The current issue and full text archive of this journal is available on Emerald Insight at:
www.emeraldinsight.com/0263-5577.htm

A detailed calculation model for costing of green manufacturing

Ifeyinwa Orji and Sun Wei
School of Mechanical Engineering,
Dalian University of Technology, Dalian, China

Received 15 April 2015
Revised 19 July 2015
Accepted 5 August 2015

Abstract

Purpose – Manufacturing firms are expected to implement green manufacturing and increase product complexity at a competitive price. However, a major problem for engineering managers is to ascertain the costs of embarking on green manufacturing. Thus, a planning and control methodology for costing of green manufacturing at the early design stage is important for engineering managers. The paper aims to discuss these issues.

Design/methodology/approach – This paper integrates "green manufacturing," concepts of industrial dynamics, and product lifecycle aiming at developing a methodology for cost calculation. The methodology comprises of a process-based cost model and a systems dynamics (SD) model. The process-based cost model focusses mainly on carbon emission costs and energy-saving activities. Important metrics usually ignored in traditional static modeling were incorporated using SD model.

Findings – Equipment costs and carbon emission costs are major components of costs in manufacturing. The total life cycle cost of product in green manufacturing is lower than that of same product in conventional manufacturing.

Research limitations/implications – The specific results of this study are limited to the case company, but can hopefully contribute to further research on ascertaining cost of implementing "green issues" in manufacturing. The proposed cost calculation model can be efficiently applied in any manufacturing firm on the basis of accessibility of real cost data. This necessitates a comprehensive cost database. At the development of the model and database management system, time and cost resources could be demanding, but once installed, use of the model becomes less demanding.

Practical implications – The cost model provides cost justifications of implementing green manufacturing. The reality is that green manufacturing will see its development peak with cost justifications. The results of the application show that the proposed detailed cost model can be effective in ascertaining costs of implementing green manufacturing. Manufacturing firms are recommended to adopt energy-saving activities based on the proposed detailed cost calculation model.

Originality/value – The main contributions of the study includes: first, to help engineering managers more accurately understand how to allocate resources for energy-saving activities through appropriate cost drivers. Second, to simulate with SD the dynamic behavior of few important metrics, often ignored in traditional mathematical modeling. The detailed model provides a pre-manufacturing decision-making tool which will assist management in implementing green manufacturing by incorporating a life cycle assessment measurement into manufacturing cost management.

Keywords Green manufacturing, Carbon emission costs, Energy-saving activities, Process-based costing, Product life cycle, Systems dynamics

Paper type Research paper

1. Introduction

Recently, with growing concerns on energy consumption and carbon dioxide emissions by industries, low-carbon manufacturing has gained very much attention. Manufacturing activities are one of the major sources of carbon dioxide emissions (IE Agency, 2007). Also, manufacturing firms have an estimated energy saving and energy efficiency potential of between 13 and 29 percent (European Commission (EU), 2006; IE Agency, 2009; IPCC, 2013a, b). Manufacturing firms are expected to implement green manufacturing and increase product complexity at a competitive price. However, a

Industrial Management & Data Systems
Vol. 116 No. 1, 2016
pp. 65-86
© Emerald Group Publishing Limited
0263-5577
DOI 10.1108/IMDS-04-2015-0140

major problem for engineering managers is to ascertain the costs of embarking on green manufacturing. At the design stage of manufacturing processes, the machines, materials, machining parameters, cutting tools and operation sequences can be harnessed for efficient resource consumption and reduction of carbon dioxide emissions at a competitive price. Thus, a planning and control methodology for costing of green manufacturing at the early design stage is important for engineering managers.

Green manufacturing can be defined as an efficient approach required in the design and production activities necessary for new product development and production system operations aimed at minimizing environmental impact. Reducing hazardous emissions, eliminating wasteful resources consumption and recycling are examples of green manufacturing activities (Deif, 2011). It is a manufacturing strategy that is conscious of the impact of operation/product on the environment and resources and incorporates such in its detailed planning and control.

In recent years, there has been a significant growth in research activities directed at reducing carbon intensity and green manufacturing. The green design and operation strategy of milling machines was studied based on the analysis of their energy consumption (Diaz *et al.*, 2010). Tridech and Cheng (2008) modeled the characteristics of low-carbon manufacturing by expanding the carbon emission analysis. An integrated low-carbon product design system based on bill of materials and embedded greenhouse gas emissions of product parts has been proposed (Song and Lee, 2010). A life cycle approach-based assessment method was proposed to characterize the carbon emissions of machine tools (Cao *et al.*, 2011). The concept of electricity carbon emission factor was introduced to establish the link between energy consumption and carbon emissions of manufacturing (Jeswiet and Kara, 2008). A thermodynamic framework to study the characteristics of the resource consumption and the environmental impact of manufacturing processes has been established (Gutowski *et al.*, 2009). The detailed breakdown of energy required to produce a single product on which energy inefficiencies were easily identified and improved has been modeled (Rahimifard *et al.*, 2010). The analysis of no-load energy characteristics of CNC machines has been researched (Hu *et al.*, 2012). An analytical method for quantifying carbon emissions generated from different processes associated with a CNC-based machining system was presented (Li *et al.*, 2013). A process planning method for reduced carbon emissions has been developed (Yin *et al.*, 2014).

Most past works as stated above target energy consumption and carbon dioxide emissions at the process level concentrating on individual equipment, machinery and work stations within a production system without considering costs. Most importantly, no study has been found which addresses how reduced costs will be achieved through green manufacturing considering the life cycle of machined product features.

The process-based cost modeling is a cost modeling approach for estimating cots more accurately and providing detailed cost consumption of products in their manufacturing process for detailed analysis. A typical process-based cost estimation method is the activity-based costing (ABC) approach. Various surveys have also indicated that the ABC approach has been used to analyze different kinds of management decisions in manufacturing firms (Lockamy, 2003; Comelli *et al.*, 2008; Lea, 2007; Tsai *et al.*, 2007; Kee, 2007, 2008; Qian and Ben-Arieh, 2008; Da Silva and Amaral, 2009; Tsai and Hung, 2009a, b; Ruiz-de-Arbulo-Lopez *et al.*, 2013). The basic assumptions in applying process-based costing (PBC) model are the homogeneity and proportionality assumptions. These assumptions limit the feasibility of the result in the presence of certain important metrics which exists in more than one category (e.g. capacity expansion and price elasticity) in manufacturing firms.

In efforts toward ensuring more reliable decision making, researchers have begun to apply soft operation research modeling techniques; these interprets, defines and explore various perspectives of the problem under scrutiny by employing predominantly qualitative, rational, interpretative and structured techniques (Orji and Wei, 2015). A good example of a soft operations research modeling technique is systems dynamics (SD). SD has a distinct advantage in analyzing, improving and managing the system characterized by long development cycle and complex feedback effects (Li *et al.*, 2012).

There exist in the literature many applications of SD (Ansari and Seifi, 2012, 2013; Aslani *et al.*, 2014; Feng *et al.*, 2013; Li *et al.*, 2012; Qudrat-Ullah, 2013; Shen *et al.*, 2009; Shih and Tseng, 2014; Thompson and Bank, 2010; Zhang *et al.*, 2014). Various necessary metrics (e.g. capacity expansion and price elasticity) which exist in more than one category during costing can be fully incorporated using SD. Therefore, SD can be applied during costing of green manufacturing.

In this work, concepts of SD, "green manufacturing," and product life cycle are integrated to develop a methodology for cost calculation. The relevant entire life cycle of the product are incorporated within a PBC decision methodology and both low-carbon manufacturing method and carbon emission costs analyzed simultaneously. Additionally, the SD approach is employed to incorporate capacity expansion and price elasticity into the costing process. The remaining parts of this paper will discuss a novel approach which is capable of: estimating the total carbon emissions and costs resulting from the life cycle assessment of machined product within a manufacturing facility; providing insight into capacity expansion and other important metrics often neglected in static modeling.

