Achieving sustainability in manufacturing systems: A quantitative study

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Abstract

This paper presents a multi-objective optimisation (MOO) mathematical model that can be employed as an aid for manufacturing systems design and evaluation aiming to minimize energy consumption, amount of carbon dioxide (CO_2) emissions and the total cost at an early stage. This approach associated with the number of machines, number of air-conditioning units and number of light bulbs involved in each process in conjunction with a quantity of material flow for processing the products in a manufacturing system. A real case study was examined for validating the applicability of the proposed approach. The research outcome demonstrates that this MOO model can be an effective decision-making approach for seeking a trade-off decision a mong multiple of decision-making objectives such as energy consumption, amount of CO_2 emissions and total cost towards a sustainable manufacturing system (SMS) design at an early stage before actual construction or use of the system.

Keywords
Sustainable manufacturing systems; Energy consumption; CO_2; Lean manufacturing; Environmental constraints.

1. Introduction

There has been a growing pressure of manufacturing industry promoting energy saving production and minimizing CO_2 emissions due to ever strict regulations and rules on environmental issues (Mohammed, 2019). The concept of lean approaches is believed as an appropriate method for pursuing sustainability in manufacturing as it can be considered a trend in modern manufacturing enterprises for reducing manufacturing wastes and improving system efficiency and productivity without additional investments. Lean manufacturing can be defined as "a systematic approach to eliminate non-value-added wastes in various forms and it enables continuous improvement". These wastes are waiting for parts to arrive, overproduction, unnecessary movement of materials, unnecessary inventory, excess motion, the waste in processing and the waste of rework. However, the current lean approaches do not include reduction of environmental wastes in terms of such as energy consumption and amount of CO_2 emissions for production which also need to be addressed as these wastes add no values on manufactured products. Consequently, it is important to develop the lean manufacturing system design towards the sustainability incorporating the economic and ecological constraints. Development of a SMS is considered as one of the effective solutions for a long-term strategy of manufacturing companies. To design a SMS, manufacturing system designers need not merely to apply traditional methods of improving system efficiency and productivity but also to examine the environmental impact on the developed system Lind et al., 2008). The traditional manufacturing system design is involved in determination and analysis of such as system capacities, material flow, material-handling methods, production methods, system flexibilities, operations and shop- floor layouts. However, there is an environmental aspect that needs also to be addressed as a new challenge for manufacturing systems designers to seek an effective approach incorporating environmental parameters or constraints (Paju et al., 2010). In the past decade, the concept of SMS has been used for promoting a balance between the environmental impact and the economic performance for production (Taghdisian et al., 2015; Mohammed et al., 2017 & 2019a). The term of manufacturing sustainability may be defined as the creation of manufactured products by reducing negative environmental impacts on usage of energy consumption or natural resources (Nujoom et al., 2016). This concept ought to be implemented as a separate objective at the early design stage, together with other classical objectives in maximizing system productivity or system efficiency and or minimizing costs for production, which form a MOO problem (Nujoom et al., 2018 & 2019).

A few researchers applied the (MOO) approaches considering environmental aspects relating to a SMS design (Dukyil, 2017 & 2018). Abdallah et al. (2010) have utilized a MOO method used for minimizing carbon emissions and investment cost of the supply chain network facilities. Wang et al presented a MOO model used for determining a trade-off decision between total cost and total amount of CO_2 emissions in some facilities within a supply chain (Wang et al., 2011). Jamshidi et al. (2012) developed a MOO model aiming to minimize effects of nitrogen dioxide, carbon monoxide and volatile organic particles caused by facilities and transportation vehicles in a supply chain network. Sahar et al. (2015) proposed a MOO model of a two-layer dairy supply chain aimed at minimizing CO_2 emissions of transportation and the total cost for product distribution.

This paper presents a study through the development of a MOO model, which was used for examining the configuration of the proposed SMS design seeking a compromised solution among conflicting objectives. The aim of the developed MOO model is to minimize the total investment cost for establishing the manufacturing system, the amount of energy consumed by the machines involved in each process and the CO_2 emissions released from the machines involved in each process within the manufacturing system. The developed model was coded using LINGO[11] in which Pareto solutions were obtained using the integrated DEMATEL-ε-constraint approach; followed by an employment of the global criterion approach in order to select the best Pareto solution.

