

Towards a sustainable manufacturing system design: A multi-objective optimization model

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Abstract— Developments of sustainable manufacturing systems are considered as one of effective solutions to minimize the environmental impact. Design of a sustainable manufacturing system can be partially achieved through the implementation of lean methods to reduce manufacturing wastes and operational costs, and increase the system efficiency and productivity. However, the lean approach does not include environmental wastes in such as energy consumption and CO₂ emissions when designing a lean manufacturing system. This paper addresses these issues by evaluating a sustainable manufacturing system design considering energy consumption, CO₂ emissions and the total cost using the multi-objective approach. To this aim, a multi-objective mathematical model was developed under economic and ecological constraints in terms of minimization of the total cost, energy consumption and CO₂ emissions associated with the number of machines involved in each process in conjunction with a quantity of material flow for processing these products in a manufacturing system. A real case study was used for examining the validation and applicability of the developed sustainable manufacturing system model.

Keywords— Sustainable manufacturing systems; Energy consumption; CO₂; Lean manufacturing; Environmental constraints; Multi-objectives.

I. INTRODUCTION

To design a sustainable manufacturing system, 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 [1]. 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 [2]. In the past decade, the concept of sustainable manufacturing systems has been used for promoting a balance between the environmental impact and the economic performance for production [3]. 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 [4]. 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 multi-objective optimization (MOO) problem [3].

Development of a sustainable manufacturing system design may be partially achieved by applying lean methods as a trend in modern manufacturing enterprises for 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” [4]. 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 [5]. Nevertheless, traditional lean manufacturing method does not consider environmental wastes of such as energy and CO₂ emissions which also need to be addressed as these wastes add no values on manufactured products [4, 5]. Consequently, it is important to develop the lean manufacturing system design towards the sustainability incorporating the economic and ecological constraints. This is because industrial factories consume energy and subsequently produce CO₂ emissions, which also need to be considered in the manufacturing system design.

There are a few studies in considering environmental aspects related to design of manufacturing systems or sustainable manufacturing systems. Heilala et al. [6] argued that manufacturing system designers need to not merely rely on traditional methods in improvements of system efficiency and productivity but also incorporate environmental considerations into design and operation of the developed manufacturing processes or systems. Wang et al. [7] proposed a method to be known as process integration (PI) method that was used for evaluating CO₂ emissions for a steel industry. Branham et al. [8] presented the quantitative thermodynamic analysis for measuring the amount of energy in various categories used by manufacturing system. Guillen-Gosalbez and Grossmann [9] developed a bi-criterion stochastic mixed-integer nonlinear program (MINLP) used for optimising a sustainable chemical supply chains design through the minimization of the environmental impact.

The multi-objective optimization approach can be used for modelling a manufacturing system based on a number of conflicting objectives (energy consumption, CO₂ emissions and costs in this study) in which each of objectives needs to be optimised using an objective function. Sahar et al. [10] proposed a multi-objective optimization model of a two-layer dairy supply chain aimed at minimizing CO₂ emissions of

transportation and the total cost for product distribution. Abdallah et al. [11] have utilized a multi-objective optimization method used for minimizing carbon emissions and investment cost of the supply chain network facilities. Wang et al. [12] studied a multi-objective optimization model that balances the trade-off between total cost and the amount of CO₂ emissions released from the supply chain facilities. Jamshidi et al. [13] developed a multi-objective mathematical model to solve a number of issues of a supply chain design in terms of minimization of annual cost with a due consideration over environmental effect. Shaw et al. [14] proposed an integrated approach for selecting the appropriate supplier in the supply chain through development of a fuzzy multi-objective linear programming that address the minimization of ordered quantity to the supplier and the minimization of the total carbon emissions for sourcing of material.

This paper presents a study through the development of a multi-objective model, which was used for examining the configuration of the proposed sustainable manufacturing system design seeking a compromised solution among conflicting objectives. The aim of objectives was 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 CO₂ emissions released from the machines involved in each process within the manufacturing system. The developed model was coded using LINGO¹¹ in which non-inferior solutions were obtained using the ϵ -constraint approach; followed by an employment of the max-min approach in order to select the best non-inferior solution.

II. PROBLEM STATEMENT AND MODEL FORMULATION

Figure 1 illustrates the sustainable manufacturing system design in which three facilities were considered, these are supplier s , factory f and warehouse w . The facility may consist of operation machines, air conditioning units, lighting bulbs and other supportive equipment such as compressors that supply compressed air to some operation machines. Between facilities, there are transportation vehicles to be used. To achieve the sustainability of a manufacturing system design, energy consumed by all those equipment in the manufacturing system as well as the amount of CO₂ emissions released from the manufacturing system need to be quantified in conjunction with the total cost that also needs to be considered for establishing the manufacturing system. To this aim, these parameters are mathematically formulated as a multi-objective optimization model aimed at obtaining a trade-off decision among 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 CO₂ emissions (equation 3) as described below. These objectives are in conjunction with (i) numbers of operation machines and (ii) quantity of materials flows in the manufacturing system.