It is believed that this work can provide cost justifications of green manufacturing.

2. Background

Manufacturing firms are facing intense pressures to embark on green manufacturing. It is therefore imperative to ascertain cost of green manufacturing at an early stage. The PBC model can assist managers to become aware of design parameters that cause demands on optional and indirect resources. Through using PBC model, non-value-adding activities can be removed during design for carbon emission cost reduction thus minimizing resource depletion.

Orji *et al.* (2015) states that designing a PBC model involve the following steps:

- Step 1: identify the different overhead activities;
- Step 2: assign the overhead costs to the different activities using a resource driver;
- Step 3: identify the activity driver for each activity;
- Step 4: determine the activity driver rate by dividing the total activity costs by the practical volume of the activity driver; and
- Step 5: multiply the activity driver rate by the activity driver consumption to trace costs to orders, products or customers.

ABC provides information about a product's cost based on the resources used in its production (Tsai *et al.*, 2012). The problem of allocating indirect costs to products is solved by ABC through estimating the cost of activities that consumes resources and by linking these costs to the products (services) that are provided (Cao *et al.*, 2006; Lin *et al.*, 2007). ABC can be applied in a wide range of activities involving environmental metrics (Da Silva and Amaral, 2009).

With increased awareness of corporate social responsibility, manufacturing firms must consider carbon emission costs to help accurately predict manufacturing costs and reduce impact on the environment. Manufacturing companies must pay huge emphasis to environmental costs during the entire life cycle of green manufacturing assessment, such as carbon emission costs. Carbon emission costs are usually quantified through carbon tax policy. Even though the carbon tax would be regarded as an additional cost borne by companies, enhancement of occupant health and comfort, and productivity as well as a reduction in pollution levels would provide long-term benefits to people and society (Tsai *et al.*, 2014). An evidence from microdata in UK industries shows that carbon tax can reduce energy intensity and electricity use (Martin *et al.*, 2014). Thus, it is crucial for manufacturing firms to understand carbon emission cost policies and also consider carbon emission costs as part of the cost planning methodology for green manufacturing.

Green manufacturing is a sustainable form of manufacturing that integrates the life cycle concept, including green designs, production and distribution of raw materials, maintenance and disposal processes which minimize resource depletion. Some researchers have employed the life cycle assessment approach in green manufacturing; the life cycle assessment methodology has been widely applied in assessing the environmental burden of products and services during their life cycle (Tsai *et al.*, 2014). A life cycle approach-based assessment method was proposed to characterize the carbon emissions of machine tools (Cao *et al.*, 2011). An environmental burden analysis for machining operation was carried out using life cycle assessment (Narita *et al.*, 2008). The life cycle thinking becomes important in green manufacturing as renewable materials and efficient energy systems are employed to achieve sustainable development. Till date to the best our knowledge, not much attention has been given to the research of providing cost justifications of green manufacturing by employing life cycle thinking. This work pioneers the integration of green manufacturing, SD concept and product life cycle to develop a cost calculation model for green manufacturing; thus it comprises of an assessment of the energy consumption of machines and carbon emissions during manufacturing process. Six main stages in the life cycle of manufactured products are studied including development stage, manufacturing/production stage, operation/use stage, maintenance stage, decoupling stage and waste collection stage for recycling and reuse.

3. Methodology

The longitudinal and cross-wise designs were adopted to collect data on carbon emissions based on the activities in the relevant life cycle of manufactured product features. A manufacturing facility in China was used as the sample population. The case company is active in gear technology/manufacturing, and designs and produces components in partnership with their suppliers and customers. The company is situated in southern China and is fast expanding its china manufacturing footprint. In this study, the main gear manufacturing site is considered that is co-located with the product development site. This main manufacturing site has around 1,500 employees. The manufacturing facility includes more than 180 machines distributed in about 25 departments and provides maintenance operations to its coupled base of products in China. The manufacturing produces new gear part prototypes using collaborations from the designers at the development site. The engineering managers are faced with pressures to implement green manufacturing. However, they are unable to ascertain the costs of embarking on green manufacturing.

The conventional manufacturing is embarked upon by the company since its inception about a decade ago. The conventional manufacturing involves the use of cutting fluids, virgin steel material and high energy consumption fuel. This implies higher carbon emission quantities and carbon tax. In this work, energy-saving activities are introduced and carbon emission quantities minimized to reduce carbon tax which could lead to subsequent reduction of total cost of green manufacturing.

The information applied in the study was gathered from observations, archival records and personnel interviews. The personnel considered in this study were technicians, coordinators and design engineers. Questionnaires were issued to personnel for data collection. Data collection was carried out over a period of two years commencing in 2013 to provide information on energy consumption drivers in the life cycle stages (development, production, operation/use, maintenance, decoupling and waste collection) of the manufactured product. Information on the number of drawings and time for design and fuel for material transport were sourced from design engineers for the development stage. The information on the production process parameters were sourced from technicians and coordinators for the manufacturing stage. Fuel data, years of operation data and machine energy consumption data were collected for the use/operation stage from technicians and coordinators. Data on frequency of maintenance, distance to recycling plant, fuel type and electric power were collected for the maintenance, decoupling and waste collection stages from technicians. A simple average method was employed to estimate the average score of sourced data of a particular variable from different personnel. It is assumed that accurate cost information can be acquired by engineering personnel from the finance department to be applied in the decision methodology.

3.1 Model formulation

A planning methodology based on PBC techniques is formulated to calculate the costs of machined products in its relevant life cycle. Specific to the methodology, costs associated with machined products in green manufacturing environment include material costs, labor costs, equipment costs, energy-saving activity costs and carbon emission costs. It should be noted that capacity expansions, purchasing discounts and carbon emission costs were preliminarily factored into the PBC model. A SD was presented to further investigate dynamic behavior of capacity expansion and other important metrics often ignored in static mathematical modeling. The following assumptions are incorporated in the process-based planning methodology:

(1) Purchasing discounts will be offered if material order exceeds a minimum order quantity. Also capacity can be expanded using overtime work or additional night shifts as well as hiring temporary workers at a higher wage rate for a short term.

(2) The manufacturing firm highly emphasizes on corporate responsibility; thus carbon emissions will be calculated from the entire life cycle of machined products and increasing carbon emissions will increase taxation.

(3) Material costs, wage costs, equipment costs, energy-saving costs and carbon emissions costs are the costs associated with the entire life cycle of machined products. Other costs were excluded from this study.

4. Energy-saving activity costs were categorized into four levels namely unit level, batch level, process level and environmental level. Two types of manufacturing processes are considered: conventional manufacturing and green manufacturing.
5. Due to budgetary restrictions, total costs should remain constant. Engineering managers can acquire accurate cost information from the firm's finance department to apply to the decision methodology.

3.2 Material costs

The material costs of the machined product M_c can be computed with the following equations:

$$M_c = N_x P_x + \sum_{x \in d} (N_x P_x + N_{dx} P_{dx}) \tag{1}$$

$$\sum_{i=1}^{n} T_{ix} Y_i \leqslant P_x, \; x \in d' \tag{2}$$

$$P_x \leqslant Q_x, \; x \in d' \tag{3}$$

$$\sum_{i=1}^{n} T_{ix} Y_i \leqslant P_x + P_{dx}, \; x \in d \tag{4}$$

$$P_{dx} \geqslant M_{dx} S_{dx}, \; x \in d \tag{5}$$

$$P_x \leqslant M_{dx} I_{dx}, \; x \in d' \tag{6}$$

$$P_{dx} \geqslant Q_x S_{dx}, \; x \in d \tag{7}$$

$$I_{dx} + S_{dx} = 1 \tag{8}$$

$$P_x \geqslant 0 \tag{9}$$

where N_x is the unit cost of material x without purchase discount, P_x is the quantity of material x without purchase discount, N_{dx} is the unit cost of material x with purchase discount, P_{dx} is the quantity of material x without purchase discount, T_{xy} is the requirement of xth material for machined product y, M_{dx} is the minimum order quantity of xth material to obtain purchase discount, Q_x is the available quantity of xth material, S_{dx} is 0/1 variable; when 1, means quantity of xth material satisfies threshold discount and when 0, otherwise, I_{dx} is 0/1 variable; when 1, means quantity of xth material dissatisfies threshold discount and when 0, otherwise, S_y is a 0/1 variable; when 1, firm executes manufacturing process and when 0, otherwise, and d' is without discount while d is with discount.

