reduce carbon content from manufacturing processes. All resources causing carbon emissions are considered as constraints in the operation model in order to prevent unnecessary wastes occurred in idle and down time while the finished products can conform to customer's demand. Therefore, it could be described in another way that this method is specific for carbon minimization.
2) Using bench-top/micro machines: These kinds of machines have been developed in the concept of less energy consumption and small space requirement for processing. The reduction of carbon content of this method is specific on machines/equipments (locations). At Brunel University, bench-top machines have been developed for micro manufacturing purposes. However, it can be also used for LCM by taking advantage of their low energy consumption, resource efficiency and small foot print.
3) Applying of Devolved manufacturing: Bateman and Cheng have introduced the concept of Devolved Manufacturing which aims at achieving mass customized rapid manufacturing in a devolved web-based manner [11]. This method can be applied to the concept of LCM by minimizing carbon emission from make to order product (upstream) by customizing product via Internet-based instead through the nearest location (downstream) to pick-up finished goods. It can be explained in another words that this approach is focused on reducing carbon emission from supply network.

5.0 Operation Models for LCM

In this section, the operation models for LCM system are presented at two levels which concentrate on minimization of total used energy. The operational models are concerned with supplied chain level and shop-floor level respectively.

5.1 An Operational Model at Supply Chain Level

The model formulation was established based on the supply network presented by Taha [12]. The objective function sums up of total used energy in unit of joules to produce electricity of electrical flow in the supply network operation (source: power plant to sink: specific shop floor). The goal of this formulation is to minimize carbon intensity in supply network by finding the optimal electricity from (X_{ij}) between node i and j in unit of kWh. The formulation can be described as:

$$\text{Min } (f = \sum_{(i,j)\in\Omega} En_{ij} X_{ij}) \tag{1}$$

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

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

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

where

Z - set of node (location) in network = {A, B, C, D, E}
Ω - set of arc (path) in network = {(A,B), (A,C), (C,B), (C,D), (B,D), (B,E), (D,E)}
En_j - energy factor coefficient for flow X_{ij} (joules)
$C_{i,j:max}$ - maximum electrical capacity of arc (i,j) (kWh)

$C_{i,j:min}$ - minimum electrical capacity of arc (i,j) (kWh)
f_j - total net flow at node j (kwh)

5.2 An Operational Model at Shop-Floor Level

This formulation is developed by using the theory of linear programming solution (LP) [12]. The goal of this formulation is to minimize primary energy used during the manufacturing process by finding the optimal time (X_{ij}) to produce product i on machine j. The problem formulation can be described as follows:

$$\text{Min } (f = \sum_{i=1}^{n}\sum_{j=1}^{\phi} En_{ij} X_{ij}) \tag{2}$$

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

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

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

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

where

A - set of machines in the system {1, 2, …, Φ}, Φ is the maximum number of machine
B - set of products {1, 2, …, N}, N is the total number of product type
En_{ij} - coefficient of energy used to produce product i on machine j
δ - coefficient of lubricant used to produce product i on machine j
C_{ij} - coefficient of electricity consumed to produce product i on machine j
S_{ij} - processing time for producing product i on machine j
P_j - demand of total finished goods on machine j
L - total lubricant per period that equipment can resist
E - total electricity in specific area per period that shop-floor's fuse can resist

6.0 Experiments and Results

6.1 The System and Processes

There are five machines in the system: cutting machine, milling machine, machine centre, inspection machine and packaging machine. Each machine has two basic devices of the motor and oil tank to enable it in operation. The system starts operation at 8.00 am and ends at 10.00 pm. The process operates as job shop sequences by producing two products: gear and spindle. Processes of gear are cutting, milling, machining, inspect and packaging. Processes of spindle are machining, cutting, milling, inspect and packaging. Processing time of both two products is listed in Table 1 and energy consumption rate in Table 2.

Table 1. Processing time of the gear and spindle on each machine

Product	P:M1	P:M2	P:M3	P:M4	P:M5
Gear	15	15	15	15	15
Spindle	15	15	15	15	15
	30	30	30	30	30

Table 2. Energy consumption rate to produce the product on each machine

product	e:m1	o:ot1	e:m2	o:ot2	e:m3	o:ot3	e:m4	o:ot4	e:m5	o:ot5
Gear	1	1	1	1	1	1	1	1	1	1
Spindle	3	2	3	2	3	2	3	2	3	2
sum	4	4	4	4	4	4	4	4	4	4

M1: cutting machine; M2: milling machine, M3; machine centre; M4: inspection and M5: packaging; P:Mj = processing time on machine j (j = 1,2, …., 5); e:mj = electricity rate (kwh/cycle time) on motor j (j = 1,2, …., 5); o:otj = oil rate (litre/cycle time) on oil tank j (j = 1,2, …., 5). Energy is still provided to the devices although they do not perform any work (down and idle time) with E = 90 kWh, L = 65 litres. If total amount used electricity and lubricant are consumed over their limit, all motors and oil tanks will be shut down for 5 hours. If total electricity and oil used are over their limits, the value of these two variables will be reset to 0.