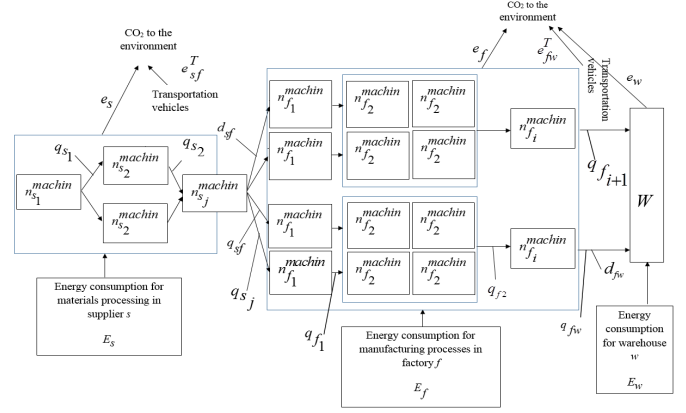


Fig. 1. Configuration of the sustainable manufacturing system design

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

Sets:

S	set of supplier
f	set of manufacturing system
W	set of warehouse
m_{s_j}, m_{f_i}	number of manufacturing processes involved in supplier s and in factory f respectively where $j \in \{1, 2, \dots, m_{s_j}\}$ and $i \in \{1, 2, \dots, m_{f_i}\}$

Parameters

C_l^{Fixed}	fixed cost (GBP) of facility l , where $l \in \{s, f, w\}$
C_s^R	unit raw materials cost (GBP) in supplier s
C_{sf}^R	raw materials cost (GBP) from supplier s to factory f
C_f^{MP}	unit manufacturing product cost (GBP) at factory f
C_{fw}^{MP}	manufacturing product cost (GBP) from factory f to warehouse w
C_w^I	unit inventory cost (GBP) per product at warehouse w
C_{fw}^I	inventory cost (GBP) from factory f to warehouse w
C_l^T	Cost of transportation of raw materials per mile between facilities l , where $l \in \{s, f, w\}$

C_{sf}^T, C_{fw}^T	unit transportation cost (GBP) per mile from supplier s to factory f and from factory f to warehouse w respectively	$N_{s_j}^{air\ comp}, N_{f_i}^{air\ comp}$	installed power (kw) for a compressor in supplier s and in factory f respectively
d_{sf}, d_{fw}	distance (miles) from supplier s to factory f and from factory f to warehouse w	$N_{s_j}^{cond}, N_{f_i}^{cond}$	installed power (kw) for an air conditioning unit involved in process j in supplier s and in process i in factory f respectively
Ca_l	maximum capacity (kg) of facility l , where, $l \in \{s, f, w\}$	$N_{s_j}^{bulb}, N_{f_i}^{bulb}$	installed power (kw) for a lighting bulb involved in process j in supplier s and in process i in factory f respectively
D_f, D_w	minimum demand (kg) of factory f and of warehouse w	\wp_s, \wp_f and \wp_w	mass production (kg/month) from supplier s , from factory f and in warehouse w respectively
E_s, E_f and E_w	energy consumption (kWh) for supplier s , for factory f and for warehouse w respectively	Ψ_{s_j}, Ψ_{f_i}	total waste ratio (%) for a machine involved in process j in supplier s and in process i in factory f respectively
$E_{s_j}^{machin}$, $E_{f_i}^{machin}$	energy consumption (kWh) for a machine involved in process j in supplier s and in process i in factory f respectively, where $j \in \{1, 2, \dots, m_{s_j}\}$ and $i \in \{1, 2, \dots, m_{f_i}\}$	$v_{s_j}^{air\ comp}$, $v_{f_i}^{air\ comp}$	compressed air per h (m ³ /h) used for a machine involved in process j in supplier s and in process i in factory f respectively
$E_{s_j}^{air\ comp}$, $E_{f_i}^{air\ comp}$	energy consumption (kWh) of compressed air needed for a machine involved in process j in supplier s and in process i in factory f respectively	$\rho_s^{air\ comp}$, $\rho_f^{air\ comp}$	capacity of a compressor (m ³ /h) in supplier s and in factory f respectively
$E_{s_j}^{cond}, E_{f_i}^{cond}$	energy consumption (kWh) for the air conditioning units involved in process j in supplier s and in process i in factory f respectively	$\Phi_{s_j}^{cond}, \Phi_{f_i}^{cond}$	covering rate per air conditioning unit (unit) that serves machines involved in process j in supplier s and in process i in factory f respectively
$E_{s_j}^{bulb}, E_{f_i}^{bulb}$	energy consumption (kWh) for the lighting bulbs involved in process j in supplier s and in process i in factory f respectively	$\varphi_{s_j}^{bulb}, \varphi_{f_i}^{bulb}$	covering rate of lighting bulbs (unit) per one machine involved process j in supplier and in process i in factory f respectively
E_w^{cond}, E_w^{bulb}	energy consumption (kWh) for the air conditioning units and lighting bulbs in warehouse w respectively	Π_w^{cond}	covering rate per air conditioning unit (kg) that services quantity of products in warehouse w
$N_{s_j}^{machin}$, $N_{f_i}^{machin}$	installed power (kw) for a machine involved in process j in supplier s and in process i in factory f respectively	λ_w^{bulb}	covering rate per lighting bulb (kg) that serves quantity of products in warehouse w
\Re_{s_j}, \Re_{f_i}	manufacturing rate (kg/h) for a machine involved in process j in supplier s and in process i in factory f respectively	e_s, e_f and e_w	amount of CO ₂ emissions (kg) released from supplier s to process raw materials, from factory f to manufacture the products and from warehouse w respectively
τ_{s_j}, τ_{f_i}	operating time (h) for a machine involved in process j in supplier s and in process i in factory f respectively	e^T	amount of CO ₂ emissions (kg) released from transportation vehicles to transfer materials from supplier s to factory f and shipped the products from factory f to warehouse w
μ_{s_j}, μ_{f_i}	efficiency (%) for a machine involved in process j in supplier s and in process i in factory f respectively		