Thus, the quantity of material should satisfy the demands of the machined product as stated in Equation (4). The terms in which a purchase discount qualified or not is stated in Equations (5) and (6). The limit condition of order quantity for purchase of material with discount is given by Equation (7). Equation (8) ensures singularity of conditions.

3.3 *Wage costs*

The wage costs for the machined products W_c are computed as follows:

$$W_c = W_1 + (W_2 - W_1)b_1 + (W_3 - W_1)b2 \tag{10}$$

$$H = \left[W_1 + (W_2 - W_1)_{b1} + (W_3 - W_1)_{b2}\right] \tag{11}$$

$$b_0 - m_1 \leqslant 0 \tag{12}$$

$$b_1 – m_1 - m_2 \leqslant 0 \tag{13}$$

$$b_2 - m_2 \leqslant 0 \tag{14}$$

$$b_0 + b_1 + b_2 = 1 \tag{15}$$

$$m_1 + m_2 = 1 \tag{16}$$

where H is the total manpower time requirement for the process, W_1 is the available manpower time to carry out work in manufacturing environment, W_2 is the overtime manpower time required for work, W_3 is the additional manpower hire time to complete work, b_0-b_2 is a set of non-negative variables, in which two consecutive variables at the most can be non-zero, W_{c1}-W_{c3} represent the total wage cost in W_1-W_3 conditions, respectively, m_1, m_2 are 0/1 variables, in which only one must be non-zero.

Equation (11) states that the process requires overtime work time and additional hire time for completion of process.

3.4 *Equipment costs*

The equipment costs E_c of machined products can be computed as follows:

$$E_c = \sum_{h=0}^{k} EC_h J_h \tag{17}$$

$$\sum_{y=1}^{n} Z_{yg} S_y - \sum_{e=1}^{t} O_e J_e \leqslant 1 \tag{18}$$

$$\sum_{e=1}^{t} J_{\mathrm{e}} = 1 \tag{19}$$

where E_h is the total equipment costs, O_e is the available equipment time, Z_{yg} is the requirement time of equipment g for process, J_e is a 0/1 variable; when 1, capacity demands of equipment can be expanded to eth level and when 0, otherwise.

3.5 Energy-saving activity costs

The energy-saving costs of machined products are categorized into four types namely unit level, batch level, environmental and process level.

The batch-level energy saving costs B_c is computed as follows:

$$B_c = \sum_{i=1}^{n} \sum_{j \in Bs} a_j f_{ij} B_{ij} \tag{20}$$

$$\sum_{y=1}^{n} f_{yj} B_{yj} = C_j, \ \ V_j \in B_s \tag{21}$$

$$S_y \leqslant \dot{\alpha}_{yj} B_{yj}, \ I = 1, \ 2, \ldots, n; \ \ V_j \in B_s \tag{22}$$

where a_j is the actual activity cost per activity driver for activity j, B_{yj} is the summation of batches during batch-level activity j, F_{yj} is the requirement expected of activity driver of batch-level activity j, C_j is the available/limit of capacity of activity driver of batch-level activity j, $\dot{\alpha}_{yj}$ is the number of materials used for batch-level activity j.

The process-level activity costs can be computed as follows:

$$\sum_{y=1}^{n} \sum_{j \in qz} a_j \beta_{yj} H_y \tag{23}$$

$$S_y \leqslant H_y, \ y = 1, 2, 3, \ldots ..n \tag{24}$$

$$\sum_{y=1}^{n} \beta_{yj} H_y \leqslant K_j, \ \ V_j \in Q \tag{25}$$

where $\boldsymbol{B}_{yj}$ is the requirement expected of activity driver of process-level activity j, K_j is the available/limit of capacity of activity driver of process-level activity j, a_j is the actual activity cost per activity driver for activity j, $V_j \in Q$ is the process-level activities.

The environmental-level activity costs can be computed as follows:

$$\sum_{y=1}^{n} \sum_{j \in PR} a_j \theta_{yj} \text{Đ}_y \tag{26}$$

$$S_y \leqslant W_y \tag{27}$$

$$\sum_{y=1}^{n} \theta_{yj} W_y \leqslant P_j, \ \ V \in R \tag{28}$$

where θ_{yj} is the requirement expected of activity driver of environmental-level activity j, P_j is the available/limit of capacity of activity driver of environmental-level activity j, a_j is the actual activity cost per activity driver for activity j, and $V_j \in R$ is the environmental-level activities.

3.6 Life cycle carbon emission costs

The carbon emission costs LCCE in the entire life cycle of machined products are computed as follows:

$$L_c = L\check{s}_1 + L\check{s}_2 + L\check{s}_3 \tag{29}$$

$$T_c = T\check{s}_1 + T\check{s}_2 + T\check{s}_3 \tag{30}$$

$$\check{s}_0 - \omega_1 \leqslant 0 \tag{31}$$

$$\check{s}_1 - \omega_1 - \omega_2 \leqslant 0 \tag{32}$$

$$\check{s}_2 - \omega_2 - \omega_3 \leqslant 0 \tag{33}$$

$$\check{s}_3 - \omega_3 \leqslant 0 \tag{34}$$

$$\check{s}_0 + \check{s}_1 + \check{s}_2 + \check{s}_3 = 1 \tag{35}$$

$$\omega_1 + \omega_2 + \omega_3 = 1 \tag{36}$$

where T_c is the total life cycle carbon emissions quantities, $\check{s}_1$-$\check{s}_3$ is a set of non-negative variables, in which two consecutive variables at the most can be non-zero, $L\check{s}_1$-$L\check{s}_3$ represent the total carbon emission costs in $T\check{s}_1$-$T\check{s}_3$ quantities, respectively, ω_1-ω_3 are 0/1 variables, in which only one must be non-zero.

It is assumed that documenting the quantities of carbon emissions in the life cycle of machined products would support carbon taxation policy and reduction of emission costs.

3.7 Total life cycle carbon emissions

The total life cycle carbon emissions can be defined as the sum of carbon emissions generated from various stages in the relevant entire life cycle of manufactured products. It is given by the following equation:

$$T_c = C_{dc} + C_{ma} + C_{op} + C_{mt} + C_{de} + C_{wc} \tag{37}$$

where C_{dc} is the carbon emissions in the development stage, C_{pr} is the carbon emissions in the production/manufacturing stage, C_{op} is the carbon emissions in the use/operation stage, C_{mt} is the carbon emissions in the maintenance/refurbishing stage, C_{dc} is the carbon emissions in the decoupling stage, C_{wc} is the carbon emissions in the waste collection for reuse/recycling stage.

3.7.1 Manufacturing stage. The carbon emission in the manufacturing stage of machined products is given by the following equation:

$$C_{pr} = C_{el} + C_{to} + C_{co} + C_{ma} + C_{ch} \tag{38}$$

where C_{el} is the carbon emissions caused by the generation of electricity, C_{to} is the carbon emissions caused by the production of cutting tools, C_{co} is the carbon emissions caused by the production of cutting fluid, C_{ma} is the carbon emissions caused by raw materials harvesting, C_{chy} is the carbon emissions generated from chip removal.

