AN OPTIMIZATION OF PRODUCT DESIGN AND MANUFACTURING BASED ON SUSTAINABILITY

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Abstract

In the 21st century, manufacturing companies are facing the challenge to remain competitive in global markets by finding a more sustainable approach to product design and manufacturing. This is associated with the main features of companies' competitive landscapes namely, simultaneous cost reduction and quality improvement of the product. It may appear that reaching both these goals together is prohibitively problematic as they are considered by "manufacturing leaders" as opposing objectives. However, much recent research has been done on introducing approaches to delivering low cost, high quality sustainable products based on finding a link between the design or the manufacturing processes and other key elements of sustainability; economic, environmental, and social. Indeed, these approaches often times include limitations such as the lack of integration between the design and manufacturing stages of the product and do not adequately address three key parts of sustainability; economic, environmental, and social. Consequently, these approaches, have a low applicability, and hence few opportunities for success. However, for delivering a sustainable product, the key parts of sustainability, as well as the integration of product design and manufacturing processes must be optimised in terms of one effective measure. This project aims to propose an approach for design and manufacturing sustainability. The combined sustainability index (CSI) is developed as a comprehensive evaluation metric for alternative scenarios of the process and also as a tool that enables decision makers to run optimal processes. The applicability of the CSI has to be tested and verified in a real industrial setting with the aim to improve the sustainability performance by designing a product and the corresponding manufacturing processes for that product. Process optimisation is carried out in terms of the highest CSI score achieved.

Keywords: Sustainable Manufacturing and Design; combined sustainability index (CSI); model, multi-objective

1. Introduction

The need to implement sustainability concept in designing and manufacturing products has become, more than ever, a matter of crucial importance in today's economy. From the descent of raw materials through to the final use and disposal, sustainable or "green" products outweigh conventional products on their environmental and social intrinsic worth. Manufacturers need to follow activities of production internalize negative environmental externalities while profits maximize and social economic benefits. Most of the manufacturing organizations expend large quantities of resources at

the same time generate wastes and pollution. However with recent increase in sustainability issues, organizations should consider taking suitable measures to enhance their sustainability aspects. It has thus become the need of the time for manufacturers to pursue manufacturing activities, which helps in minimizing environmental impacts while maintaining social and economic benefits (Joung et al. 2013) [1]. One of definitions of the sustainability is Brundtland description. It explains sustainability as “meeting the needs of the present generation without compromising the ability of future generations to meet their own needs [2]. The purpose of this paper is to determine the sustainable product and to set major operational parameters to maximize a proposed manufacturing sustainability index.

2. Literature Review

Siddhartha Kushwaha (2005), proposed index term as “A Comprehensive Sustainability Index (CSI) Balanced Social, Economic & Environmental Approach” to measure sustainability of countries based on the triangular tradeoff among environment, economy and society. The comprehensive sustainability index (CSI) is based on genuine saving, ESI, EPI and HDI. Collected hierarchal clustering method is used to group 101 countries with their peers into two groups : (1) More Sustainable Nations (63 countries) and (2) Less Sustainable Nations (38 countries). The low standard deviation in CSI represents the clustering of nations about mean CSI value. The clustering is an indicator of mediocre sustainability of nations. Hence severe measures are needed to be taken by governments, policy makers, industry and residents to increase the sustainable environment [3].

Schmidt and Butt (2006) developed method term as product sustainability index (PSI), was based on LCA impact assessment categories. It includes eight key environmental indicators across three major aspects of the product sustainability. The economic indicators are from Life-cycle Costing (LCC) assessment method. The societal indicators are aimed at evaluating the safety and mobile capability of a product. This methodology was further applied to two of their vehicle models [4].

de Silva et al.(2009) , Ungureanu et al.(2007) developed sustainability scoring method to quantitatively assess the potential benefits of using aluminum alloys for manufacturing of an auto body. This method involves six major elements of the Design for Sustainability (DfS): environmental impact, functionality, manufacturability, recyclability and re-manufacturability, resource utilization/economy and societal impact. Each of these elements was sub-divided into several corresponding sub-elements. Different levels of influencing factors were categorized based on their significance to the product. The level of importance of each sub-element was assigned with high, medium, or low weights. Finally, sustainability scores of two different materials (steel alloy and aluminum alloy) were computed and their levels of sustainability performance were compared [5] [6].