$e_{s_j}^{machin}$ amount of CO₂ emissions (kg) released from the machines involved in process j of supplier s and in process i of factory f respectively

$e_{f_i}^{machin}$,

$e_{s_j}^{air\ comp}$ amount of CO₂ emissions (kg) released from a compressor system involved in process j of supplier s and in process i of factory f respectively

$e_{f_i}^{air\ comp}$,

$e_{s_j}^{cond}$ amount of CO₂ emissions (kg) released from the air conditioning units involved in process j of supplier s and in process i of factory f respectively

$e_{f_i}^{cond}$,

$e_{s_j}^{bulb}$, $e_{f_i}^{bulb}$ amount of CO₂ emissions (kg) released from the lighting bulbs involved in process j of supplier s and in process i of factory f respectively

e_{sf}^T , e_{fw}^T amount of CO₂ 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_j^s , ω_i^f CO₂ emission factor (kg/kWh) in supplier s and in factory f respectively

ω_{sf}^T , ω_{fw}^T CO₂ emission factor (kg/mile) released for transportation from supplier s to factory f and from factory f to warehouse w respectively

Decision variables

q_{s_j} , q_{f_i} mass of material (kg) involved in process j in supplier s and in process i in factory f respectively where, $j \in \{1, 2, \dots, m_{s_j}\}$ and $i \in \{1, 2, \dots, m_{f_i}\}$

$q_{s_{(j+1)}}$, mass of material (kg) transferred from the machines involved in process j in supplier s and in process i in factory f respectively

$q_{f_{(i+1)}}$,

q_{sf} , q_{fw} mass of material (kg) transported from supplier s to factory f and shipped as products from factory f to warehouse w

$n_{s_j}^{machin}$, number of machines (unit) involved in process j in supplier and in process i

$n_{f_i}^{machin}$ in factory f respectively where, $j \in \{1, 2, \dots, m_{s_j}\}$ and $i \in \{1, 2, \dots, m_{f_i}\}$

$n_{s_j}^{cond}$, $n_{f_i}^{cond}$ number of air conditioning units (unit) involved in process j in supplier s , in process i in factory f and in warehouse w respectively

and n_w^{cond}

$n_{s_j}^{bulb}$, $n_{f_i}^{bulb}$ number of lighting bulbs (unit) involved in process j in supplier s , in process i in factory f and in warehouse w respectively

Based on the aforementioned notations, the multi-objective mathematical model can be formulated as follows:

Objective function 1: total investment cost Z_1

$$\begin{aligned} Min Z_1 = & C_s^{Fixed} + C_f^{Fixed} + C_w^{Fixed} + C_s^R q_{sf} \\ & + C_f^{M.P} q_{fw} + C_{sf}^T \frac{q_{sf}}{V} d_{sf} + C_{fw}^T \frac{q_{fw}}{V} d_{fw} + C_w^I q_{fw} \end{aligned} \quad (1)$$