C_{el} can be calculated as follows:

$$C_{el} = F_{el} E_{ma} \tag{39}$$

where F_{el} is the electricity carbon emission factor, E_{ma} is the energy consumption of the machine.

Usually, machining process involves the interaction between the cutting tool, the material to be cut and the cutting fluid. Thus, the total power consumption P_t of a machine tool consists of idle power P_i, cutting power P_c and additional load loss P_a (Hu *et al.*, 2012). Thus the total power consumption required for the manufacturing is given in the following equation:

$$P_t(t) = P_i(t) + P_c(t) + P_a(t) \tag{40}$$

where t is time.

In this work, a product is denoted as y. Thus, the energy consumption of a machine tool required to manufacture a product is given in the following equation:

$$E_{my} = \int_0^T P_t(t)dt = \int_0^{t_i+t_c} P_i(t)dt + \int_0^{t_c} P_c(t)dt + \int_0^{t_i+t_a} P_a(t)dt \tag{41}$$

t_a is the summation of loading time, cleaning time and unloading time. Given that idle/passive power is defined as the power consumed by the machine when the system of its spindle is rotating with the necessary cutting speed before the process of manufacturing and is often constant. The idle time is the sum of handling (rapid axis movement, spindle motor, coolant, tool changer) time and cutting time. The cutting/machining power is power consumed during the machining process while additional loss/feed power is the power loss generated by the spindle of the machine.

Thus, Equation (41) is transformed to the following equation:

$$E_{may} = P_i(t_i + t_c) + P_c t_c + P_a(t_a + t_i) \tag{42}$$

The total power consumption P_t and the passive power P_i can be measured by power testing instruments. The idle time on the machine during the manufacture of product y t_i can be determined from historical data and observations.

The cutting time t_c is a function of the cutting speed, cutting depth, feed rate, product length, cutting edges, product diameter and machining allowance. The following equation shows the factors affecting the cutting time during the manufacture of product y:

$$t_c = \frac{\prod dL_y g}{1,000 v_c f z a_p} \tag{43}$$

where v_c is cutting speed, a_p is cutting depth, f is feed rate, L is product length, Z is cutting edges, d is product diameter, g is machining allowance.

The chip emissions CE_{chy} considered in this work are caused by the energy required for re-melting of chip material.

Hence, the following equation shows the carbon emissions generated from chip removal:

$$C_{ch} = F_{ch} W_{ch} \tag{44}$$

where F_{ch} is the carbon emission factor of chips. W_{ch} is the mass of removed material and is calculated in the following equation:

$$W_{ch} = \frac{MRRt_{cy}\rho}{10^3} = v_c a_p f z t_{cy} \rho \tag{45}$$

where ρ is the density of material expressed in (kg/cm^3). MRR is the removal rate and is determined by multiplying the cutting speed v_c, cutting depth a_p, number of cutting edges z and feed rate f as shown in the following equation:

$$MRR = v_c a_p f z \tag{46}$$

The carbon emissions C_{co} caused by the production of cutting fluid is comprised of two parts: C_{oil} and C_{wc}.

C_{oil} is the carbon emissions generated through the production of pure mineral oil. C_{wc} is the carbon emissions generated by the disposal of cutting fluid waste.

The various compositions of the carbon emissions caused by the production of cutting fluid are given in Equation (47):

$$C_{co} = \frac{t(C_{oil} + C_{wc})}{T_{co}} \tag{47}$$

$$t = t_c + t_i + t_a \tag{48}$$

where t is the machining throughput time, T_{co} is the life cycle of cutting fluid, C_{oil} is the carbon emission factors for the production of cutting fluid during machining, C_{wc} is the carbon emission factors for the disposal of cutting fluid.

In this work, C_{oil} is 2.895 kgCO$_2$/L while C_{wc} is 0.2 kgCO$_2$/L.

The carbon emissions of raw material harvesting C_{ma} is given by the following equation:

$$C_{ma} = F_{ma} M_{ma} \tag{49}$$

where F_{ma} is the carbon emission factor of the raw material which comprises of its embodied energy, M_{ma} is the mass of work piece material required for production.

The carbon emissions caused by the production of cutting tools CE_{to} is calculated in the following equation:

$$C_{to} = \frac{t_c F_{to} M_{to}}{L_{to}} \tag{50}$$

where M_{to} is the mass of cutting tool, F_{to} is the carbon emission factor of cutting tool, $L_{to}$is the life cycle of the cutting tool.

The carbon emission factor of cutting tools is dependent on its embodied energy which comprises of the embodied tool material energy and the further manufacturing steps of the cutting tool.

4. Results and discussion

In this study, carbon emission quantities are evaluated using carbon emission factors according to IPCC (2006). The machining activities are carried out on CNC machines based on a typical high-production scenario for the gear part shown in Figure 1.

Two types of manufacturing processes namely conventional and green manufacturing were considered in this work as stated in the methodology for machining the gear part to the same cutting standard. The parameters of conventional and green manufacturing are shown in Table I.

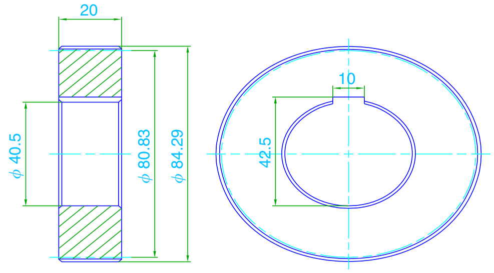

Figure 1.
Gear part

Table I.
Process parameters for machining

Parameter	Conventional manufacturing	Green manufacturing
Number of teeth	46	46
Cutting speed (m/min)	39	44
Thickness of tooth (mm)	20	20
Pressure angle (degrees)	30	30
Feed rate (mm/min)	73.5	83
Spindle speed (rpm)	147	166
Volume removal rate (mm^3/min)	315,290	356,041
Cutting time per cut (sec)	35	22
Volume of chips (mm^3)	85,793	85,793
Machining power (kW)	15.65	17.68
Cutting energy (kJ)	547.75	389.03
Idle power (kW)	10	15
Idle time (sec)	39	25
Energy consumption of machine (kJ)	1,792.75	1,514
Weight of cutting tool (kg)	1.50	2.70
Life cycle of cutting tool (min)	208	420
Cutter material	Cemented carbide	Cemented carbide
Replacement cycle	1 month	–
Rapid traverse (horizontal, *X*, *Y*) (m/min)	30	30
Rapid traverse (vertical, *Z*) (m/min)	24	24
Initial amount of mineral oil (L)	22	–
Additional amount of oil in replacement cycle (L)	0.09	–
Mass of work piece (kg)	3.50	2.54
Work piece material	Steel	Recycled steel

The carbon emissions of the gear part during the manufacturing stage were calculated as shown in Table II.

The carbon emissions generated from various stages in the relevant entire life cycle of the manufactured product are calculated based on Equation (37) as shown in Table III.

The various costs associated with the manufactured product are calculated based on Equations (1)-(28) as shown in Table IV.

As shown in Table IV, eight energy-saving activities are namely production, maintenance, material transport, product transport, waste collection, operation activity, waste reuse/recycling and design/development.

Three materials were considered for manufacturing as shown in material costs constraints. The supplier of materials 1 and 3 allows a purchase discount if a minimum order quantity of $PD_1 = 1{,}000$ kg and $PD_3 = 2{,}300$ kg is exceeded as shown in Table IV. The available man-hours is denoted by WO_1 and has a cost which increases when man-hours increases due to overtime work/additional night-shifts. Capacity of machines can also be expanded from $EO_1 = 3{,}000$ hr to $EO_3 = 6{,}000$ hr through machine rental from vendor which is at an increased cost. It is assumed that engineering managers can choose energy-saving activities depending on cost and quality requirements of the manufacturing process. Also the tax rate of carbon emissions depends on the quantity of carbon emissions. Increasing carbon emission quantity form $TLCCE_1 = 2{,}000$ kg to $TLCCE_3 = 7{,}000$ kg increases the tax rate to about twice. The life cycle cost of product in green manufacturing is less than cost of same product in conventional manufacturing.

