A sustainable manufacturing system design: A fuzzy multi-objective optimization model

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Abstract. **In the past decade, there has been a growing concern about the environmental protection in the public society as governments almost in all over the world has initiated certain rules and regulation to promote energy saving and minimalize the production of carbon dioxide (CO_2) emissions in many manufacturing industry. Development of sustainable manufacturing systems is considered as one of effective solutions to minimize the environmental impact. Lean approach is considered as a proper method for achieving the sustainability as it can reduce manufacturing wastes and increase the efficiency and productivity. However, the lean approach does not include an environmental waste in such as waste of energy consumption and CO_2 emissions when designing a lean manufacturing system. This paper addresses these issues by evaluating a sustainable manufacturing system design by considering a measurement of energy consumption and CO_2 emissions using deferent source of energy (oil as direct energy source to generate thermal energy, oil as indirect energy source to generate electricity and solar as indirect energy source to generate electricity). To this aim, a multi-objective mathematical model is developed incorporating the economic and ecological constraints in terms of minimization of the total cost, energy consumption and CO_2 emissions for a manufacturing system design. To come closer to real world, the uncertainty in some of the input parameters were handled through a development of a fuzzy multi-objective model. The study also addresses a decision making in the number of machines, the number of air conditioning units and the number of bulbs involved in each process of the manufacturing system in conjunction with a quantity of material flow for processing the products. 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; CO_2; Lean manufacturing; Environmental constraints; Multi-objectives.

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I. INTRODUCTION

To design a sustainable manufacturing system, manufacturing system designers need not merely relay to apply traditional methods of improving system efficiency and productivity but also to examine the environmental impact on the developed system (Heilala 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 aspects that needs also to be addressed today which leads towards a new challenge for designers of manufacturing system to create an effective approach incorporating environmental parameters or constraints (Paju et al. 2010). In the past decade, the concept such as sustainable manufacturing systems has been used for promoting a balance between the environmental impact and the economic performance for production (Taghdisian et al. 2014). 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. 2016a). This concept has usually been implemented when environmental problems are to be taken as completely separate objective in the process synthesis at initial stage. In this concept, each of environmental aspects is considered as a separate objective together with other classical objectives in maximizing system productivity or system efficiency and or minimizing cost of the desired product, which forms a multi-objective optimization (MOO) problem (Taghdisian et al. 2014 and Nujoom et al. 2016).

Moreover, development of a sustainable manufacturing system design should also consider lean methods as it has become a trend in modern manufacturing enterprises for optimizing 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" (Nujoom et al. 2016a). 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 (Wang et al. 2009). Nevertheless, traditional lean manufacturing method does not consider environmental wastes such as waste of energy and CO_2 emissions which also need to be considered as these wastes add no values on manufactured products (Nujoom et al. 2016 and Wang et al. 2009). Consequently, it is important to optimize the traditional lean manufacturing system design to achieve the sustainability and make a balance under the economic and ecological constraints. Moreover, industrial factories consume a massive amount of energy and produce a huge amount of CO_2 emissions, which lead to a huge amount of costs that need to be considered in the manufacturing system design (Ghadiri et al. 2017).

There are a few studies in considering environmental aspects related to manufacturing and sustainable manufacturing system. Heilala et al. (2008) 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. (2008) proposed a method to be known as process integration (PI) method that was used for evaluating CO_2 emissions for a steel industry. Branham et al. (2008) used the quantitative thermodynamic analysis for measuring the amount of energy to be used by various categories by manufacturing system. Guillen-Gosalbez and Grossmann (2009) developed a mathematical model named as a bi-criterion stochastic mixed-integer nonlinear program (MINLP) used for the maximization of the network present value and the minimization of the environmental impact on a sustainable chemical supply chains design.