Nomeda Dobrovolskiienė and Rima Tamošiūnienė (2015) proposed a tool term as composite sustainability index of a project (CSIP) which to measure the sustainability of a business project in the construction industry, take 15 criteria (four economic, six environmental and five social criteria) of construction sustainability selected, then group of professionals had to rank the importance of each criterion from 1 to 15, where the highest score was 15 points and the lowest 1 point. The next step is normalization by applying a distance to a reference method, the normalized value is calculated as the ratio between the indicator and an external benchmark (or target value). The final step is aggregation. At this stage, an aggregate index, called a composite sustainability index of a project is developed. The most common form of aggregation is the summing-up of the weighted and normalized individual indicators [7].

Peihao Li and Mingjia Liu (2015) develop a mathematical model term as Comprehensive Sustainability Index (CSI) that can be used to comprehensively evaluate and clearly define a country's sustainability based on factor analysis. Sustainability index was determined by a linear combination of a set of indicators. They selected 10 representative indicators coming from three aspects: social development, economic development and environmental protection. They used factor analysis to convert observations of correlated variables into values of linearly uncorrelated variables called factors thus determining the weights of indicators. In the evaluation section, they select 15 countries to form the sample, 5 least developed countries, 5 developing countries and 5 developed countries. By calculating the value of CSI of each country, they found out that there are clear differences among the CSIs of the three kinds of countries. And based on such differences, they reached classification of CSI [8].

Zhang et al. (2013) Presenting methodology involving the use of total life-cycle approach, including the life-cycle assessment (LCA) method, for improving the product sustainability performance of metallic automotive components sustainability aspects (economic, environmental and social) [9].

C. Vilaa, J.V. Abellán-Nebota , J.C. Albiñanaa and G. Hernándezb proposed framework developed the key stages for a sustainable product lifecycle strategy. Proposed model establishes all the processes carried out through the product lifecycle and indicates the application and interaction of specific methodologies, tools and knowledge at each stage that will help to achieve sustainability. The processes applied are controlled by means of the ecodesign and sustainable manufacturing approach throughout the lifecycle of the product. This makes it possible to increase the efficiency in product development and sustainable lifecycle management. [10]

The contribution of this paper is to determine the sustainable product capturing the totality of sustainability aspects (economic, environmental and social). The current work differs from previous work in that it offers a mathematical model considering the totality of aspects of sustainability, not only environmental, to help systematically plan and improve sustainable manufacturing activities.

3. Mathematical Model Development

3.1. Problem Definition

Manufacturing companies aim to increase profits by reducing manufacturing cost of product, but given to the increase in taxes paid versus each amount of CO₂ emitted through manufacturing of product. Therefore the world towards to manufacture "green product". Consider a manufacturing system, such as that described in Figure 1, producing a variety of products. The system transforms a set of natural resources with the aid of labor, technology and financial resources to outputs. These outputs are the required products to be sold in the market in addition to scrap resulting from inefficiencies in the transformation process and some recyclable material. The operation of this manufacturing system has economic, environmental, as well as social impacts on its surrounding environment. Most of researchers introducing approaches to reducing manufacturing cost and others introducing approaches reducing CO₂ emission, often include limitations such as the lack of integration between the design and manufacturing stages of the product and three key parts of sustainability; economic, environmental, social. Quantity and variety decisions have to be made that shape the efficiency of the manufacturing operation. These decisions are Production process method, Skill levels of workers, number of workers, Number of machine, and type of material. These decisions heavily affect the economic, environmental and social aspects of the facility and, thus, determine the manufacturing sustainability. The target is to arrive at decisions concerning the sustainable product and the aforementioned operating parameters, so as to maximize system sustainability.