A SD model is developed to examine the dynamic behavior of capacity (manpower and machine) expansion, purchasing discounts and carbon emission quantities and their relationship to costs. Figure 2 shows the SD model in Vensim.

The SD model presented shows the costs associated with the entire manufactured product life cycle which exist in more than one category and ignored during mathematical modeling. The costs considered as shown are material costs, wage costs, equipment costs and carbon emissions costs. The various costs are estimated by using capacity expansion and purchasing discounts to reach net requirement. The various costs are influenced by their respective rates and quantities. The aggregation of all the considered costs gives the total costs.

For a proper understanding of the dynamic behavior of capacity (manpower and machine) expansion, purchasing discounts and carbon emission quantities, an analysis of the variables has been carried out by simulations in Vensim. Simulation runs were carried out using data presented on Table IV.

Figure 3 shows the behavior of manpower. Figure 4 shows the behavior of manpower costs in manufacturing. Figures 5 and 6 shows the behavior of carbon emission costs and material costs, respectively. The behavior of machine capacity

	Conventional manufacturing (gCO_2)	Green manufacturing (gCO_2)
Carbon emissions of electricity	266	225.4
Carbon emissions of raw materials	9,415	1,882.14
Carbon emission of chips	243	176.5
Carbon emissions of cutting tools	124.5	69.8
Carbon emissions of coolant	3.91	–
Total carbon emissions	10,052.4	2,353.84

Table II.
Carbon emissions in manufacturing stage

Table III. Carbon emissions in the product life cycle

Life cycle stage	Carbon emission factor	Energy consumption driver	Conventional manufacturing	Green manufacturing
Development				
Product design planning	0.536 kgCO$_2$	Drawings	6	6
		Days	200	100
Material transport	2.2631 kgCO$_2$/L	Motor gasoline	0.0315	0.0187
	2.606 kgCO$_2$/L	Diesel oil	0.35 L	0.254 L
Carbon emissions in the development stage			1.555 kgCO$_2$	1.026 kgCO$_2$
Production				
Electricity consumption	0.536 kgCO$_2$ of electric power	Energy consumption of machine	1,792 kJ	1,514 kJ
Chip production	0.361 kgCO$_2$ of chip	Mass of chips	0.673 kg	0.488 kg
Cutting tool production	29.6 kgCO$_2$ of cutting tool	Mass of cutting tool	1.50 kg	2.70 kg
		Cutting tool life cycle	208 minutes	420 minutes
		Cutting time	35 seconds	22 seconds
Raw material harvesting	0.741 kgCO$_2$ of steel	Mass of steel material	3.50 kg	–
	2.69 kgCO$_2$	Mass of recycled steel	–	2.54 kg
Cutting fluid production	0.2 kgCO$_2$/L of cutting fluid waste	Total time	114 seconds	100 seconds
	2.895 kgCO$_2$/L of oily substances	Replacement time of coolant	1 month	–
Carbon emissions in the production stage			10,052.4 gCO$_2$	2,353.84 gCO$_2$
Use/operation				
Product coupling	0.536 kgCO$_2$	Electric power	0.0166 hours	0.0166 hours
Product transportation	2.2631 kgCO$_2$/L	Motor gasoline	0.0424 L	0.03076 L
Operation	0.536 kgCO$_2$	Machine energy consumption	0.0975 kJ	0.0707 kJ
		Years of operation	10	10
Carbon emissions in the use/operation stage			1.5 kgCO$_2$	1.16 kgCO$_2$
Maintenance				
Product maintenance	0.536 kgCO$_2$	Electric power	0.00694 hours	0.00694 hours
		Frequency	240	240
Carbon emissions in the maintenance/ refurbishing stage			0.89 kgCO$_2$	0.89 kgCO$_2$
Decoupling				
Product decoupling	0.536 kgCO$_2$	Electric power	0.0166 hours	0.0166 hours
Carbon emissions in the decoupling stage			0.0088 kg CO$_2$	0.0088 kgCO$_2$
Waste collection for reuse/recycling				
Waste transport	2.2631 kgCO$_2$/L	Motor gasoline	0.0424 L	0.03076 L
Carbon emissions in the waste collection for reuse/recycling stage			0.0959 kgCO$_2$	0.0696 kgCO$_2$
Total life cycle carbon emissions			14.10 kgCO$_2$	5.498 kgCO$_2$

and machine costs are shown in Figures 7 and 8, respectively. Thebehaviors depicted by the costs as shown in Figures 4-6 and 8 are due to the respective target requirements. In Figure 4, manpower costs remain constant over a period of time after which it increases due to capacity expansion resulting from overtime labor. A further increase in labor hours also leads to increase in manpower costs. The effect of carbon

		Conventional manufacturing	Green manufacturing
Unit level			
Production	Machining time (s)	149	114
	Unit cost ($/hr)	180	170
Maintenance	Labor time (minutes)	0.416	0.416
	Technician cost ($/hr)	1	1
Batch level			
Material transport	Transportation distance (km)	1,000	980
	Number of order	1	1
	Activity cost ($/km)	0.005	0.005
Product transport	Transportation distance (km)	1,200	1,200
	Cost per product ($/km)	0.005	0.005
Waste collection	Transportation distance (km)	1,200	1,200
	Batch size	1	1
	Activity cost ($/km)	0.005	0.005
Environment level			
Operation activity	Energy cycle (years)	10	10
	Unit cost ($/yr)	12	12
Waste reuse/recycling	Recycled waste (kg)	–	2.54
	Unit cost ($/kg)	–	3
Process level			
Design/development	Drawings/sketches	6	6
	Unit cost ($/cutter)	3	3
Material costs constraints			
$N_1 = \$2/kg$	$N_{d1} = \$1.5/kg$	$P_{d1} = 1{,}000$ kg	
$N_2 = \$5/kg$			
$N_3 = \$7/kg$	$N_{d3} = \$5.5/kg$	$P_{d3} = 2{,}300$ kg	
Wage costs constraints			
$W_1 = 1{,}000$ hr	$b_1 = \$1/hr$		
$W_2 = 1{,}600$ hr	$b_2 = \$1.8/hr$		
$W_3 = 2{,}900$ hr	$b_3 = \$2.5/hr$		
Equipment costs constraints			
$E_1 = 2{,}000$ hr	$E_2 = 3{,}500$ hr	$E_3 = 5{,}000$ hr	
$J_1 = \$180/hr$	$J_2 = \$290/hr$	$J_3 = \$350/hr$	
Carbon emission costs			
$T_{c1} = 2{,}000$ kg, $T_{c2} = 4{,}000$ kg, $T_{c3} = 7{,}000$ kg	14.10 $kgCO_2$	5.498 $kgCO_2$	
$s_1 = \$2$, $s_2 = \$3$, $s_3 = \$4$	\$2	\$2	
Total costs ($)	190.65	179.22	

Table IV. Activity-based costs of product

tax rate is shown in Figure 5. As shown, tax rate increases with increased carbon emission quantities. Figure 6 depicts the effect of purchasing discounts. As shown, a material vendor offers discounts for if the purchasing quantity exceeds a particular threshold.