The multi-objective optimization approach is one of the mathematical methods that can be used for modelling a manufacturing system by satisfying a number of conflicting objectives (such as energy consumption, CO_2 emissions and costs) in which each objective needs to be optimized based on a separate objective function (Mohammed and Wang 2016). Li et al. (2009) used a multi-objective mixed integer non-linear model incorporating environmental and economic factors for design and optimization of chemical process. Abdallah et al. (2010) have utilized a multi-objective optimization method used for minimizing carbon emissions and investment cost of the supply chain Network facilities. Wang et al. (2011) studied a multi-objective optimization model that balances the trade-off between total cost and the amount of CO_2 emissions released from the supply chain facilities. Jamshidi et al. (2012) 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. (2012) presents 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. Moreover, in real world, several input parameters such as purchasing cost and demands are normally subject to uncertainty. Thus, uncertainty in the input parameters should also be measured in a manufacturing design (Mohammed et al. 2016). Fuzzy logic is one of the main approaches that was used to handle the uncertainty in a given data.

This paper presents an investigation into a sustainable manufacturing system design under multiple uncertainties through a development of a fuzzy multi-objective model. The developed model was used for examining the configuration and performance measures of the proposed sustainable manufacturing system design in terms of (1) number of machines involved in each process in the manufacturing system (2) number of air conditioning units and number of bulbs involved in each process (3) optimal material quantity flows along the line and (4) a compromised solution among conflicting objectives by minimizing the total investment cost for establishing the manufacturing system, minimizing the amount of energy consumed by the machines involved in each process in the manufacturing system and minimizing the CO_2 emissions released from the machines involved in each process in the manufacturing system. Afterward, the developed multi-objective model was re-developed in terms of a fuzzy multi-objective model to cope with the uncertainties in some of the parameters e.g., raw material cost, demands and CO_2 emission. The ε-constraint approach was used to reveal a set of non-inferior solutions derived from the developed fuzzy mathematical model; followed by an employment of the max-min approach in order to select the best non-inferior solution.

The rest of this paper is organized as follows: section II gives an explanation of problem description and model formulation. Section III presents the optimization approach. Application and evaluation of the model have been presented in Section IV and finally the paper has been concluded in section V

II. PROBLEM STATEMENT AND MODEL FORMULATION

Figure 1 illustrates a framework of a sustainable manufacturing system design which consists of operation machines, air conditioning units, lighting bulbs and other supportive equipment such as compressors which supply compressed air to some machines. Energy and CO_2 emissions are generated directly by combusting fossil fuels or by using electricity which is generated indirectly by using either fossil fuels or renewable resources. 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 CO_2 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. In this study, 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 CO_2 emissions (equation 3) as described below. The model is also aimed at making design decisions in terms of (i) numbers of operation machines, air conditioning units and lighting bulbs that needs to be involved in the sustainable manufacturing system and (ii) quantity of materials flows through the operation machines that need to be involved in the manufacturing system.

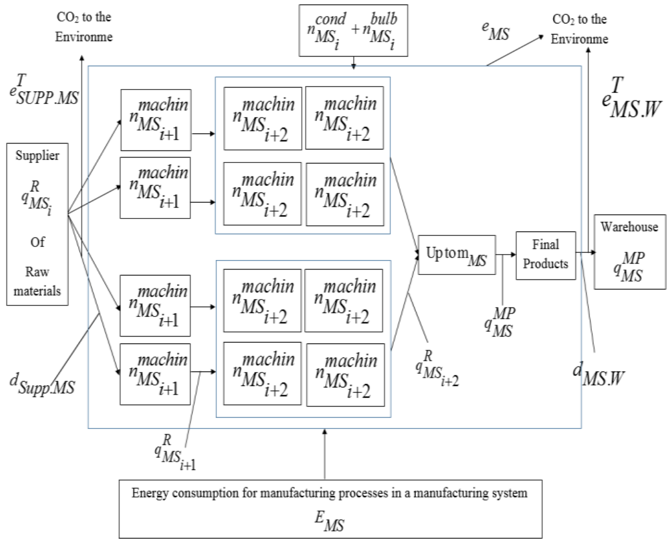

Fig. 1. Strcuture of a sustainable manufacturing system design

The following notations are used for formulating the mathematical model:

Sets:

S	set of a supplier
MS	set of a manufacturing system
W	set of a warehouse
m_{MS_i}	number of processes involved in the manufacturing system, where $i \in \{1,\ 2,\ ....,\ m_{MS}\}$

Parameters

C^{Fixed}_{MS}	fixed cost (GBP) of the manufacturing system
$C^{R}_{SUPP.MS}$	raw materials cost (GBP)
C^{R}_{SUPP}	unit raw materials cost (GBP) in supplier
$C^{MP}_{MS.W}$	manufactured products cost (GBP)
C^{MP}_{MS}	unit manufactured products cost (GBP)
$C^{I}_{MS.W}$	inventory cost (GBP) from manufacturing system to warehouse
C^{I}_{w}	unit inventory cost (GBP) in warehouse
$C^{T.R}_{SUPP.MS}$	transportation cost (GBP) of raw materials from supplier to manufacturing system
$C^{T.R}_{SUPP}$	unit transportation cost (GBP) per mile of raw materials from supplier to manufacturing system

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$C^{T.MP}_{MS.W}$	transportation cost (GBP) of manufacturing products from manufacturing system to warehouse
$C^{T.MP}_{MS}$	unit transportation cost (GBP) per mile of manufacturing products from manufacturing system to warehouse
$d_{SUPP.MS}$	distance (mile) from a supplier to a manufacturing system
$d_{MS.W}$	distance from a manufacturing system to a warehouse
V	capacity (kg) per vehicle
$E^{machin}_{MS_i}$	energy consumption (kWh) for the machines involved in process i in a manufacturing system, where, $i \in \{1,\ 2,\ ....,\ m_{MS}\}$
$E^{air\ comp}_{MS_i}$	energy consumption (kWh) of compressed air needed for the machines involved in process i
$E^{cond}_{MS_i}$	energy consumption (kWh) for the air conditioning units involved in process i
$E^{bulb}_{MS_i}$	energy consumption (kWh) for the lighting bulbs involved in process i
$N^{machin}_{MS_i}$	installed power (kw) for a machine involved in process i
$N^{cond}_{MS_i}$	installed power (Kw) for an air conditioning unit involved in process i
	installed power (Kw) for
$N^{bulb}_{MS_i}$	an illumination bulb involved in process i
$N^{air\ comp}_{MS_i}$	installed power for a compressor involved in process i
$\Re^{machin}_{MS_i}$	manufacturing rate (kg/h) for a machine involved in process i
$\tau^{machin}_{MS_i}$	operating time (hr) for a machine involved in process i
$\mu^{machin}_{MS_i}$	efficiency (%) for a machine involved in process i
G^{month}_{MS}	mass production (kg) per month for the manufacturing system
$\Psi^{machin}_{MS_i}$	total waste ratio (%) for a machine involved in process i
$\upsilon^{air\ comp}_{MS_i}$	compressed air (m^3/h) used for the machines involved in process i
$\rho^{air\ comp}_{MS_i}$	capacity of compressed air (m^3/h) of a compressor
$\Phi^{cond}_{MS_i}$	covering rate per air conditioning unit that services machines involved in process i
$\varphi^{bulb}_{MS_i}$	covering rate of lighting bulbs per one machine involved in process i
$N^{air\ comp}_{MS_i}$	installed power (kWh) for a compressor
e_{MS}	amount of CO_2 emissions (kg) released from the manufacturing system due to manufacturing the products