2. Problem statement and model formulation

Figure 1 illustrates the SMS design which consists of operation machines, air conditioning units, illumination systems and other supportive equipment such as compressors which supply compressed air to some machines. To achieve the sustainability of a manufacturing system design, energy consumed by all the equipment in the manufacturing system as well as the amount of CO_2 emissions released from the manufacturing system need to be quantified in conjunction with the total cost that also needs to be considered. In this study, these pre-defined objectives are mathematically formulated as a MOO model aimed at obtaining a trade- off decision among multiple of decision making objectives aimed at minimization of total investment cost for establishing the manufacturing system (equation 1), minimization of the total energy consumed by the manufacturing system (equation 2), and minimization of the total amount of CO_2 emissions (equation 3) as described below. These pre-defined objectives are in conjunction with (i) numbers of operation machines (ii) number of air-conditioning units and number of light bulbs involved in each process and (iii) quantity of materials flows in the manufacturing system.

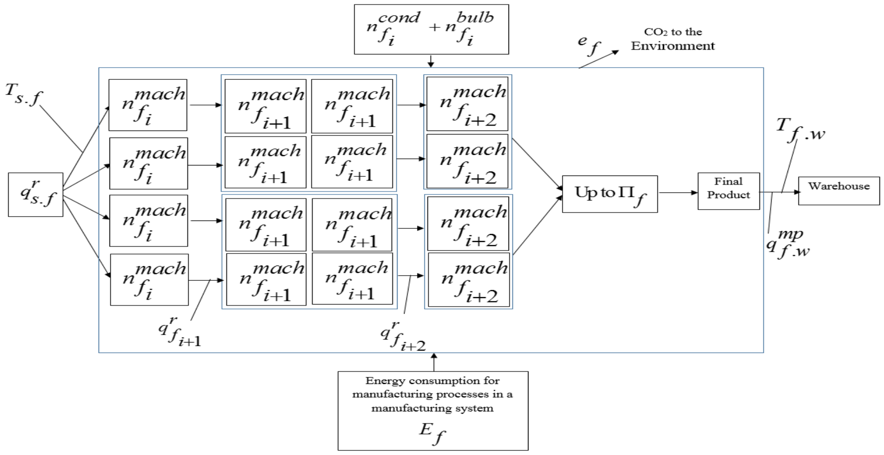


Figure 1. Structure of a sustainable manufacturing system design

The following notations which includes sets, parameters and decision variables are used for formulating the MOO mathematical model:

Sets

s	set of suppliers $(1 \ldots s \ldots S)$.
f	set of factories $(1 \ldots f \ldots F)$.
w	set of warehouses $(1 \ldots w \ldots W)$.
Π_f	number of manufacturing processes involved in factory *f*.
i	Process number in factory *f*.

Parameters

C_f^{es}	cost required (GBP) for establishing factory *f*. This cost includes: C_f^{land} , $C_f^{building}$, $C_f^{equipment}$, $C_f^{services}$, $C_f^{saleries}$.
$C_{f_i}^{mach}$, $C_{f_i}^{cond}$ and $C_{f_i}^{bulb}$	unit cost (GBP) per machine, per air-conditioning unit and per light bulb unit respectively required for engaged in process *i* at factory *f*, where, $i \in \{1,\ 2,\ \ldots.,\ \Pi_f\}$.
C_s^r	unit raw materials cost (GBP) at supplier *s*
C_f^{mp}	unit manufacturing product cost (GBP) at factory *f*.
C_w^I	unit inventory cost (GBP) per product at warehouse *w*.
C_{sf}^t and C_{fw}^t	unit transportation cost (GBP) per mile of raw material from supplier *s* to factory *f* and for products from factory *f* to warehouse *w* respectively.
T_{sf} and T_{fw}	distance (miles) from supplier *s* to factory *f* and from factory *f* to warehouse *w*.
Ca_l	maximum operations capacity (kg) of facility *l*, *w*here $l \in \{s,\ f,\ w\}$
D_f D_w	minimum demand (kg) of factory *f* and warehouse *w*.
q_0^r	Initial mass of material (kg) from supplier *s*.
$\perp_{fi}^{mach}$	capacity (kg) of a machine involved in process *i* at factory *f*.
$N_{f_i}^{mach}$, $N_{f_i}^{cond}$ and $N_{f_i}^{bulb}$	installed power (kw) for a machine, air-conditioning unit and lighting bulb involved in process *i* at factory *f* respectively.
$N_{f_i}^{comp}$	installed power (kw) for a compressor at factory *f*.
$\wp_f$	mass production (kg/month) from factory *f* and stored at warehouse *w*.
$\Re_{f_i}$	manufacturing rate (kg/h) for a machine involved in process *i* at factory *f*.
τ_{f_i}	operating time (hr) for a machine involved in process *i* at factory *f*.
μ_{f_i}	efficiency (%) for a machine involved in process *i* at factory *f*.