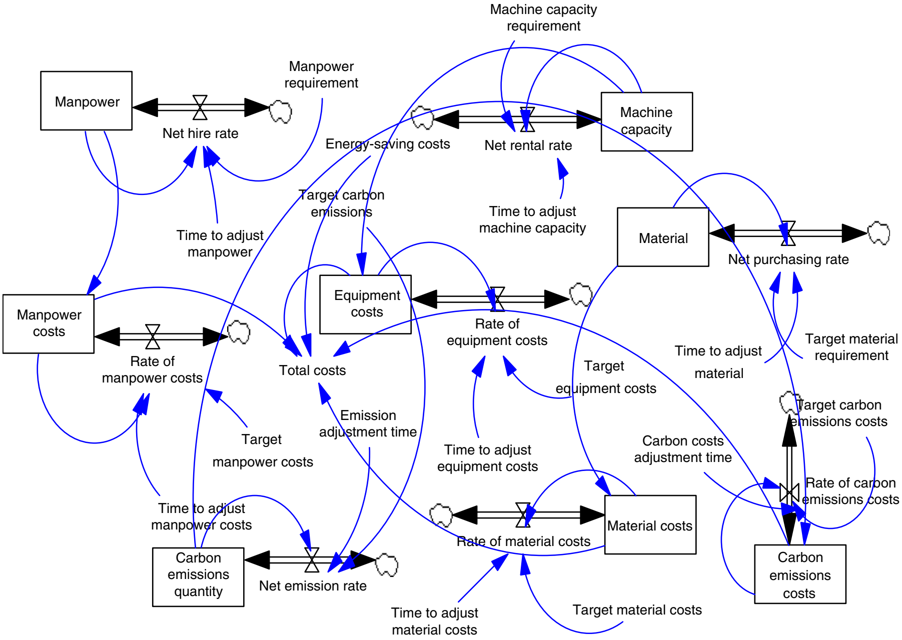

Figure 2. Systems dynamics model for costs in green manufacturing

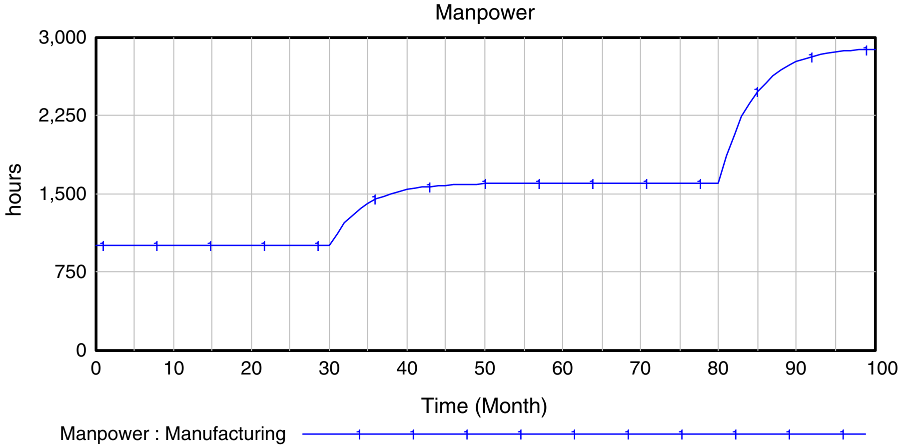

Figure 3. Vensim simulation results for manpower in manufacturing

The dynamic behavior of machine capacity is depicted in Figure 7. Machine capacity is increased through rental form vendors. With increased machine capacity, cost also increases as shown in Figure 8. From the Vensim simulation results, equipment costs and carbon dioxide emission costs are the major cost components influencing the product costs in manufacturing. Green manufacturing lowers carbon emission to provide environmentally friendly manufacturing thereby decreasing carbon emission costs. Thus, life cycle costs in manufacturing can be reduced through green manufacturing.