Objective function 2: total energy consumption Z_2

$$\begin{aligned} Min Z_2 = & \sum_{j=1}^{m_s} \left[\frac{q_{s_j}}{\Re_{s_j} \times \mu_{s_j}} N_{s_j}^{machin} \frac{machin}{n_{s_j}} \right. \\ & + \frac{q_{s_j}}{\Re_{s_j} \times \mu_{s_j}} \frac{N_{s_j}^{air\ comp}}{\rho_{s_j}} v_{s_j}^{air\ comp} \frac{machin}{n_{s_j}} \\ & \left. + N_{s_j}^{cond} \frac{cond}{n_{s_j}} \frac{q_{s_{j+1}}}{\wp_s} + N_{s_j}^{bulb} \frac{bulb}{n_{s_j}} \frac{q_{s_{j+1}}}{\wp_s} \right] \\ & + \sum_{i=1}^{m_f} \left[\frac{q_{f_i}}{\Re_{f_i} \times \mu_{f_i}} N_{f_i}^{machin} \frac{machin}{n_{f_i}} \right. \\ & + \frac{q_{f_i}}{\Re_{f_i} \times \mu_{f_i}} \frac{N_{f_i}^{air\ comp}}{\rho_{f_i}} v_{f_i}^{air\ comp} \frac{machin}{n_{f_i}} \\ & \left. + N_{f_i}^{cond} \frac{cond}{n_{f_i}} \frac{q_{f_{i+1}}}{\wp_f} + N_{f_i}^{bulb} \frac{bulb}{n_{f_i}} \frac{q_{f_{i+1}}}{\wp_f} \right] \\ & + \left[N_w^{cond} \frac{cond}{n_w} \frac{q_w}{\wp_w} + N_w^{bulb} \frac{bulb}{n_w} \frac{q_w}{\wp_w} \right] \end{aligned} \quad (2)$$

Objective function 3: total CO₂ emissions Z_3

$$\begin{aligned}
 \text{Min } Z_3 = & \sum_{j=1}^{m_s} \left[\omega_{s_j} E_{s_j}^{machin} q_{s_j} \right. \\
 & \left. + 0.689(E_{s_j}^{air\ comp} + E_{s_j}^{cond} + E_{s_j}^{bulb}) \right] \\
 & + \omega_{sf}^T \frac{q_{sf}}{V} d_{sf} + \omega_{fw}^T \frac{q_{fw}}{V} d_{fw} \\
 & + \sum_{i=1}^{m_f} \left[\omega_{f_i} E_{f_i}^{machin} q_{f_i} \right. \\
 & \left. + 0.689(E_{f_i}^{air\ comp} + E_{f_i}^{cond} + E_{f_i}^{bulb}) \right] \\
 & + 0.689(E_w^{cond} + E_w^{bulb})
 \end{aligned} \quad (3)$$

Where, the CO₂ emission factor ω_{s_j} , ω_{f_i} and $\omega_{sf, fw}^T$ is shown in Table I [15, 16].

TABLE I. AMOUNT OF CO₂ EMISSION FACTOR PER KWH AND PER MILE.

Energy source	Emission factor ω_{s_j} , ω_{f_i} and ω_w (kg/kWh)	Emission factor $\omega_{sf, fw}^T$ for truck (kg/mile)
Oil as indirect energy source to generate electricity	0.6895	0.420

Constraints:

$$q_{sf} \leq Ca_f \quad (4)$$

$$q_{fw} \leq Ca_w \quad (5)$$

$$q_{sf} \geq D_f \quad (6)$$

$$q_{fw} \geq D_w \quad (7)$$

$$(1 - \Psi_{s_j}) q_{s_j} \geq q_{s_{(j+1)}} \quad (8)$$

$$(1 - \Psi_{f_i}) q_{f_i} \geq q_{f_{(i+1)}} \quad (9)$$

$$\Phi_{s_j}^{cond} n_{s_j}^{cond} \geq n_{s_j}^{machin} \quad (10)$$

$$\Phi_{f_i}^{cond} n_{f_i}^{cond} \geq n_{f_i}^{machin} \quad (11)$$

$$n_{s_j}^{bulb} \geq \varphi_{s_j}^{bulb} n_{s_j}^{machin} \quad (12)$$

$$n_{f_i}^{bulb} \geq \varphi_{f_i}^{bulb} n_{f_i}^{machin} \quad (13)$$

$$\Pi_w n_w^{cond} \geq q_{fw} \quad (14)$$

$$\lambda_w n_w^{bulb} \geq q_{fw} \quad (15)$$

$$q_{s_j}, q_{sf}, q_{f_i}, q_{fw} \geq 0 \quad (16)$$

$$\Re_{s_j} n_{s_j}^{machin} \geq q_{s_{(j+1)}} \quad (17)$$

$$\Re_{f_i} n_{f_i}^{machin} \geq q_{f_{(i+1)}} \quad (18)$$

Where, equations 4, 5, 6, 7, 8, 9 and 16 are quantity constraints; and equation 10-15, 17 and 18 are constraints in numbers of machines, air conditioning units and bulbs.