e^{T}	amount of CO_2 emissions (kg) released from transportation vehicles to transfer materials from supplier to manufacturing system and shipped the products from manufacturing system to warehouse
$e^{machin}_{MS_i}$	amount of CO_2 emissions (kg) released from the machines involved in process *i*
$e^{air\ comp}_{MS_i}$	amount of CO_2 emissions (kg) released from a compressor system involved in process *i*
$e^{cond}_{MS_i}$	amount of CO_2 emissions (kg) released from the air conditioning units involved in process *i*
$e^{bulb}_{MS_i}$	amount of CO_2 emissions (kg) released from the illumination bulbs involved in process *i*
$e^{T}_{SUPP.MS}$	amount of CO_2 emissions (kg) released for transportation from supplier to manufacturing system
$e^{T}_{MS.W}$ (kg)	amount of CO_2 emissions (kg) released for transportation from manufacturing system to warehouse
ω_{MS_i}	CO_2 emission factor (kg/kWh) Based on the source of energy used by the manufacturing system
$\omega^{T}_{SUPP.MS,\ MS.W}$	CO_2 emission factor (kg/mile) released for transportation from supplier to manufacturing system and from manufacturing system to warehouse

Decision variables

$q^{R}_{SUPP.MS}$	mass of material (kg) transported from supplier to manufacturing system
$q^{R}_{MS_i}$	mass of materials (kg) involved in process *i*
$q^{R}_{MS_{i+1}}$	mass of materials (kg) transferred from a machine involved in process *i*
q^{MP}_{MS}	mass of material (kg)shipped as a final products to warehouse
$n^{machin}_{MS_i}$	number of machines (unit) involved in process *i*
$n^{cond}_{MS_i}$	number of air conditioning units (unit) involved in process *i*
$n^{bulb}_{MS_i}$	number of lighting bulbs (unit) involved in process *i*
$q_{MS.W}$	mass of material (kg) transported from manufacturing system to warehouse

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

Objective function 1: Total investment cost Z_1

In the proposed sustainable manufacturing system design, the total investment cost is a combination of fixed cost (costs of the land, buildings, equipment, services and salaries), costs of raw materials and transportation of raw materials, and costs of manufacturing and inventory and so on. Thus, the total investment cost Z_1 can be minimised as follows:

$$Min\ Z_1 = C^{Fixed}_{MS} + C^{R}_{SUPP.MS} + C^{MP}_{MS.W} + C^{I}_{MS.W} + C^{T}_{MS} \tag{1}$$

Where, fixed cost $C^{Fixed}_{M.S}$ of establishing the manufacturing system is given as bellow:

$$C^{Fixed}_{MS} = C^{Land}_{MS} + C^{Building}_{MS} + C^{Equipment}_{MS} + C^{Services}_{MS} + C^{Saleries}_{MS} \tag{2}$$

Cost of unit raw materials $C^{R}_{SUPP.MS}$ is calculated as follows:

$$C^{R}_{SUPP.MS} = C^{R}_{SUPP} q^{R}_{SUPP.MS} \tag{3}$$

Cost of manufacturing products in a manufacturing system $C_{MS.W}^{MP}$ given by the following equation:

$$C_{MS.W}^{MP} = C_{MS}^{MP} q_{MS.W} \tag{4}$$

Cost of inventory $C_{MS.W}^{I}$ at warehouse is determined as below:

$$C_{MS.W}^{I} = C_{w}^{I} q_{MS.W} \tag{5}$$

Cost of transportation of raw materials from supplier to manufacturing system per mile $C_{SUPP.MS}^{T.R}$ is given as follows:

$$C_{SUPP.MS}^{T.R} = C_{SUPP}^{T.R} \frac{q_{SUPP.MS}^{R}}{V} d_{SUPP.MS} \tag{6}$$

Cost of transportation of manufactured products from manufacturing system to warehouse $C_{MS.W}^{T.R}$ is given as follows:

$$C_{MS.W}^{T.MP} = C_{MS}^{T.MP} \frac{q_{MS.W}^{MP}}{V} d_{MS.W} \tag{7}$$

Hence, equation (1) will be as follows:

$$\begin{aligned} Min\ Z_1 = {} & C_{MS}^{Land} + C_{MS}^{Building} + C_{MS}^{Equipment} \\ & + C_{MS}^{Services} + C_{MS}^{Saleries} + C_{SUPP}^{R} q_{SUPP.MS}^{R} \\ & + C_{MS}^{MP} q_{MS.W}^{MP} + C_{w}^{I} q_{MS.W} \\ & + C_{SUPP.MS}^{T.R} \frac{q_{SUPP.MS}^{R}}{V} d_{SUPP.MS} \\ & + C_{MS.W}^{T.MP} \frac{q_{MS.W}^{MP}}{V} d_{MS.W} \end{aligned}$$