Fig. 1. Elements of a manufacturing system affecting its sustainability [11]

3.2. Mathematical Model

The aim of this paper is to devise a mathematical model as a comprehensive evaluation metric for alternative scenarios of the process and also as a tool that enables decision makers to setting up optimal vital operating parameters, so as to maximize manufacturing sustainability. Thus, the objective function should reflect sustainability, while the constraints reflect the limited available resources. Since the sustainability consists of three pillars, economic, environmental and social, the objective function has to include these elements. An integration of these incommensurable aspects is challenging. It addresses the three pillars of sustainability: environmental, economic and social. Each of the pillars is evaluated by a set of sub-indicators; economic evaluated by total manufacturing cost of product (C_{TM}); environment and social evaluated by carbon dioxide emission from machines during manufacturing process (C_E). All of the indicators are so devised such that they have a value ranging from zero to one. The two performance measures discussed in this paper C_{TM} and C_E belong to the smaller-the-better characteristic. In order to find the best decision variable set values satisfying the two performance measures applying linear programming method (LP), it is a requirement that these multiple measures are converted into a single measure. This single measure is referred to as comprehensive sustainability index (CSI). The CSI is an overall representative measure and needs to be finally optimised. The desirability function approach is used to convert from multiple measures to a single measure as described in the following sub-sections.

3.2.1 Model Assumptions

The following assumptions

- Only one type of emissions is considered, which is CO₂.
- Demand is deterministic and constant.
- Exact amounts of raw material required for producing each product.
- Ability of machine to produce exact amount of product each day.

3.2.2 Model Nomenclature

Parameters

C_{Tm} : Total manufacturing cost required to produce specified production quantity each year.
 C_o : Ordering cost of raw materials monetary unit (MU).
 C_H : Holding cost of raw materials within the production.
 C_{tr} : Transportation cost for delivering raw materials to the production system (MU).
 C_P : The purchasing cost of raw materials required to produce the product (MU).
 C_U : Utilities cost of the final product (MU).
 C_D : Duties cost arising from procuring raw material from an external supplier (MU).
 T_{pi} : Transfer price required for procuring raw material i from an external supplier i (MU).
 S : Origin of ordered raw materials.
 v : Destination of required raw materials.
 m_i : Transportation mode for transporting raw material i to its customer.
 N_T : Number of transportation modes used for shipping raw materials to the production system (unit).
 M_i : Raw material types required in producing one unit of product i .
 N_p : Number of parts required to produce one product (unit).
 C_{Uo} : Ordering cost of raw materials for the final product (MU).
 C_{UH} : Holding cost of raw materials of each final product in the production system warehouse (MU/ day).
 C_{UMi} : Unit cost of the raw material i at the beginning of each cycle (MU);
 d_{RM} : Daily demand of raw materials required to meet customer satisfaction (unit);
 $\%d_{RM}$: Daily demand percentage of raw materials required to meet customer satisfaction (unit).
 C_{TOMang} : Total managerial ordering cost per order (MU).
 C_{THmang} : Total managerial holding cost for keeping raw materials to produce final product during the lead time duration.
 SF : Storage factor for keeping raw materials in the warehouse.
 OF : Ordering factor for procuring each order from the supplier.
 $\%Util$: Utilities cost percentage of the final product (MU).
 t_p : Raw material cost percentage incurred for procuring raw material i from an external supplier j (MU).
 $T_{Si,v,m}$: Tensor for transportation cost per critical measurement (MU).
 t_m : Critical transportation measurement of raw materials shipped using transportation mode m .
 $\%V$: Volume percentage value required for transporting raw materials to their customer.
 D_i : Duty rate (%) per price of raw material i supplied by external supplier j (MU).
 $\%sale$: Sales percentage value offered from selling extra raw materials during the same order.
 N_{RM} : Number of raw materials supplied to the production system (unit).
 C_E : Carbon emission.
 C_{En} : Energy consumption kwh/year by machines.
 C_{OP} : Operating cost of machine
 C_E : Energy cost, the cost of energy used to operate the machines
 $C_{L,i,y}$: Cost of labour by time of one operation.
 h : Hourly operation time required to produce the product (hr.)
 AU : Annual use of power (kwh) per year.
 $E_{(C)}$: Energy consumption of power (Kwh/hr.) used per day.
 P : power (kWh).
 P_E : Price of one kWh used to operate machine.
 Sk : Skill level of worker.
 P_r : Price of the machine.
 C_{Ei} : Carbon dioxide (CO₂) emission for the quantity of raw material i ordered in each patch required to produce the final product per week (unit)
 Q_{Mi} : i Raw material weekly batch quantity ordered to produce final required product (unit).
 M_i : Raw material type required in producing one unit of product i .
 C_{EC} : Carbon dioxide (CO₂) emission from machines c in each department.
 TEU : Twenty Foot Equivalent Unit. The two most common international standardized container types are twenty and forty foot. A twenty foot unit measures about 6 meters, a forty foot about 12 meters (external dimensions).
 C_{CP} : The cost of waste collection per CP per year
 c_{vy} : is the annual cost of collection per vehicle
 N_{cp} : is the number of served CPs.
 b_v : is the backup rate for the collection vehicle (backup vehicle per collection vehicle).
 C_{cv} : The capital cost of vehicle amortized over its economic life.
 N_{wb} : The number of waste bins that a vehicle can service during one collection trip.
 C_{cwb} : The annual capital cost per waste bin.