III. APPLICATION AND EVALUATION

In order to examine the applicability and the validation of the developed multi-objective optimisation model as described above, a real case study was applied. The sustainable manufacturing system consists of three facilities (supplier s , factory f and warehouse w), and each facility has different processing tasks, each process task may involve a number of machines, number of air conditioning units and number of illumination bulbs. Each of those equipment has consumption of energy, releases an amount of CO₂ emissions and has mass inputs with different specifications. The study was carried out by analysing the total cost for establishing these facilities, the energy consumption and the amount of CO₂ emissions towards a sustainable manufacturing design.

Table II shows the collected data were taken from a real manufacturing system which includes three facilities (1 supplier, 1 factory and 1 warehouse) used for producing plastic and woven sacks. In this case, the production line is powered by electricity which is generated using oil as indirect source of energy. LINGO¹¹ software was used for computing results based on the developed multi-objective mathematical model aiming to seek the optimization solutions. In aiming to obtain non-inferior solutions, ε -constraint approach was utilized [17]. In this approach, the developed multi-objective model can be converted into a single-objective by adding constraints; the higher priority objective (total energy consumption) is considered to be an objective function (equation 19) and the other two objective functions (the total cost and the total CO₂ emissions) are shifted to be ε -based constraints; i.e. which (equation 20) restricts the value of the first objective function to be less than or equal to ε_1 which gradually varies between the minimum value and the maximum value for objective function one (equation 21). Equation 22 restricts the value of the third objective function to be less than or equal to ε_2 which gradually varies between the minimum value and the maximum value for objective function three (equation 23). The equivalent solution formula Z is presented as follows

$$MinZ_2 \tag{19}$$

Eq. (19) is subject to the following constrains:

$$Z_1 \leq \epsilon_1 \tag{20}$$

$$(Z_1)^{\min} \leq \epsilon_1 \leq (Z_1)^{\max} \tag{21}$$

$$Z_3 \leq \epsilon_2 \tag{22}$$

$$(Z_3)^{\min} \leq \epsilon_2 \leq (Z_3)^{\max} \tag{23}$$

And additional constraints including (equation. 4-18)

Table III, illustrates the non-inferior solutions that were obtained by an assignment of ϵ -values from 20,781,782 to 26,000,000 for objective one and from 103.75×10^9 to 158.75×10^9 for objective three. It can be noted in Table III that the values of objective one and three are highly corresponding to the assigned values of ϵ_1 and ϵ_2 which vary between the minimum and maximum value for objectives one and three, respectively. As an example, solution 1 obtained by an assignment of $\epsilon_1=20,781,782$, and $\epsilon_2=103.75 \times 10^9$ accordingly, the minimum total cost for establishing the manufacturing system is 20,500,000GBP, the minimum total amount of energy consumed by the manufacturing system is 2,357,288 kWh and the minimum total amount of CO₂ emissions released from the manufacturing system is 103748×10^6 kg.