Ψ_{f_i}	total waste ratio (%) for a machine involved in process *i* at factory *f*.
e^t_{sf} e^t_{fw}	amount of CO_2 emissions (kg) released for transportation from supplier *s* to factory *f* and from factory *f* to warehouse *w* respectively.
V	capacity (units) per vehicle.
ω_{f_i}	CO_2 emission factor (kg/kWh) at factory *f*.
ω^t_{sf} and ω^t_{fw}	CO_2 emission factor (kg/mile) released for transportation from supplier *s* to factory *f* and from factory *f* to warehouse *w* respectively

Decision variables

$q^r_{f_i}$	mass of material (kg) involved in process *i* at factory *f*, where, $i \in \{1,\ 2,\ ....,\ \Pi_f\}$
$q^r_{f(i+1)}$	mass of material (kg) transferred from the machines involved in process *i* at factory *f*
q^{mp}_{fw}	mass of products (kg) transported from factory *f* to warehouse *w*
$n^{mach}_{f_i}$	number of machines (unit) involved in process *i* at factory *f*.
$n^{cond}_{f_i}$	number of air-conditioning units (unit) involved in process *i* at factory *f*.
$n^{bulb}_{f_i}$	number of light bulbs (unit) involved in process *i* at factory *f*.

Based on the over mentioned notations, the MOO mathematical model can be formulated as follows:

$$
\begin{aligned}
Min\ Z_1 = {} & C^{land}_f + C^{building}_f + C^{equipment}_f + C^{services}_f + C^{salaries}_f \\
& + \sum_{i=1}^{\Pi_f} C^{mach}_{fi} n^{mach}_{fi} + \sum_{i=1}^{\Pi_f} C^{cond}_{fi} n^{cond}_{fi} + \sum_{j=1}^{\Pi_f} C^{bulp}_{fi} n^{bulb}_{fi} + \sum_{s=1}^{S} \sum_{f=1}^{F} C^r_s q^r_{sf} \\
& + \sum_{f=1}^{F} \sum_{w=1}^{W} C^{mp}_f q^{mp}_{fw} + \sum_{f=1}^{F} \sum_{w=1}^{W} C^I_w q^{mp}_{fw} + \sum_{s=1}^{S} \sum_{f=1}^{F} C^t_{sf} \frac{q^r_{sf}}{V} T_{sf} + \sum_{f=1}^{F} \sum_{w=1}^{W} C^t_{fw} \frac{q^{mp}_{fw}}{V} T_{fw}
\end{aligned}
\tag{1}
$$

$$
Min\ Z_2 = \sum_{i=1}^{\Pi_f} \left(\begin{array}{l} \dfrac{q^r_{fi}}{\Re_{fi} \times \mu_{fi}} N^{mach}_{fi} n^{mach}_{fi} + N^{cond}_{fi} n^{cond}_{fi} \dfrac{q^r_{f(i+1)}}{\wp f} \\ + N^{bulb}_{fi} n^{bulb}_{fi} \dfrac{q^r_{f(i+1)}}{\wp f} + \dfrac{q^r_{fi}}{\Re_{fi} \times \mu_{fi}} \dfrac{N^{comp}_{fi}}{\rho^{comp}_{fi}} \upsilon^{comp}_{fi} n^{mach}_{fi} \end{array} \right)
\tag{2}
$$