C_{ov} : is the annual operating cost of vehicle.
 e : is the administrative rate.
 C_v : is the unit price of vehicle.
 CRF_{wb} : is the capital recovery factor.
 U_c : is the vehicle utilization factor (usable per total vehicle capacity).
 V_c : is the vehicle capacity.
 F_c : is the frequency of waste collection per week.
 W_{mix} : is the weekly waste generation rate per CP.
 P_{mix} : is the overall density of mixed waste. Overall density of mixed waste.
 P_i : is the weight fraction for waste component i .
 p_{ci} : is the compacted density of waste component i .
 C_{vwb} : is the unit price of waste bin and CRF_{wb} is the capital recovery factor.
 i : The yearly discount rate.
 L : is the economic life of collection vehicle.
 a : is the fringe benefit rates.
 b_w : is the backup rate for collection workers.
 S_w : is the salary rate per hour per worker.
 N_w : is the number of collection workers per vehicle.
 S_d : is the driver salary rate per hour.
 MH_D Man-hours/Day

Decision Variables:

γ Skill levels of workers
 N_W No. of workers
 N_c No. of machine
 T_{RM} Type of material

3.2.3 Objective Function

The objective function for the proposed model is the comprehensive sustainability index, which is to be maximized is by minimizing the total manufacturing cost C_{Tm} , carbon emission C_E , in production system. This objective can be formulated as following:

$$\text{Minimise } \sum (C_{Tm} + C_E) \quad (1)$$

I. Total manufacturing cost C_{Tm}

Various costs associated with total manufacturing costs, in this paper total manufacturing cost includes the operating cost " C_{op} ", , raw material cost " C_{RM} ", Utilities Cost " C_U ", , and cost of waste collection " C_{cp} " therefor it can be calculate as :

$$C_{TM} = C_{op} + C_{RM} + C_U + C_{cp} \quad (2)$$

Each component of the total cost of the final product is described as follows:

A. Operating cost (C_{op})

Operating cost is the expenses related to operating machines to produce final product, involves cost of workers operate on the machine to produce product and cost of energy to operate machines, it can be calculated as:

$$C_{OP} = \sum (C_E + C_W) \quad (3)$$

C_W worker cost is considered as the rate resulting from multiplying the cost of working time by the time required for producing the final product (hour), which can be calculated as follows Equation (4):

$$C_{OP} = \sum (C_E + C_W) \quad (4)$$

Skill of i = (1 or 0.9, 0.8, 0.7)

$$C_E = AU \times P_E \quad (5)$$

B. Raw Material Cost (C_{RM})

Raw material cost is the cost of raw materials used to produce the final product in the production system. In this research, raw material cost includes the ordering cost C_O , holding cost C_H , purchasing cost C_P , transportation cost C_{TR} , duties cost C_D and transfer price cost TP. Therefore, it can be calculated as equation (6) [12]:

$$C_{RM} = C_O + C_H + C_P + C_{TR} + C_D \quad (6)$$

- *Ordering Cost (C_O)*

Ordering costs are the cost of ordering and receiving an amount of raw materials each order. These costs include determining how much is required, preparing invoices, inspecting goods upon arrival for quality and quantity against shipping lists and moving the goods to temporary storage. Generally, they are expressed as a fixed value per order, regardless of the order batch size (Chopra and Meindl, 2010).