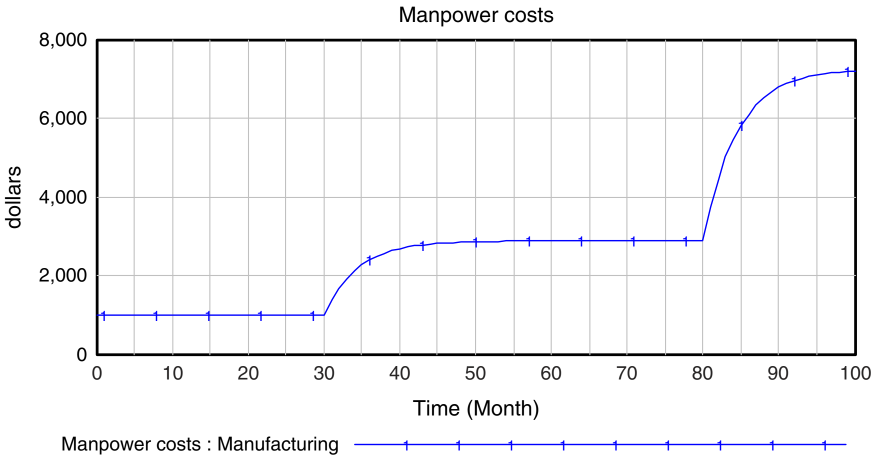

Figure 4. Vensim simulation results for manpower costs

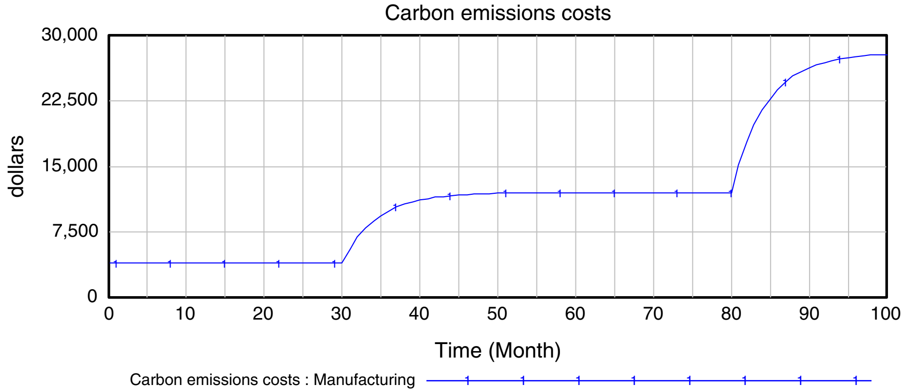

Figure 5. Vensim simulation results for carbon emissions costs

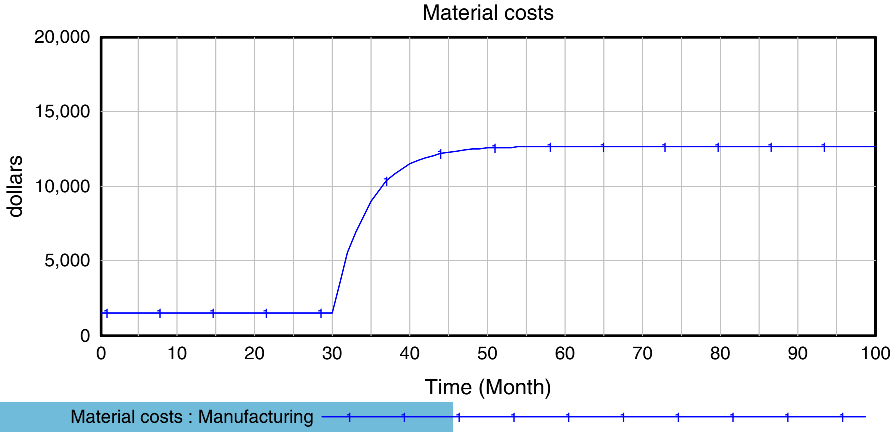

Figure 6. Vensim simulation results for material costs

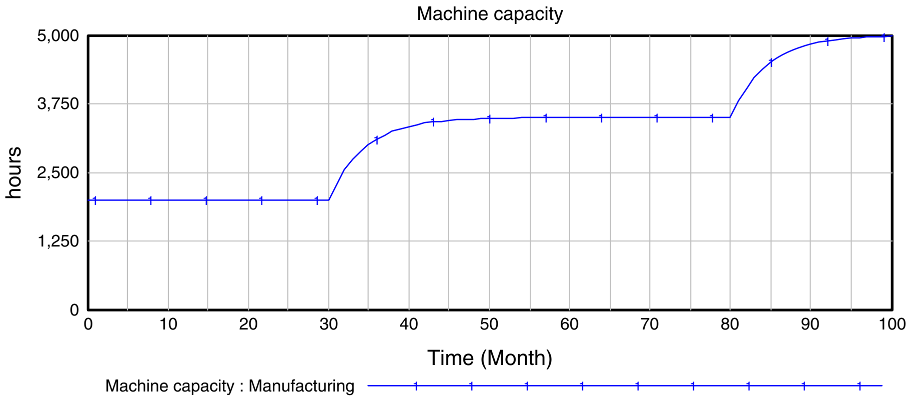

Figure 7.
Vensim simulation results for machine capacity

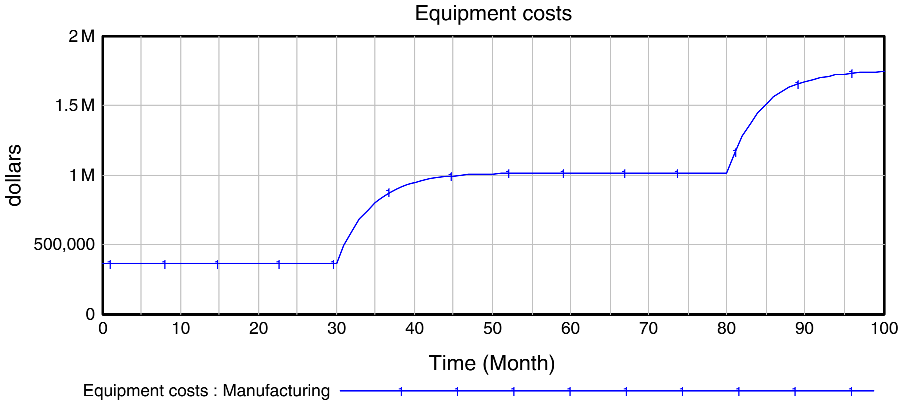

Figure 8.
Vensim simulation results for equipment costs

5. Conclusion, managerial implications and recommendations

This paper integrates “green manufacturing,” concepts of industrial dynamics, and product lifecycle aiming at developing a methodology for cost calculation. The methodology comprises of a process-based cost model and a SD model. The process-based cost model focusses mainly on carbon emission costs and energy-saving activities. SD model was applied to incorporate important metrics usually ignored in traditional static modeling. The study provides a decision-making tool which will assist management in implementing green manufacturing by incorporating a life cycle assessment measurement into manufacturing cost management.

It is possible to reduce the manufacturing costs by incorporating “green issues” at the unit level and batch level. At the unit level, production and maintenance activities are carried out. The cost reduction can be achieved through minimizing wastes during production and employing electric power. Waste minimization during production can be achieved through the use of recycled material and avoidance of cutting fluids. The carbon emissions of virgin materials accounts for the highest percentage of carbon emissions during production due to their high carbon emission factor. Using recycled materials which are characterized by low carbon emission factor can lead to a significant reduction in total carbon emission during production. Minimizing total carbon emission during production can cause a reduction in carbon emission tax which constitutes a larger part of total life cycle cost of product. Lengthened tool life, increased dimensional accuracy and reduced power consumption are some of the advantages of using cutting fluids during manufacturing. However, cutting fluid can pose a huge threat to the environment by emitting high carbon dioxide. Thus, it is recommended to management to use recycled materials and avoid use of cutting fluid during manufacturing. At the batch level, material and finished/used product are transported to the manufacturing facility, customer and waste reuse/recycling center. Costs at the batch level can be minimized through employing low energy consumption fuel type (e.g. motor gasoline) and electric power. Thus, engineering mangers are recommended to use electric power and low energy consumption fuel having low carbon emission factor. At the process level, design and development activities are carried out using drawings. Engineering managers are recommended to minimize cost through reducing number of drawings and design time for a new product prototype.

The specific results of this study are limited to the case company, but can hopefully contribute to further research on ascertaining cost of implementing "green issues" in manufacturing. The proposed cost calculation model can be efficiently applied in any manufacturing firm on the basis of accessibility of real cost data thus necessitating a comprehensive cost database. At the development of the model and database management system, time and cost resources could be demanding, but once installed, use of the model becomes less demanding.

The results of the application show that the proposed detailed cost model can be effective in ascertaining costs of implementing green manufacturing. Manufacturing firms are recommended to adopt energy-saving activities mainly at the unit level and batch level based on the proposed detailed cost calculation model. This work provides costs justification of green manufacturing.

References

Ansari, N. and Seifi, A. (2012), "A systems dynamics analysis of energy consumption and corrective policies in Iranian iron and steel industry", *Energy*, Vol. 43 No. 1, pp. 334-343.

Ansari, N. and Seifi, A. (2013), "A systems dynamics model for analyzing energy consumption and CO_2 emission in Iranian cement industry under various production and export scenarios", *Energy Policy*, Vol. 58 No. 1, pp. 75-89.

Aslani, A., Helo, P. and Naaranoja, M. (2014), "Role of renewable energy policies in energy dependency in Finland: systems dynamics approach", Vol. 113 No. 1, pp. 758-765.

Cao, H., Li, H.C. and Song, S.L. (2011), "Evaluation method and application for carbon emissions of machine tool based on life cycle assessment", *Computer Integrated Manufacturing Systems*, Vol. 17 No. 4, pp. 2432-2437 (in Chinese).

Cao, P., Toyabe, S., Kurashima, S., Okada, M. and Akazawa, K. (2006), "A modified method of activity-based costing for objectively reducing cost drivers in hospitals", *Methods of Information in Medicine*, Vol. 45 No. 4, pp. 462-469.

Comelli, M., Fenies, P. and Tchernev, N. (2008), "A combined financial and physical flows evaluation for logistic process and tactical production planning: application in a company supply chain", *International Journal of Production Economics*, Vol. 112 No. 1, pp. 77-95.

Da Silva, P.R.S. and Amaral, F.G. (2009), "An integrated methodology for environmental impacts and costs evaluation in industrial processes", *Journal of Cleaner Production*, Vol. 17 No. 15, pp. 1339-1350.

Deif, A.M. (2011), "A system model for green manufacturing", *Journal of Cleaner Production*, Vol. 19 No. 14, pp. 1553-1559.

Diaz, N., Choi, S., Helu, M., Chen, Y.F., Jayanathan, S., Yasui, Y., Kong, D., Pavanaskar, S. and Dornfeld, D. (2010), "Machine tool design and operation strategies for green manufacturing", *Proceedings of 4th CIRP International Conference on High Performance Cutting, Nagaragawa, October 24-26*, pp. 1-7.

European Commission (EU) (2006), "Action plan for energy efficiency: realising the potential", European Commission (EU), Paris.

Feng, Y.Y., Chen, S.Q. and Zhang, L.X. (2013), "Systems dynamics modeling for urban energy consumption and CO_2 emissions: a case study of Beijing, China", *Ecological Modelling*, Vol. 252 No. 1, pp. 44-52.

Gutowski, T.G., Branham, M.S., Dahmus, J.B., Jones, A.J. and Thiriez, A. (2009), "Thermodynamic analysis of resources used in manufacturing processes", *Environmental Science and Technology*, Vol. 43 No. 1, pp. 1584-1590.

Hu, S.H., Liu, F., He, Y. and Hu, T. (2012), "An on-line approach for energy efficiency monitoring of machine tools", *Journal of Cleaner Production*, Vol. 27 No. 1, pp. 133-140.