$$Min\ Z_3 = \sum_{i=1}^{\Pi_f} \left[\begin{array}{l} \omega_{f_i} \dfrac{q^r_{f_i}}{\Re_{f_i}\mu_{f_i}} N^{mach}_{f_i} n^{mach}_{fi} \\ +0.689 \left(\begin{array}{l} N^{cond}_{fi} n^{cond}_{fi} \dfrac{q^r_{f(i+1)}}{\wp f} + N^{bulb}_{fi} n^{bulb}_{fi} \dfrac{q^r_{f(i+1)}}{\wp f} \\ + \dfrac{q^r_{fi}}{\Re_{fi}\mu_{fi}} \dfrac{N^{comp}_{fi}}{\rho^{comp}_{fi}} \upsilon^{comp}_{fi} n^{mach}_{fi} \end{array} \right) \end{array} \right]$$

$$+ \sum_{s=1}^{S} \sum_{f=1}^{F} \left(\omega^t_{sf} \frac{q^r_{sf}}{V} T_{sf} \right) + \sum_{f=1}^{F} \sum_{w=1}^{W} \left(\omega^t_{fw} \frac{q^{mp}_{fw}}{V} T_{fw} \right) \qquad (3)$$

Where, the CO2 emission factor ω_{f_i} , ω^t_{sf} and ω^t_{fw} is shown in Table 1 (EPA, 2008., Nujoom *et al.,* 2016., 2017).

Constraints:

Equations (4) and (5) ensure that the quantity of raw material shipped from supplier *s* to a manufacturing system at factory *f* and products shipped from the manufacturing system at factory *f* to warehouse *w* cannot be greater than their capacity, respectively.

$$q^r_{sf} \le Ca_s \qquad (4)$$

$$q^{mp}_{fw} \le Ca_f \qquad (5)$$

Equations (6) and (7) ensure that the requirement for the quantity of raw material shipped from supplier *s* to manufacturing system in factory *f* and from the manufacturing system to warehouse *w* should be exceed their demands, respectively.

$$q^r_{sf} \ge D_f \qquad (6)$$

$$q^{mp}_{fw} \ge D_w \qquad (7)$$

Equation (8) defines that quantity of materials of process task *i* must be bigger than or equal to the quantity of materials of the next process task *(i+1).*

$$(1 - \Psi^{mach}_{f_i}) q^r_{f_i} \ge q^r_{f_{(i+1)}} \qquad (8)$$

Equation (9) ensures that the initial quantity of raw material must be less than or equal to capacity of the machines.

$$q^{r}_{sf} \leq n^{mach}_{fi} \perp^{mach}_{fi} \tag{9}$$

Equation (10) defines that the number of machines involved in process *i* (being served by one air conditioning unit) must be less than or equal to the number of air-conditioning units involved in this process.

$$\Phi^{cond}_{f_i} n^{cond}_{f_i} \geq n^{mach}_{f_i} \tag{10}$$

Equation (11) defines that the number of light bulbs, which serve all the machines involved in process *i*, must be greater than or equal to the number of machines involved in this process.

$$n^{bulb}_{f_i} \geq \varphi^{bulb}_{f_i} n^{mach}_{f_i} \tag{11}$$

Equation (12) defines the quantity of materials, which flow from supplier to manufacturing system and from manufacturing system to warehouse, must be bigger than or equal to zero.

$$q^{r}_{sf},\ q^{r}_{f_i},\ q^{r}_{f_{i+1}},\ q^{mp}_{fw} \geq 0 \tag{12}$$

Equation (13) defines that the manufacturing rate of process task *i* must be greater than or equal to the quantity of materials involved in process task *(i+1).*

$$\Re^{mach}_{f_i} n^{mach}_{f_i} \geq q^{r}_{f_{(i+1)}} \tag{13}$$

Where, equations (4), (5), (6), (7), (8) and (12) are quantity constraints; and equation (9), (10) and (11) are constraints in the numbers of manufactured machines, air- conditioning units and illumination bulbs.