$$C_{UOj} = \frac{C_{Tomang}}{\%d_{RM} \times L_T} \quad (7)$$

$$\%d_{RM} = \frac{d_p}{d_{RM}} \quad (8)$$

$$C_O = C_{UO} \times OF \quad (9)$$

- *Holding Cost (C_H)*

Holding cost is the cost of keeping one unit of raw materials in warehouses for a specified time period (Chopra and Meindl, 2010). The rate of C_H if the production system procures its raw materials from an external supplier equals Equation (10):

$$C_{UHj} = \frac{C_{THmang}}{N_{RM}} \quad (10)$$

$$C_H = \sum_{i=1}^{N_P} (C_{UHi})_s \times \%d_{RM} \times (LT + SF) \quad (11)$$

$$i = 1, 2, 3, \dots, N_P.$$

- *Purchasing Cost (C_P)*

Purchasing cost is the cost of goods acquired from suppliers required to produce the final product in the production facility.

In this research, it is considered as the unit cost of raw material at the beginning of that cycle (CUM). C_P Can be calculated as Equation (12):

$$C_{UMSEj} = \%sale \times C_{UPi} \quad (12)$$

$$C_P = \sum_{i=1}^{N_P} (C_{UMSEi}) \quad (13)$$

- *Duties Cost (C_D)*

This is the tax incurred by importing goods from supplier in one country to a customer in another country. It is based on the value of goods or upon some criteria of the item such as weight and dimensions.

This work considers C_D as the cost arises from supplying raw materials by a regular external supplier SE_j to the production system. It can be calculated as Equation (14):

$$C_D = \sum_{i=1}^{N_P} C_{UPi} (1 - IF) \times D \quad (14)$$

$$IF_j = 0 \text{ if } SE_j = 1, \text{ otherwise } IF = 1.$$

C. Utilities Cost (C_U)

Utilities cost is the cost arising from using the required utilities such as electricity, gas, heat, water and maintenance to produce final product in the production facility. This research considers C_U as a raw material cost percentage of the final product. It equals Equation (15):

$$C_{UMSEj} = \sum_{i=1}^{Np} \%C_{RMI} \quad (15)$$

D. The cost of waste collection (C_{CP})

The cost of waste collection per CP (collection point) per year is calculated according to [13]:

$$C_{CP} = \frac{c_{vy}}{N_{cp}} \quad (16)$$

$$c_{vy} = [(1+b_v) \times C_{cv}] + N_{wb} \times C_{cwb} + C_{ov} \quad (17)$$

$$C_{cv} = (1+e) \times C_v \times CRF \quad (18)$$

$$N_{wp} = \frac{N_{cp}}{a_{wp}} \quad (19)$$

$$N_{cp} = \frac{U_c \times V_c \times F_c}{\frac{W_{mix}}{P_{mix}}} \quad (20)$$

$$P_{mix} = \frac{1}{\sum \frac{P_i}{P_{ci}}} \quad (21)$$

$$C_{cwb} = (1+e) \times C_{vwb} \times CRF_{wb} \quad (22)$$

$$CRF_{wb} = \frac{i \cdot (1+i)^L}{(1+i)^L - 1} \quad (23)$$

$$C_{ov} = (1+e) \cdot (1+a) \cdot (1+b_w) \cdot (S_w \cdot N_w + S_d) \quad (24)$$

II. CO2 emissions (C_E):

In regard to the carbon emissions from machines, formula (24) computes the total carbon emissions occurring during the operating of machines

$$C_{EC} = E_c \times E_{fi} \quad (25)$$

3.3 Constraints

Three type of constraints considered in the proposed model, as described next. Production quantity: The amount of product that produces each month should be less than or equal to the maximum demand of that product as in Equation (26),

$$S_K \leq D_K \quad (26)$$

Manufacturing cost: the cost of manufacturing product that comprises, energy cost, labour cost, raw material cost, and utilities cost should be not exceeded working capital as in Equation (27),

$$C_{TM} \leq B_{TM} \quad (27)$$

CO2 emission: Ensures that the amount of CO2 cannot exceed the maximum technically feasible emission amount during manufacturing processes as in Equation (28),

$$C_E \leq \lambda_E \quad (28)$$

Finally Type of material, Number of machines, number of labor and skill: should be between the minimum and maximum target values set by the authority or the organization as in equation (29), (30), (31), and (32) respectively:

$$RM_{min} \leq RM_t \leq RM_{max} \quad (29)$$

$$C_{min} \leq C_n \leq C_{max} \quad (30)$$

$$W_{min} \leq W_n \leq W_{max} \quad (31)$$

$$\gamma_{min} \leq \gamma \leq \gamma_{max} \quad (32)$$

4. Numerical Example Illustration

In this section, an example problem is tested to evaluate the performance of the proposed approach. The objective is to demonstrate how the proposed approach works in optimizing the product design and its manufacturing processes based on maximum sustainability. For this purpose, alternative configurations of the product are performed to obtain highest level of sustainability. The proposal considers a bottle opener design and its manufacturing processes (see table 1) in local small-sized manufacturing company. It is beneficial to reiterate that the fixed data are variables that are set as constant values during the numerical experimentation in implementing the modeling product design and manufacturing approach (see table 2)

	Alternative Design	Material	Manufacturing Processes	No. of stations
1		Steel	<ul style="list-style-type: none"> •Cutting •Punching •Quality control 	3
2		Aluminium	<ul style="list-style-type: none"> •Cutting •Extrusion •Sawing •Remove burrs •Drilling •Quality control 	6
4		Thermoplastics	<ul style="list-style-type: none"> •cutting •Punching •Insert molding •Quality control 	4

Table 1. Bottle opener design and manufacturing alternatives

Parameter	Value	units	Parameter	Value	unit	Parameter	Value	unit
MH_D	7	hour	N_{RM}	500.5 100.5 60.5	kg	I	2	
$C_{Li,y}$	7 8 9 10	\$	C_{UPi}	3.42 1.92 2.4	\$	L	12	
						S_w	15	
						N_w	2	
						S_d	15	
AU	21 36.4 176.4	kwh	D	0.15 0.05 0.05	\$	RM_{max}	3	
P_E	0.2	\$	E_{fi}	0.812045	(kg CO2-e/kWh)	RM_{min}	1	—
N_p	0.05 0.01 0.006	kg	C_v	9000	\$	C_{max}	4	—
						C_{min}	2	

C_{TOMang}	10	\$	CRF_{wb}	7	W_{max}	5	—
	8		U_c	8			
	9		V_c	2			
C_{THmang}	100	\$	F_c	1	W_{min}	2	—
	70		W_{mix}	1			
	50						
d_{RM}	25	kg	P_i	5	γ_{max}	100%	—
	5		p_{ci}	5			
	3						
D_K	500	part	C_{vwb}	2	γ_{min}	70%	—

Table 2. Input data

The input data are based on the following assumptions: number of hour's work is 8 hour/day; the production ability of machines is 500 parts each day; and scrap and recyclable percentages is constant product.

5. Results and Discussion

The proposed model has been solved using linear programming optimization (Microsoft excel 2010), and a global optimum solution has been obtained. Table 3 summarizes results. The optimum sustainability achieve for the manufacturing system under study is 0.8. The results call, the best type of material is 2 Aluminium, Number of worker is 2, Number of machine 2, and skill level of worker is 70%.

variable	value
T_{RM}	2 Aluminium
N_W	2
N_c	2
γ	70%

Table 3. Summary of the result

Performance measures values and individual desirability's				Sustainability index (CSI)
Environmental Impact		Economic Impact		
C_E	$d_q(C_E)$	C_{Tm}	$d_q(C_{Tm})$	D_a
0.0008535	1.00	1.001904	0.778	0.8

Table 4. Performance measure value and sustainability index

6. Conclusion

This proposed model introduced a formulation for a sustainable product problem in the manufacturing industry. The contribution of the proposed formulation is its ability to addresses pillars of sustainability at the planning level. The essential feature of the proposed model for measuring sustainability is the least amount of effort required in data collection. It mainly depends on data generally collected in all plants for cost analysis. This fact makes the model applicable in facilities introducing sustainability concepts.

It thus contributes to encouraging the implementation of sustainable practices in manufacturing, especially in emerging economies, where there is still a lack of sustainability awareness and related legislation. The inclusion of Microsoft excel (2010) to apply optimization in the form of alternative scenario for manufacturing product, make model suitable to small-scale MTO manufacturers because it can meet the required specifications according to the customer order. The result provides the least total cost and at the same time maintain environment by decreasing emission of carbon dioxide.

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