IE Agency (2007), "Tracking industrial, energy efficiency and CO_2 emissions", available at: www.iea.org/publications/freepublications/publication/tracking-industrial-energy-efficiency-and-co2-emissions.html (accessed April 1, 2015).

IE Agency (2009), *Towards a More Energy Efficient Future*, OECD/IEA, Stockholm and Paris, p. 15.

IPCC (2006), "Guidelines for national greenhouse gas inventories", *Energy*, Vol. 2.

IPCC (2013a), *Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*, Paris, IPCC.

IPCC (2013b), "Climate change 2013: the physical science basis", IPCC, Paris, available at: www.ipcc.ch/ (accessed April 1, 2015).

Jeswiet, J. and Kara, S. (2008), "Carbon emissions and CES in manufacturing", *CIRP Annals-Manufacturing Technology*, Vol. 57 No. 1, pp. 17-20.

Kee, R. (2007), "Cost-volume-profit analysis incorporating the cost of capital", *Journal of Managerial Issue*, Vol. 19 No. 4, pp. 478-493.

Kee, R. (2008), "The sufficiency of product and variable costs for production-related decisions when economies of scope are present", *International Journal of Production Economics*, Vol. 114 No. 2, pp. 682-696.

Lea, B.-R. (2007), "Management accounting in ERP integrated MRP and TOC environments", *Industrial Management & Data Systems*, Vol. 107 No. 8, pp. 1188-1211.

Li, C., Tang, Y., Cui, L. and Yi., Q. (2013), "Quantitative analysis of carbon emissions of CNC-based machining systems", *IEEE*, Vol. 10 No. 5.

Li, F., Dong, S., Li, Z., Li, Y., Li, S. and Wan, Y. (2012), "The improvement of CO_2 emission reduction policies based on system dynamics method in traditional industrial region with large CO_2 emission", *Energy Policy*, Vol. 51 No. 5, pp. 683-695.

Li, F.J., Dong, S.C. and Li, F. (2012), "A systems dynamics model for analyzing the eco-agriculture system with policy recommendations", *Ecological Modeling*, Vol. 227 No. 2, pp. 34-45.

Lin, B.Y., Chao, T.H., Yao, Y., Tu, S.M., Chern, J.Y. and Shaw, K.Y. (2007), "How can activity-based costing methodology be performed as a powerful tool to calculate costs and secure appropriate patient care?", *Journal of Medical Systems*, Vol. 31 No. 2, pp. 85-90.

Lockamy, A. III (2003), "A constraint-based framework for strategic cost management", *Industrial Management & Data Systems*, Vol. 103 No. 8, pp. 591-599.

Martin, R., de Preux, L.B. and Wagner, U.J. (2014), “The impact of a carbon tax on manufacturing: evidence from microdata”, Vol. 117 No. 1, pp. 1-14.

Narita, H., Desmira, N. and Fujimoto, H. (2008), “Environmental burden analysis for machining operation using LCA method”, *The 41st CIRP Conference on Manufacturing Systems, Hongo Campus, May 26-28*, pp. 65-68.

Orji, I.J. and Wei, S. (2015), “An innovative integration of fuzzy logic and systems dynamics in sustainable supplier selection: a case on manufacturing industry”, *Computers & Industrial Engineering*, Vol. 88 No. 10, pp. 1-12.

Orji, I.M.-J., Akanbi, O. and Wei, S. (2015), “Cost modelling in healthcare systems: a case of radiology department of a teaching hospital”, *International Journal of Industrial and Systems Engineering*, Vol. 19 No. 1, pp. 50-74.

Qian, L. and Ben-Arieh, D. (2008), “Parametric cost estimation based on activity-based costing: a case study for design and development of rotational parts”, *International Journal of Production Economics*, Vol. 113 No. 2, pp. 805-818.

Qudrat-Ullah, H. (2013), “Understanding the dynamics of electricity generation capacity in Canada: a systems dynamics approach”, *Energy*, Vol. 59 No. 4, pp. 285-294.

Rahimifard, S., Seow, Y. and Childs, T. (2010), “Minimizing embodied product energy to support energy efficient manufacturing”, *CIRP Annals – Manufacturing Technology*, Vol. 59 No. 3, pp. 25-28.

Ruiz-de-Arbulo-Lopez, P., Fortuny-Santos, J. and Cuatrecasas-Arbós, L. (2013), “Lean manufacturing: costing the value stream”, *Industrial Management & Data Systems*, Vol. 113 No. 5, pp. 647-668.

Shen, Q., Chen, Q., Tang, B.-S., Yeung, S., Hu, Y. and Cheung, G. (2009), “A systems dynamics model for the sustainable land use planning and development”, *Habitat International*, Vol. 33 No. 1, pp. 15-25.

Shih, Y.-H. and Tseng, C.-H. (2014), “Cost-benefit analysis of sustainable energy development using life-cycle co-benefits assessment and the system dynamics approach”, *Applied Energy*, Vol. 119 No. 4, pp. 57-66.

Song, J.S. and Lee, K.M. (2010), “Development of a low-carbon product design system based on embedded GHG emissions”, *Resources Conservation and Recycling*, Vol. 54 No. 9, pp. 547-556.

Thompson, B.P. and Bank, L.C. (2010), “Use of system dynamics as a decision-making tool in building design and operation”, *Building and Environment*, Vol. 45 No. 4, pp. 1006-1015.

Tridech, S. and Cheng, K. (2008), “Low carbon manufacturing: characterization, theoretical models and implementation”, *The 6th International Conference on Manufacturing Research, Brunel University*, pp. 403-412.

Tsai, W.H. and Hung, S.J. (2009a), “A fuzzy goal programming approach for green supply chain optimization under activity-based costing and performance evaluation with a value-chain structure”, *International Journal of Production Research*, Vol. 47 No. 18, pp. 4991-5017.

Tsai, W.H. and Hung, S.J. (2009b), “Treatment and recycling system optimization with activity-based costing in WEEE reverse logistics management: an environmental supply chain perspective”, *International Journal of Production Research*, Vol. 47 No. 19, pp. 5391-5420.

Tsai, W.-H., Hsu, J.-L. and Chen, C.-H. (2007), “Integrating activity-based costing and revenue management approaches to analyse their manufacturing outsourcing decision with qualitative factors”, *International Journal of Revenue Management*, Vol. 1 No. 4, pp. 367-387.

Tsai, W.H., Chih-Hao, Y., Jui-Chu, C. and Lee, H. (2014), "An activity-based costing decision model for life cycle assessment in green building projects", *European Journal of Operational Research*, Vol. 238 No. 2, pp. 607-619.

Tsai, W.H., Lee, K.C., Lin, H.L., Chou, Y.W. and Jin, S.J. (2012), "A mixed activity-based costing decision model for green airline fleet planning under the constraints of the European union emissions trading scheme", *Energy*, Vol. 39 No. 1, pp. 218-226.

Yin, R., Cao, H., Li, H. and Sutherland, J.W. (2014), "A process planning method for reduced carbon emissions", *International Journal of Computer Integrated Manufacturing*, Vol. 27 No. 12, pp. 1175-1186.

Zhang, X., Wu, Y., Shen, L. and Skitmore, M. (2014), "A prototype system dynamic model for assessing the sustainability of construction projects", *International Journal of Project Management*, Vol. 32 No. 1, pp. 66-76.

Further reading

Forrester (1961), *Industrial Dynamics*, Wiley-Interscience, New York, NY.

Liu, J. and Chen, J. (2010), "Variation modeling and analysis for complex products multi-stage machining process", *IEEE.*

Sterman (2000), *Business Dynamics: Systems Thinking and Modeling for a Complex World*, McGraw Hill Education, Boston, MA.

Corresponding author

Ifeyinwa Orji can be contacted at: ifindustrial@yahoo.com