Objective function 2: Total energy consumption Z_2

$$Min\ Z_2 = \sum_{i=1}^{m_{MS}} \left(\begin{aligned} & E_{MS_i}^{machin} + E_{MS_i}^{air\ comp} \\ & + E_{MS_i}^{cond} + E_{MS_i}^{bulb} \end{aligned} \right) \tag{8}$$

Where, $i \in \{1,\ 2,\ ....,\ m_{MS}\}$

Energy consumption $E_{MS_i}^{machin}$ for machines involved in process i is given by:

$$E_{MS_i}^{machin} = \frac{q_{MS_i}^{R}}{\Re_{MS_i} \mu_{MS_i}} N_{MS_i}^{mach} n_{MS_i}^{mach} \tag{9}$$

Energy consumption of compressed air $E_{MS_i}^{air\ comp}$, which is needed for machines involved in process i is calculated by:

$$E_{MS_i}^{air\ comp} = \frac{q_{MS_i}^{R}}{\Re_{MS_i} \mu_{MS_i}} \frac{N_{MS_i}^{air\ comp}}{\rho_{MS_i}^{air\ comp}} v_{MS_i}^{air\ comp} n_{MS_i}^{mach} \tag{10}$$

Energy consumption $E_{MS_i}^{cond}$ for air conditioning units involved in process i is given by:

$$E_{MS_i}^{cond} = N_{MS_i}^{cond} n_{MS_i}^{cond} \frac{q_{MS_{i+1}}^{R}}{G_{MS}} \tag{11}$$

Energy consumption $E_{MS_i}^{bulb}$ for lighting bulbs involved in process i is calculated by:

$$E_{MS_i}^{bulb} = N_{MS_i}^{bulb} n_{MS_i}^{bulb} \frac{q_{MS_{i+1}}^{R}}{G_{MS}} \tag{12}$$

Hence, equation 8 is given as follows:

$$MinZ_2 = \sum_{i=1}^{m_{M.S}} \left(\begin{aligned} & \frac{q_{MS_i}^{R}}{\Re_{MS_i} \mu_{MS_i}} N_{MS_i}^{mach} n_{MS_i}^{mach} \\ & + \frac{q_{MS_i}^{R}}{\Re_{MS_i} \mu_{MS_i}} \frac{N_{MS_i}^{air\ comp}}{\rho_{MS_i}^{air\ comp}} v_{MS_i}^{air\ comp} n_{MS_i}^{mach} \\ & + N_{MS_i}^{cond} n_{MS_i}^{cond} \frac{q_{MS_{i+1}}^{R}}{G_{MS}} + N_{MS_i}^{bulb} n_{MS_i}^{bulb} \frac{q_{MS_{i+1}}^{R}}{G_{MS}} \end{aligned} \right)$$

Objective function 3: Total CO2 emissions Z_3

$$Min\ Z_3 = e_{MS} + e^{T} \tag{13}$$

Where, amount of CO2 emissions released from the manufacturing system is calculated as follows:

$$e_{MS} = \sum_{i=1}^{m_{MS}} \left(e_{MS_i}^{machin} + e_{MS_i}^{air\ comp} + e_{MS_i}^{cond} + e_{MS_i}^{bulb} \right) \tag{14}$$