3. Application and evaluation

In order to examine the applicability and the validation of the MOO model, a real case study was applied. The production line comprised 8 different processing tasks, each process task could involve a number of machines and each machine had consumption of energy, released CO_2 and had mass inputs with different specifications. Table 2 shows the manufacturing process in which the symbols represent each task of a manufacturing process to produce plastic and woven sacks in a woven sacks factory. Table 3 shows the data collected from the real production line at the woven sacks company. In this case, the production line was powered by electricity which was generated using oil as a fossil fuel. LINGO[11] software was used for computing results based on the MOO model.

Table. 2. Manufacturing processes tasks for producing plastic and woven sacks

Tasks	Description	Predecessors
R.M	Raw material (Polypropylene)	None
G	Extruding the Polypropylene to make stands	R.M
W	Weaving the strands into rolls of sacks	G
L	Laminating the rolls	W

P	Printing and branding	L
C	Cutting the rolls into bags	P
K	Liner stick, inserts and smoothest	C
S	Film sewed into bag	K
Z	End product compressed using baling machines	S

Table 3. Data collected from a plastic and woven sacks company

C_f^{es} (GBP): 6000000, C_{fi}^{mach} (GBP/unit): 5000, 3000, 4000, 3000, 3000, 100, 200, 2000, C_{fi}^{cond} (GBP/unit): 1000, 1000, 1000, 1000, 1000, 1000, 1000, 1000, C_{fi}^{bulb} (GBP/unit): 50, 50, 50, 50, 50, 50, 50, 50, where $i \in \{1, 2, 3, 4, 5, 6, 7, 8\}$, C_s^r (GBP/kg): 2, C_f^{mp} (GBP/unit): 3, C_W^I (GBP/unit): 2, C_s^t (GBP/unit):2, C_f^t (GBP/unit):2, T_{sf} (mile):50, T_{fw} (mile):10, V (kg): = 20000, $q_0^r = q_{sf}^r$ (kg): 1000000
Ca_f (kg/month): 990,000, Ca_W (kg/month): 900000, D_f (kg/month): 850000, D_W (kg/month): 850000
$\Pi_f = 8$, $\Re_{f_i}^{mach}$ (kg/h): 1852, 1815, 1742, 1716, 1699, 1665, 1660, 1643, where $i \in \{1, 2, ..., \Pi_f\}$, μ_{fi}^{mach} (%): 80, $\Psi_{f_i}^{mach}$ (%):0.02, 0.04, 0.015, 0.01, 0.02, 0.003, 0.01, 0
$N_{f_i}^{mach}$ (kw): 200, 20, 7, 40, 7, 0, 0.8, 4, $N_{f_i}^{comp}$ (kw):200, $\rho_{f_i}^{comp}$ (m³/h): 666, $\upsilon_{f_i}^{comp}$ (m³/h): 5, 4, 13, 0, 7, 5, 20, 0
$\wp_f$ (kg): 831540, ω_{fi} (kg/kWh): 0.6895, $\omega_{s.f,f.w}^t$ (kg/mile):0.420

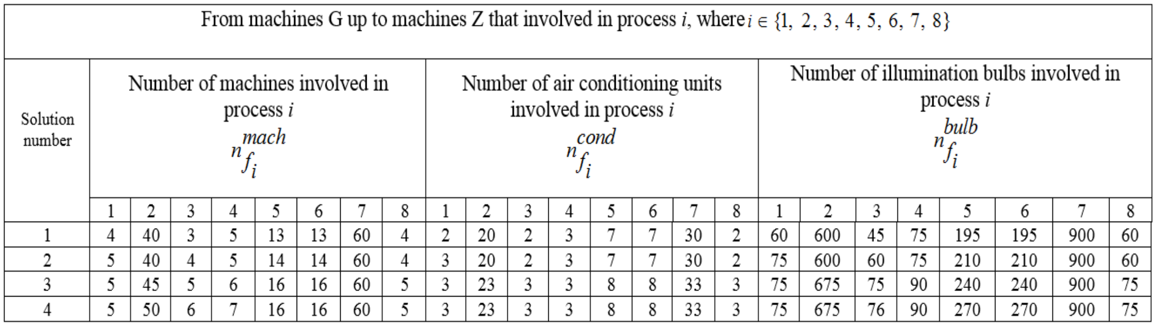
In aiming to obtain pareto solutions, the integrated DEMATEL-ε-constraint approach was utilized. In view of the fact that determining the most important objective is actually an intricate multi-criteria decision-making problem, thus DEMATEL algorithm was used. In this approach, the created MOO model can be converted into a single-objective by adding some constraints; the higher priority objective (total energy consumption) is considered to be an objective function and the other two objective functions (the total cost and the total CO_2 emissions) are shifted to be ε-based constraints.