TABLE II. DATA COLLECTED FROM A PLASTIC AND WOVEN SACKS COMPANY

Facilities		
Supplier <i>s</i>	Factory <i>f</i>	Warehouse <i>w</i>
C_s^{Fixed} (GBP): 5000000	C_f^{Fixed} (GBP): 6000000	C_w^{Fixed} (GBP): 2000000
C_s^R (GBP/kg): 2	$C_f^{M,P}$ (GBP/kg): 3	C_w^T (GBP/kg): 2
C_{sf}^T (GBP/mile): 2	C_{fw}^T (GBP/mile): 2	
d_{sf} (mile): 50, V (kg): 20000	d_{fw} (mile): 10, V = 20000	
$C\alpha_s$ (kg/month): 1000000	$C\alpha_f$ (kg/month): 990,000	$C\alpha_w$ (kg/month): 900000
	D_f (kg/month): 850000	D_w (kg/month): 850000
$m_s = 4$ process	$m_f = 8$ process	
\mathfrak{R}_{s_j} (kg/h): 1976, 1936, 1932 and 1929, where $j \in \{1, 2, \dots, m_s\}$	\mathfrak{R}_{f_i} (kg/h): 1852, 1815, 1742, 1716, 1699, 1665, 1660 and 1643, where $i \in \{1, 2, \dots, m_f\}$	
μ_{s_j} (%): 80 for all machines	μ_{f_i} (%): 80 for all machines	
Ψ_{s_j} (%): 0.03, 0.02, 0.002, 0.15	Ψ_{f_i} (%): 0.02, 0.04, 0.015, 0.01, 0.02, 0.003, 0.01, 0	
$N_{s_j}^{machin}$ (kw): 700, 500, 300, 600	$N_{f_i}^{machin}$ (kw): 200, 20, 7, 40, 7, 0, 0.8, 4	
$N_{s_j}^{air comp}$ (kw): 0	$N_{f_i}^{air comp}$ (kw): 200	
$\rho_{s_j}^{air comp}$ (m ³ /h): 0	$\rho_{f_i}^{air comp}$ (m ³ /h): 666	
$\upsilon_{s_j}^{air comp}$ (m ³ /h): 0	$\upsilon_{f_i}^{air comp}$ (m ³ /h): 5, 4, 13, 0, 7, 5, 20, 0, 0, 0	
$N_{s_j}^{cond}$ (kw): 2.2	$N_{f_i}^{cond}$ (kw): 2.2	N_w^{cond} (kw): 2.2
$N_{s_j}^{bulb}$ (kw): 0.4	$N_{f_i}^{bulb}$ (kw): 0.4	N_w^{bulb} (kw): 0.4
$\Phi_{s_j}^{cond}$ (units): 2, $\phi_{s_j}^{bulb}$ (units): 15	$\Phi_{f_i}^{cond}$ (units): 2, $\phi_{f_i}^{bulb}$ (units): 15	Γ_w^{cond} (kg): 1000, λ_w^{bulb} (kg): 500
g_p (kg): 950000	g_f (kg): 840000	g_w (units): 9,032,258
ω_{s_j} (kg/kWh): 0.6895	ω_{f_i} (kg/kWh): 0.6895	ω_w (kg/kWh): 0.6895
ω_{sf}^T (kg/mile): 0.420	ω_{fw}^T (kg/mile): 0.420	

TABLE III. NON-INFERIOR SOLUTIONS OBTAINED BY USING THE ϵ -CONSTRAINT APPROACH

Solution number	ϵ -values		Objective function solutions		
	ϵ_1	ϵ_2	Min Z_1	Min Z_2	Min Z_3
1	20781782	103.75×10^9	20500000	2357288	103748×10^6
2	22123925	117.5×10^9	21879729	2557194	117498×10^6
3	23466068	131.25×10^9	23239639	2842852	131248×10^6
4	24808211	145×10^9	24640700	3128510	144998×10^6
5	26000000	158.75×10^9	26000000	3414168	158748×10^6

As shown in Table IV, each solution has a potential group of number of machines that is involved in process j in supplier s ($n_{s_j}^{machin}$) where $j \in \{1, 2, 3, 4\}$. For instance, in solution 1, number of machines involved in process task j is (1, 1, 1, 1).

TABLE IV. NUMBERS OF MACHINES INVOLVED IN PROCESS J IN SUPPLIER S UNDER THE ϵ -CONSTRAINT APPROACH

Solution number	Numbers of machines involved in process j , $n_{s_j}^{machin}$ Where $j \in \{1, 2, 3, 4\}$.			
	n_{s1}	n_{s2}	n_{s3}	n_{s4}
1	1	1	1	1
2	1	1	1	1
3	2	2	1	1
4	2	2	2	1
5	2	2	1	2

Table V shows the result for solution 1 using the ϵ -constraint approach which gives the group of machines involved in process i in factory f ($n_{f_i}^{machin}$) where $i \in \{1, 2, 3, 4, 5, 6, 7, 8\}$ is (4, 32, 3, 5, 9, 9, 35, 3).