Amount of CO2 emissions $e_{MS_i}^{machin}$ released from the machines involved in process *i* is calculated as follows:

$$e_{MS_i}^{machin} = \omega_{MS_i} E_{MS_i}^{machin} q_{MS_i} \qquad (15)$$

Amount of CO2 emissions $e_{MS_i}^{air\ comp}$ released from a compressor system involved in process *i* calculated as follows:

$$e_{MS_i}^{air\ comp} = \omega_{MS_i} E_{MS_i}^{air\ comp} \qquad (16)$$

Amount of CO2 emissions $e_{MS_i}^{cond}$ released from the air conditioning units involved in process *i* is calculated as follows:

$$e_{MS_i}^{cond} = \omega_{MS_i} E_{MS_i}^{cond} \qquad (17)$$

Amount of CO2 emissions $e_{MS_i}^{bulb}$ released from the illumination bulbs involved in process *i* is calculated as follows:

$$e_{MS_i}^{bulb} = \omega_{MS_i} E_{MS_i}^{bulb} \qquad (18)$$

Amount of CO2 emissions e^T released from transportation vehicles to transfer materials from supplier to manufacturing system and shipped the products from a manufacturing system to warehouse is calculated by:

$$e^T = e_{SUPP.MS}^{T.R} + e_{MS.W}^{T.MP} \qquad (19)$$

where, amount of CO2 emissions $e_{SUPP.MS}^{T.R}$ per one unit in distance (mile in this study), which are released for transportation from supplier to manufacturing system is given below:

$$e_{SUPP.MS}^{T.R} = \omega_{SUPP.MS}^{T} \frac{q_{SUPP.MS}}{V} d_{SUPP.MS} \qquad (20)$$

Amount of CO2 emissions $e_{MS.W}^{T.MS}$ per one unit in distance (mile in this study), which are released for transportation from manufacturing system to warehouse, is given as below:

$$e_{MS.W}^{T.MP} = \omega_{MS.MS}^{T} \frac{q_{MS.W}}{V} d_{MS.W} \qquad (21)$$

Hence, equation 13 is given as follows:

$$Min\ Z_3 = \sum_{i=1}^{m_{MS}} \left(\begin{array}{l} \omega_{MS_i} E_{MS_i}^{machin} q_{MS_i} + \omega_{MS_i} E_{MS_i}^{air\ comp} \\ + \omega_{MS_i} E_{MS_i}^{cond} + \omega_{MS_i} E_{MS_i}^{bulb} \\ + \omega_{SUPP.MS}^{T} \frac{q_{SUPP.MS}}{V} d_{SUPP.MS} \\ + \omega_{MS.MS}^{T} \frac{q_{MS.W}}{V} d_{MS.W} \end{array} \right)$$

Where, the CO2 emission factor ω_{MS_i} and $\omega_{SUPP.MS,\ MS.W}^{T}$ can be defined as shown in Table I (Nujoom et al. 2016b; EPA. 2008).

TABLE I. AMOUNT OF CO2 EMISSION FACTOR PER KWH USING DEFERENT ENERGY SOURCES AND PER MILE.

Energy source	Emission factor ω_{MS_i} (kg/kWh)	Emission factor $\omega_{SUPP.MS,\ MS.W}^{T}$ for truck (kg/mile)
Oil as direct energy source when oil is combusted to generate thermal energy	0.5	0.420
Oil as indirect energy source to generate electricity	0.6895	
Solar as indirect energy source to generate electricity	0.05	

Constraints:

Equation 22 and 23 ensure that the quantity of raw material shipped to the manufacturing system and warehouse cannot be greater than their capacity.

$$q_{SUPP.MS}^{R} \le Ca_{MS} \qquad (22)$$

$$q_{MS.W}^{MP} \le Ca_{W} \qquad (23)$$

Equation 24 and 25 ensure that demands of manufacturing system and warehouse are fulfilled, respectively.

$$q_{SUPP.MS}^{R} \ge D_{MS} \qquad (24)$$

$$q_{MS.W}^{MP} \ge D_{W} \qquad (25)$$

Equation 26 defines that quantity of materials of the first process task must be bigger than or equal to quantity of materials of the next process task.