6.2 Optimization Procedures

Operation model aims at the optimal value by using optimization function in MATLAB programing. Optimal values can be the optimal time to turn-off each device. Secondly, optimal values can be used to establish operational shift for each device. In this research, two systems are established with same conditions and simulated to observe energy used from the process on ProModel simulations. The configuration of the systems in ProModel is illustrated in Figure 3. The first system is run normally but the second system is run with LP (shop-floor) model. Operational shift for the second system is presented in Table 3.

Table 3. Operational shift for each device

Device	Time
Motor 1, 2, 3, 4 and Oil tank 1, 2, 3, 4	16.30 pm
Motor 5 and Oil tank 5	13.00 pm

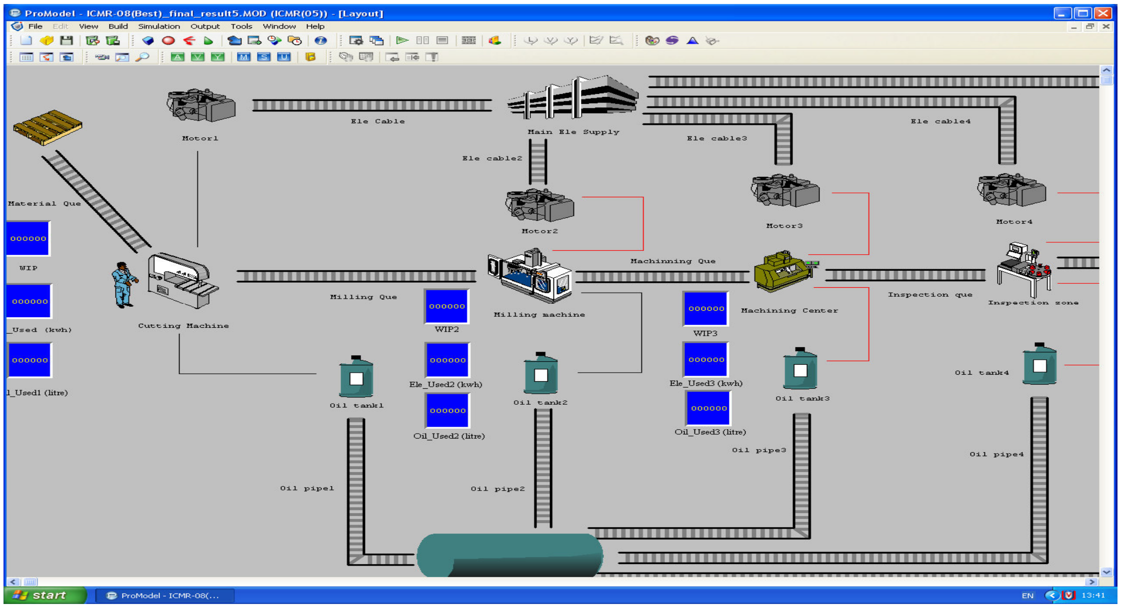
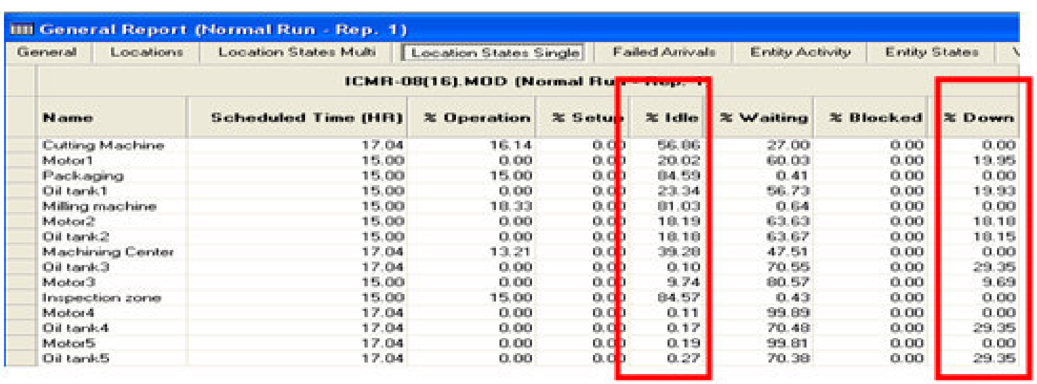


Fig. 3. The configuration of the systems in ProModel simulations

6.3 Results

Both systems are operated from 8.00 am to 1.00 am (to get results at steady state) in the same condition including inter arrival time of entity and operating algorithm. After running system simulation by using ProModel, the comparison of location states single between two systems are shown in Figure 4 and 5. Running the system with shop-floor model, the second system can eliminate percent of down time from operating period.