Table 4 illustrates the Pareto solutions that were obtained by an assignment of ε-values from 9,639,090 to 13,668,548 for objective (1) and from 9.2×10^9 to 10.9×10^9 for objective (3). It can be noted in Table 4 that the values of objective (1) and (3) are sensitive to the assigned values of ε_1 and ε_2 which vary between the minimum value and the maximum value for objectives (1) and (3), respectively. As an example, Pareto solution 1 obtained by an assignment of $\varepsilon_1 = 9{,}639{,}090$, and $\varepsilon_2 = 9.2\times10^9$ accordingly, the minimum total cost for establishing the manufacturing system is 9,639,090 GBP, the minimum total amount of energy consumed by the manufacturing system is 1,250,000 kWh and the minimum total amount of CO_2 emissions released from the manufacturing system is 9.2×10^9 kg. As shown in Table 5, each Pareto solution has a potential group of number of machines, number of air conditioning units and number of bulbs that are involved in process task *i* in the manufacturing system. For instance, in pareto solution 1, the number of machines involved in process task *i* in a manufacturing system $n_{f_i}^{mach}$ where $i \in \{1, 2, 3, 4, 5, 6, 7, 8\}$ are (4, 40, 3, 5, 13, 13, 60, 4), number of air-conditioning units involved in process task *i* $n_{f_i}^{cond}$ are (2, 20, 2, 3, 7, 7, 30, 2) and number of bulbs $n_{f_i}^{bulb}$ are (60, 600, 45, 75, 195, 195, 900, 60). A pairwise comparison among the three conflicting objectives is illustrated in Figure 2a and 2b.

Table 4. Pareto solutions obtained by using the integrated DEMATEL-ε-constraint approach

No of solutions	ε-values		Objective function solutions		
	ε_1	ε_2	Min Z_1	Min Z_2	Min Z_3
1	9,639,090	9.2×10^9	9,639,090	1,250,000	9.2×10^9
2	10,909,100	9.75×10^9	10,909,090	1,420,000	9.7×10^9
3	12,300,000	10.3×10^9	12,288,819	1,580,000	10.3×10^9
4	13,668,548	10.9×10^9	13,668,548	1,710,000	10.9×10^9

Table 5. Number of machines, air conditioning units and number of bulbs



From machines G up to machines Z that involved in process *i*, where $i \in \{1, 2, 3, 4, 5, 6, 7, 8\}$																								
Solution number	Number of machines involved in process *i* $n_{f_i}^{mach}$								Number of air conditioning units involved in process *i* $n_{f_i}^{cond}$								Number of illumination bulbs involved in process *i* $n_{f_i}^{bulb}$							
	1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
1	4	40	3	5	13	13	60	4	2	20	2	3	7	7	30	2	60	600	45	75	195	195	900	60
2	5	40	4	5	14	14	60	4	3	20	2	3	7	7	30	2	75	600	60	75	210	210	900	60
3	5	45	5	6	16	16	60	5	3	23	3	3	8	8	33	3	75	675	75	90	240	240	900	75
4	5	50	6	7	16	16	60	5	3	23	3	3	8	8	33	3	75	675	76	90	270	270	900	75