$$(1-\Psi_{MS_i}^{machin})q_{MS_i}^{R} \geq q_{MS_{(i+1)}}^{R} \quad (26)$$

Equation 27 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.

$$\Phi_{MS_i}^{cond} n_{MS_i}^{cond} \geq n_{MS_i}^{machin} \quad (27)$$

Equation 28 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.

$$n_{MS_i}^{bulb} \geq \varphi_{MS_i}^{bulb} n_{MS_i}^{machin} \quad (28)$$

Equation 29 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.

$$q_{SUUP.MS}^{R},\ q_{MS_i}^{R},\ q_{MS_{(i+1)}}^{R},\ q_{MS.W}^{MP} \geq 0 \quad (29)$$

Equation 30 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)*.

$$\Re_{MS_i}^{machin} n_{MS_i}^{machin} \geq q_{MS_{(i+1)}}^{R} \quad (30)$$

Where, equations 22, 23, 24, 25, 26 and 29 are quantity constraints; and equation 27, 28 and 30 are constraints in numbers of manufactured machines, air conditioning units and illumination bulbs.

2.1 Treating the uncertainty

In real world, several data are subject to uncertainty. Decision makers should consider this uncertainty into their network design. In this study, to cope with the dynamic nature of the input parameters in transportation and raw material costs, demands and CO$_2$ emissions throughout the transportation activity, the multi-objective model was re-developed in terms of a fuzzy multi-objective model. The equivalent crisp model can be formulated as follows: (Jiménez et al. 2007; and Mohammed and Wang 2017).

$$\begin{aligned}
Min\ Z_1 = {} & C_{MS}^{Land} + C_{MS}^{Building} + C_{MS}^{Equipment} \\
& + C_{MS}^{Services} + C_{MS}^{Saleries} \\
& + \left(\frac{C_{SUPP}^{R\ \ pes} + 2C_{SUPP}^{R\ \ mos} + C_{SUPP}^{R\ \ opt}}{4} \right) q_{SUPP.MS}^{R} \\
& + C_{MS}^{MP} q_{MS.W}^{MP} + C_{w}^{I} q_{MS.W} \\
& + \left(\frac{C_{SUPP.MS}^{T.R\ \ pes} + 2C_{SUPP.MS}^{T.R\ \ mos} + C_{SUPP.MS}^{T.R\ \ opt}}{4} \right) \\
& \frac{q_{SUPP.MS}^{R}}{V} d_{SUPP.MS} \\
& + \left(\frac{C_{MS.W}^{T.MP\ pes} + 2C_{MS.W}^{T.MP\ mos} + C_{MS.W}^{T.MP\ opt}}{4} \right) \frac{q_{MS.W}^{MP}}{V} d_{MS.W}
\end{aligned} \quad (31)$$

$$Min\ Z_2 = \sum_{i=1}^{m_{MS}} \left(\begin{aligned} & E_{MS_i}^{machin} + E_{MS_i}^{air\ comp} \\ & + E_{MS_i}^{cond} + E_{MS_i}^{bulb} \end{aligned} \right) \quad (32)$$

$$Min\ Z_3 = \sum_{i=1}^{m_{MS}} \left[\begin{aligned}
& \omega_{MS_i} E_{MS_i}^{machin} q_{MS_i} + \omega_{MS_i} E_{MS_i}^{air\ comp} \\
& + \omega_{MS_i} E_{MS_i}^{cond} + \omega_{MS_i} E_{MS_i}^{bulb} \\
& + \left(\frac{\omega_{SUPP.MS}^{T\ \ pes} + 2\omega_{SUPP.MS}^{T\ \ mos} + \omega_{SUPP.MS}^{T\ \ opt}}{4} \right) \\
& \frac{q_{SUPP.MS}}{V} d_{SUPP.MS} \\
& + \left(\frac{\omega_{MS.MS}^{T\ \ pes} + 2\omega_{MS.MS}^{T\ \ mos} + \omega_{MS.MS}^{T\ \ opt}}{4} \right) \\
& \frac{q_{MS.W}}{V} d_{MS.W}
\end{aligned} \right] \quad (33)$$

s.t.