General Report (Normal Run - Rep. 1)

ICMR-08(16).MOD (Normal Run - Rep. 1)

Name	Scheduled Time (HR)	% Operation	% Setup	% Idle	% Waiting	% Blocked	% Down
Cutting Machine	17.04	16.14	0.00	56.86	27.00	0.00	0.00
Motor1	15.00	0.00	0.00	20.02	60.03	0.00	19.95
Packaging	15.00	15.00	0.00	84.59	0.41	0.00	0.00
Oil tank1	15.00	0.00	0.00	23.34	56.73	0.00	19.93
Milling machine	15.00	18.33	0.00	81.03	0.64	0.00	0.00
Motor2	15.00	0.00	0.00	18.19	63.63	0.00	18.18
Oil tank2	15.00	0.00	0.00	18.18	63.67	0.00	18.15
Machining Center	17.04	13.21	0.00	39.28	47.51	0.00	0.00
Oil tank3	17.04	0.00	0.00	0.10	70.55	0.00	29.35
Motor3	15.00	0.00	0.00	9.74	80.57	0.00	9.69
Inspection zone	15.00	15.00	0.00	84.57	0.43	0.00	0.00
Motor4	17.04	0.00	0.00	0.11	99.89	0.00	0.00
Oil tank4	17.04	0.00	0.00	0.17	70.48	0.00	29.35
Motor5	17.04	0.00	0.00	0.19	99.81	0.00	0.00
Oil tank5	17.04	0.00	0.00	0.27	70.38	0.00	29.35

Fig. 4. Location states single of the first system

General Report (Normal Run - Rep. 1)

General | Locations | Location States Multi | Location States Single | Failed Arrivals | Entity Activity | Entity States

ICMR-08(Best)_final_result4.MOD (Normal Run - Rep. 1)

Name	Scheduled Time (HR)	% Operation	% Setup	% Idle	% Waiting	% Blocked	% Down
Cutting Machine	15.00	25.00	0.00	57.70	17.30	0.00	0.00
Motor1	16.14	0.00	0.00	0.06	99.94	0.00	0.00
Packaging	17.14	14.58	0.00	27.91	45.57	11.94	0.00
Oil tank1	16.14	0.00	0.00	3.17	96.83	0.00	0.00
Milling machine	17.14	14.58	0.00	61.17	24.25	0.00	0.00
Motor2	14.08	0.00	0.00	0.01	99.99	0.00	0.00
Oil tank2	16.14	0.00	0.00	0.03	99.97	0.00	0.00
Machining Center	15.00	20.00	0.00	69.19	10.81	0.00	0.00
Oil tank3	16.14	0.00	0.00	0.11	99.89	0.00	0.00
Motor3	16.14	0.00	0.00	0.05	99.95	0.00	0.00
Inspection zone	15.00	16.67	0.00	82.85	0.48	0.00	0.00
Motor4	17.14	0.00	0.00	0.11	99.89	0.00	0.00
Oil tank4	16.14	0.00	0.00	0.18	99.82	0.00	0.00
Motor5	13.14	0.00	0.00	0.26	99.74	0.00	0.00
Oil tank5	13.14	0.00	0.00	0.34	99.66	0.00	0.00

Fig. 5. Location states single of the second system

Devices in the first system are down after and can not operate again until the end of operation shift. It can be described that unnecessary carbon emission occurred and thus the wasted energy. The statuses of device in the first and second system are shown in Figure 6.

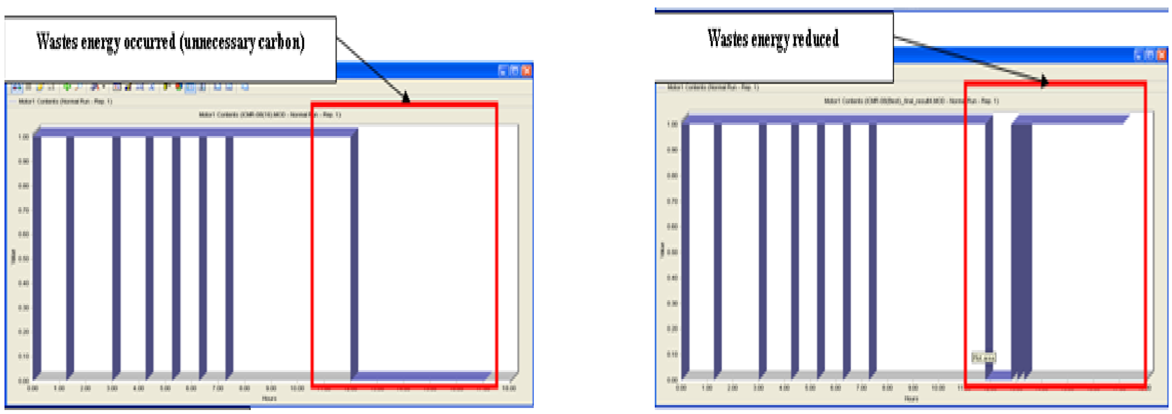


Fig. 6. The status of Motor1 in the first (left) system and second (right) system