TABLE V. NUMBERS OF MACHINES INVOLVED IN PROCESS I IN FACTORY F UNDER THE ϵ -CONSTRAINT APPROACH

Solution number	Numbers of machines involved in process i , $n_{f_i}^{machin}$ Where $i \in \{1, 2, 3, 4, 5, 6, 7, 8\}$.							
	n_{f1}	n_{f2}	n_{f3}	n_{f4}	n_{f5}	n_{f6}	n_{f7}	n_{f8}
1	4	32	3	5	9	9	35	3
2	4	32	3	5	10	10	40	3
3	4	40	3	5	13	13	60	4
4	5	40	4	5	14	14	60	4
5	5	45	5	6	16	16	60	5

A pairwise comparison among the three conflicting objectives is illustrated in Figure 2a and 2b. The results shown

in Figure 2a and 2b indicate that the non-inferior solution 1 gives values of the total cost, the total energy consumption and total CO₂ emissions less compared to the other solutions. Additionally, as indicated in Tables IV and V that the non-inferior solution 1 in terms of number of machines that need to be involved in supplier *s* and factory *f*, gives values less than the other solutions. By balancing the three objectives with of $\epsilon_1=20,781,782$, and $\epsilon_2=103.75 \times 10^9$, it leads to compromise solution 1, which includes an installation of machines that need to be involved in processes task *j* in supplier *s* where, $j \in (1, 2, 3, 4)$ is (1, 1, 1, 1), and installation of machines that need to be involved in processes task *i* in factory *f* where, $i \in (1, 2, 3, 4, 5, 6, 7, 8)$ is (4, 32, 3, 5, 9, 9, 35, 3). This solution gives a minimum total cost for establishing the manufacturing system is (20,500,000) GBP, the minimum total amount of energy consumed by the manufacturing system is (2,357,288) kWh and the minimum total amount of CO₂ emissions released from the manufacturing system is (103748 × 10⁶) kg.

solution as it has the minimal distance 3.45 to the value of the ideal solution. Table VI shows the optimal solutions in quantity of material flows (i) among the machines involved in process task *j* in supplier *s* (ii) from supplier *s* to factory *f* (iii) among the machines involved in process task *i* in factory *f* and (iv) from factory *f* to warehouse *w*.

TABLE VI. THE OPTIMAL QUANTITY OF MATERIAL FLOW FOR THE SUSTAINABLE MANUFACTURING SYSTEM DESIGN

Supplier <i>s</i>									
Solution number	q_{sj} where $j \in (1, 2, 3, 4)$				q_{sf}	-	-	-	-
	q_{s1}	q_{s2}	q_{s3}	q_{s4}					
1	940300	935200	933090	928184	915358	-	-	-	-
2	955355	950050	948100	946084	934570	-	-	-	-
3	985500	965200	963040	960084	935805	-	-	-	-
4	1000000	980000	978040	976084	937040	-	-	-	-
5	1020000	1002000	996100	994084	955150	-	-	-	-
6	1045000	1027000	1009000	991100	973050	-	-	-	-
7	1066000	1048000	1033000	1015000	997040	-	-	-	-
8	1083000	1065000	1047050	1029100	1014100	-	-	-	-

Factory <i>f</i>									Warehouse <i>w</i>
Solution number	q_{fi} where $i \in (1, 2, 3, 4, 5, 6, 7, 8)$								
	q_{f1}	q_{f2}	q_{f3}	q_{f4}	q_{f5}	q_{f6}	q_{f7}	q_{f8}	q_{fw}
1	918358	900100	852898	832220	810660	633131	580407	550100	5,915,053 sacks
2	934570	902423	880500	842459	830550	730100	600010	580200	6,238,709 sacks
3	935805	909227	881567	853478	842344	838459	790939	600100	6,452,688 sacks
4	937040	918299	889824	868344	850660	840467	835940	831540	8,941,290 sacks
5	955150	928300	904824	883344	865660	855467	850940	846540	9,102,580 sacks
6	973050	940200	919700	898400	883660	870500	868940	864499	9,295,688 sacks
7	997040	955100	934824	919344	901660	888399	886950	880550	9,468,279 sacks
8	1014100	968188	952824	931344	916660	906467	904940	880555	9,468,333 sacks

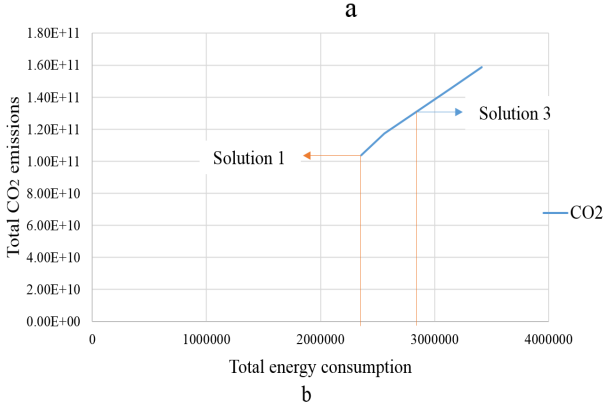
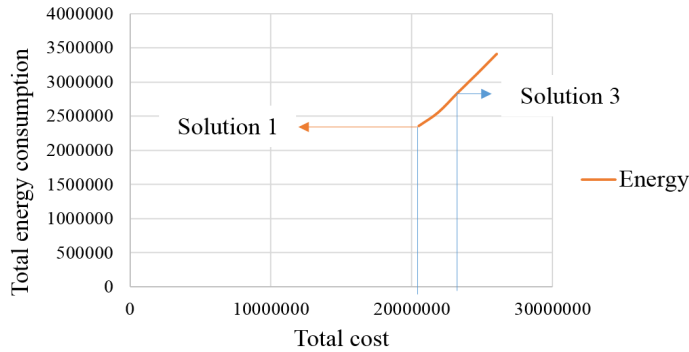