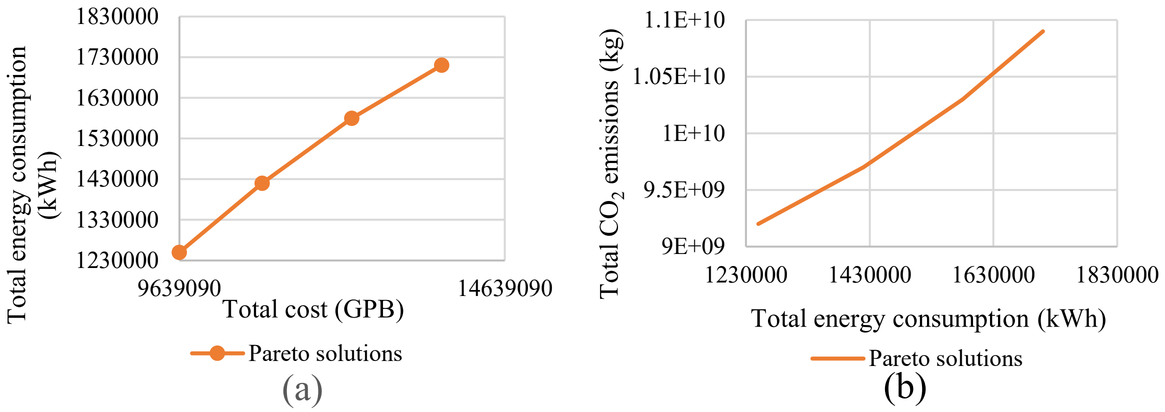


Figure 2. Comparison between solutions obtained

In order to design a SMS based on the obtained Pareto solutions using integrated DEMATEL-ε-constraint approach, one of these solutions needs to be selected based on the preferences of decision makers. Based on their experts to design the SMS, Pareto solution 1 is determined as the best solution. Furthermore, this Pareto solution shows the optimum input quantity of materials q^{r}_{fi}, the quantity of materials flow among the machines involved in process task *i* q^{r}_{fi+1} and then shipped as a final product q^{mp}_{fw}. As shown in Table 6, based on Pareto solution 1 the optimal decisions in the quantity of materials flows through the machines involved in process task 1, 2, 3, 4, 5, 6, 7, 8 are 1000,000 kg, 980,000 kg, 978,040 kg, 976,084 kg, 937,040kg, 918,299 kg, 889,824 kg, 868,344 kg, 850,660 kg, respectively before being shipped to the warehouse as a final products as 7655940 sacks per month.

Table 6. The quantity of materials flows through the system

$q^{r}_{f_i}$ (kg), where $i \in \{1, 2, 3, 4, 5, 6, 7, 8\}$										q^{mp}_{fw} (unit)
Solution number	0	1	2	3	4	5	6	7	8	
1	1000000	980000	978040	976084	937040	918299	889824	868344	850660	7655940 sacks
2	1020000	1002000	996100	994084	955150	928300	904824	883344	865660	7790940 sacks
3	1045000	1027000	1009000	991100	973050	940200	919700	898400	883660	7952940 sacks
4	1066000	1048000	1033000	1015000	997040	955100	934824	919344	901660	8114940 sacks

Table 7 shows the number of machines, the number of air-conditioning units, the number of bulbs and quantity of materials that need to be involved in processes task *i* to achieve the SMS design based on Pareto solution 1.

Table.7. The best Pareto solution for a sustainable manufacturing system

The best solution for a sustainable manufacturing system design				
Number of process task *i*	Number of machines involved in process *i* $n_{f_i}^{mach}$	Number of air conditioning units involved in process *i* $n_{f_i}^{cond}$	Number of bulbs involved in process *i* $n_{f_i}^{bulb}$	Quantity of materials involved in process *i* $q_{f_i}^{r}$
0	-	-	-	1000000
1	4	2	60	980000
2	40	20	600	978040
3	3	2	45	976084
4	5	3	75	937040
5	13	7	195	918299
6	13	7	195	889824
7	60	30	900	868344
8	4	2	60	850660
Number of manufacturing products q_{fw}^{mp} Units				850660≈ 7,655,940 sack

Finally, Figure 3 shows the optimal sustainable manufacturing system design model based on the determined Pareto solution 1, which is obtained with $\varepsilon_1 = 9{,}639{,}090$, and $\varepsilon_2 = 9.2\times10^9$ that yields a minimum total cost of 9,639,090 GBP with the minimum total amount of energy consumption of 1,250,000 kWh and the minimum total amount of CO_2 emissions of 9.2×10^9 kg.