6.4 Carbon Emissions

The amount of used energy is transformed into the unit of joules firstly then multiplied with emission factor and fraction of carbon oxidised to get carbon content in unit of Gg C according to the IPCC [13] approach. Energy consumption rate of motor and oil tank at down time & idle time are assumed to be at the rate of 0.067 kwh/min and 0.067 litre/ min respectively (each device's capacity = 1 and it is assumed that energy is consumed every 15 minutes at down & idle time: 1/15 = 0.067). The calculation of carbon emission from the first and second system is listed in Table 4.

Table 4. Carbon emissions from the first and second system

Device	Carbon Emissions (G gram Carbon * 10^{-3}) System 1	Carbon Emissions (G gram Carbon * 10^{-3}) System 2
Motor1	1723.986	2.77
Motor2	1565.982	0.396
Motor3	838.134	2.376
Motor4	5.74	5.742
Motor5	9.12	9.702
Oil1	26872.36	2115.822
Oil2	22566.06	19.998
Oil3	20785.64	74.448
Oil4	20827.22	119.988
Oil5	20909.99	165.528

7.0 Concluding Remarks

In this paper, the characterization and implementation for low carbon manufacturing (LCM) have been explored specifically for the manufacturing system from the upstream (demand of the product) through downstream (finished goods) of the process chain. In the simulated experiment, the results show the reduction of total used energy and carbon emissions when applied operation model at shop-floor level. The idle time and down time have been considered as main factors for the unnecessary wastes which can be reduced with energy constraints in mathematical model. However, the operation model can be improved in the future by taking account of more queuing system constraints. For the future work, energy consumption data from the bench-top machine developed at Brunel University will be used to further evaluate and validate the models and simulations and the analytical approach as a whole. Furthermore, the operation model will be applied to Devolved Manufacturing scenario for reducing CO_2 emissions at the extended manufacturing supply chain level.

References

[1] Fan Y., Liang Q., Wei Y and Okada N., 'A model for China's energy requirements and CO_2 emissions analysis', *Environmental Modelling & Software*, 22, 378-393, 2007.
[2] Golove W. H. and Schipper L. J., 'Long-Term Trends in U.S. Manufacturing Energy Consumption and Carbon Dioxide Emissions', *Energy*, 21, 683-692, 1996.
[3] Gugor, A. and Gupta, S.M., 'Issues in environmentally conscious manufacturing and product recover: a survey'. *Computers & Industrial Engineering*, 36, 811-853, 1999.
[4] Mouzon G., Yildirim M. B. and Twomey J., 'Operational methods for minimization of energy consumption of manufacturing equipment', *International Journal of Production Research*, 45, 4247-4271, 2007.
[5] Okazaki Y., Mishima N. and Ashida K., 'Microfactory-Concept, History and Development', *Transactions of the ASME: Journal of Manufacturing Science and Engineering*, 126, Issue 4, 837-844, 2004.
[6] Mishima N., 'A Study on a Microfactory and an Evaluation Method of its System Configuration', *Proceedings of IEEE International Conference on Mechatronics and Automation*, 25-28, 837-842, 2006.
[7] Bateman J.R. and Cheng K., 'Extending the product portfolio with devolved manufacturing: methodology and case studies', *International Journal of Production Research*, 44, No. 16, 3325-3343, 2006
[8] Wikipedia, in link: http://en.wikipedia.org/wiki/Energy_efficiency accessed on 19/02/2008
[9] Mulholland K.L. and Dyer J.A., 'Process Analysis via Waste Minimization: Using Dupont's Methodology to Identify Process Improvement Opportunities', *Environmental Progress*, 20, No. 2, 75-79, 2001.
[10] Sivasubramanian R., Selladurai V. and Gunasekaran A., 'Utilization of bottleneck resources for profitability through a synchronized operation of marketing and manufacturing', *Integrated Manufacturing*, 14/3, 238-246, 2003.
[11] Bateman J.R. and Cheng K., 'Devolved Manufacturing: theoretical perspectives', *Concurrent Engineering: Research and Applications*, 10, No.4, 291-297, 2002.
[12] Taha H.M., 'Operations Research An Introduction', Prentice-Hall, Inc., USA, 1997
[13] Intergovernmental Panel on Climate Change (IPCC), CO_2 Emissions from Fuel Combustion (2006 Edition), 2006.