Fig. 2. Comparison between solutions obtained

In order to design a sustainable manufacturing system based on the obtained solutions using the ϵ -constraint approach, one of these solutions needs to be selected based on the preferences of decision makers or using the Max-Min approach [18]. Based on this Max-Min approach, although solution 1 has less values of the total cost, the total energy consumption, total CO₂ emissions and number of machines than the other solutions, solution 3 is determined as the best

Table VII shows the result of solution 3 in terms of numbers of machines and the quantity of materials that need to be involved in the design of the sustainable manufacturing system. Figure 3 shows the optimal design of the sustainable manufacturing system based on solution 3, which was obtained with $\epsilon_1=23,466,068$, and $\epsilon_2=131.25 \times 10^9$ that yields the minimum total cost of 23,239,639 GBP, the minimum total amount of energy consumption of 2,842,852 kWh and the minimum total amount of CO₂ of 131,248 × 10⁶ kg.

TABLE VII. THE OPTIMAL SOLUTION FOR A SUSTAINABLE MANUFACTURING SYSTEM DESIGN

Process number <i>j</i>	Number of machines involved in process <i>j</i> n_{sj}^{machin} units	Quantity of materials involved in process <i>j</i> q_{sj} (kg)
1	2	980000
2	2	978040
3	1	976084
4	1	937040

The optimal solution for factory <i>f</i>		
Process number <i>i</i>	Number of machines involved in process <i>i</i> n_{fi}^{machin} (units)	Quantity of materials involved in process <i>i</i> q_{fi} (kg)
1	4	937040
2	40	918299
3	3	889824
4	5	868344
5	13	850660
6	13	840467
7	60	835940
8	4	831540

Number of manufacturing products q_{fw} (units)	8,941,290 sacks
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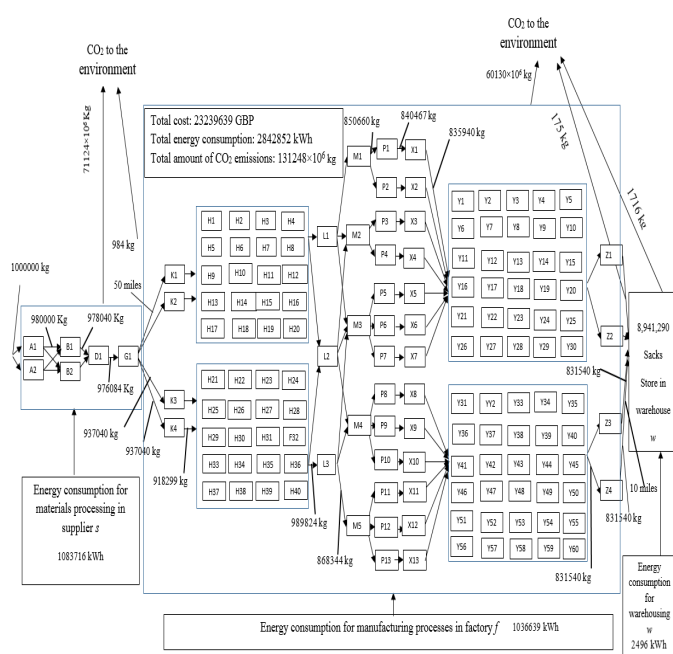


Fig. 3. An optimal sustainable manufacturing system design

IV. CONCLUSION

When designing a manufacturing system, engineers used to focus on the key performance indicators in terms of such as system productivity and capacity; environmental considerations are often overlooked. This paper presents the development of a three-objective mathematical model as an aid 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 to seek a trade-off solution in minimizing the total investment cost, minimizing the total energy consumption and minimizing the total CO₂ emissions released from the manufacturing system. The computational results were validated based on data collected from a real industrial case. The study indicates that this is a useful and effective way as a decision-making tool used for optimizing a traditional manufacturing system design towards the sustainability under the economic and ecological constraints.

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