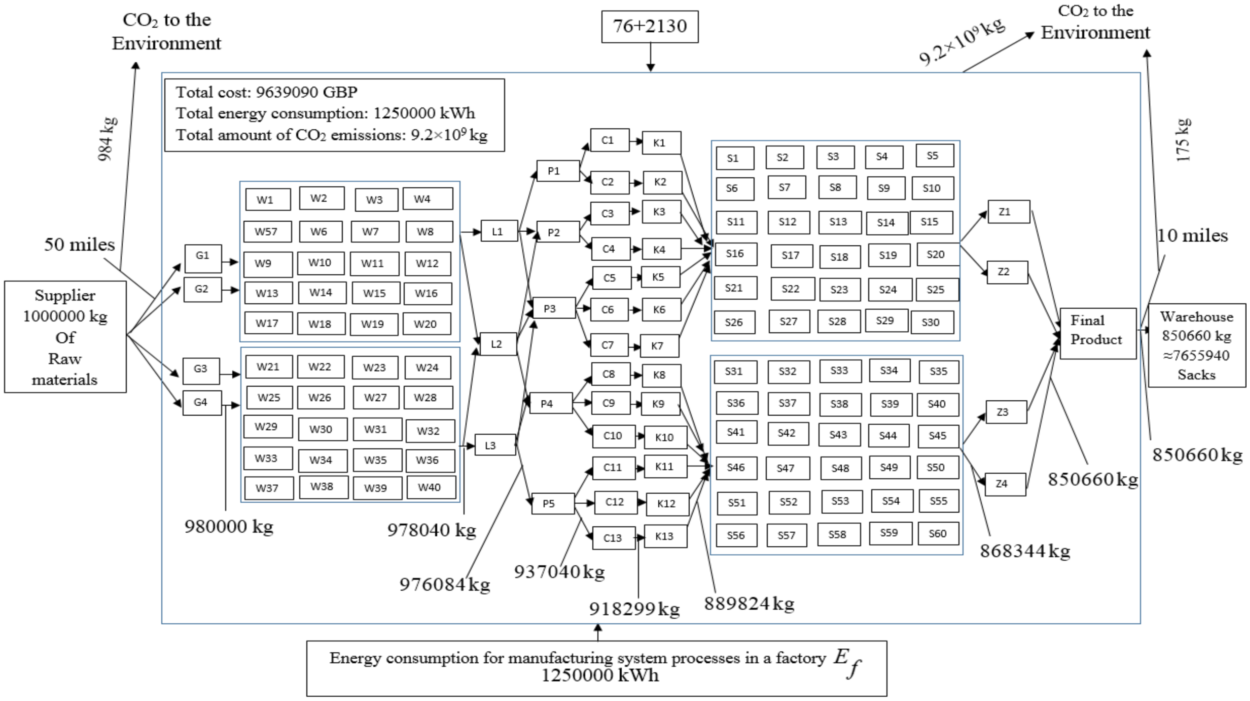


Figure 3. An optimal sustainable manufacturing system design model

4. Conclusion

When designing a manufacturing system, engineers used to focus on the key performance indicators in terms of system productivity and capacity; environmental considerations are often overlooked. This paper presents the development of a three-objective mathematical model for optimizing a sustainable manufacturing system design which addresses environmental sustainability relating to manufacturing activities. The developed multi-objective mathematical model can be used as a reference for manufacturing system designers in finding a trade-off solution in minimizing the total investment cost, minimizing the total energy consumption and minimizing the total CO_2 emissions released from the manufacturing system. The computational results were validated based on data collected from a real industrial case. The initial results indicate that this is a useful and effective aid for optimizing traditional manufacturing system design in order to achieve sustainability under economic and ecological constraints.

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