$$q_{SUPP.MS}^{R} \geq \left[\begin{aligned} & \frac{\alpha}{2} \cdot \frac{D_{MS1} + D_{MS2}}{2} \\ & + \left(1 - \frac{\alpha}{2}\right) \frac{D_{MS3} + D_{MS4}}{2} \end{aligned} \right] \quad (34)$$

$$q_{MS.W}^{MP} \geq \left[\begin{aligned} & \frac{\alpha}{2} \cdot \frac{D_{W1} + D_{W2}}{2} \\ & + \left(1 - \frac{\alpha}{2}\right) \frac{D_{W3} + D_{W4}}{2} \end{aligned} \right] \quad (35)$$

In addition to equations 22, 23 and 26-30.

Based on this fuzzy formulation, the constraints in the multi-objective model should be satisfied with a confidence value which is denoted as α and it is normally determined by decision makers. Also, mos, pes and opt are the three prominent points (the most likely, the most pessimistic and the most optimistic values), respectively (Jiménez et al. 2007).

Each objective function (equation. 31-33) corresponds to an equivalent linear membership function, which can be determined by using Eq. 36.

$$\mu_b=\begin{cases}1 & if\ A_b\le Max_b\\ \dfrac{Max_b-A_b}{Max_b-Min_b} & if\ Min_b\le A_b\le Max_b\\ 0 & if\ A_b\ge Min_b\end{cases} \tag{36}$$

Where A_b represents the value of bth objective function and Max_b and Min_b represent the maximum and minimum values of bth objective function, respectively.

The minimum and maximum values for each objective function can be obtained using the individual optimization as follows:

For the minimum values

$$\begin{aligned}Min\ Z_1 &= C_{MS}^{Land}+C_{MS}^{Building}+C_{MS}^{Equipment}\\ &+C_{MS}^{Services}+C_{MS}^{Saleries}+C_{SUPP}^{R}q_{SUPP.MS}^{R}\\ &+C_{MS}^{MP}q_{MS.W}^{MP}+C_{w}^{I}q_{MS.W}\\ &+C_{SUPP.MS}^{T.R}\frac{q_{SUPP.MS}^{R}}{V}d_{SUPP.MS}\\ &+C_{MS.W}^{T.MP}\frac{q_{MS.W}^{MP}}{V}d_{MS.W}\end{aligned} \tag{37}$$

$$Min\ Z_2=\sum_{i=1}^{m_{MS}}\left(\begin{array}{l}E_{MS_i}^{machin}+E_{MS_i}^{air\ comp}\\ +E_{MS_i}^{cond}+E_{MS_i}^{bulb}\end{array}\right) \tag{38}$$

$$Min\ Z_3=\sum_{i=1}^{m_{MS}}\left[\begin{array}{l}\omega_{MS_i}E_{MS_i}^{machin}q_{MS_i}+\omega_{MS_i}E_{MS_i}^{air\ comp}\\ +\omega_{MS_i}E_{MS_i}^{cond}+\omega_{MS_i}E_{MS_i}^{bulb}\\ +\left(\dfrac{{\omega_{SUPP.MS}^{T}}^{pes}+2{\omega_{SUPP.MS}^{T}}^{mos}+{\omega_{SUPP.MS}^{T}}^{opt}}{4}\right)\\ \dfrac{q_{SUPP.MS}}{V}d_{SUPP.MS}\\ +\left(\dfrac{{\omega_{MS.MS}^{T}}^{pes}+2{\omega_{MS.MS}^{T}}^{mos}+{\omega_{MS.MS}^{T}}^{opt}}{4}\right)\\ \dfrac{q_{MS.W}}{V}d_{MS.W}\end{array}\right] \tag{39}$$

For the maximum values

$$\begin{aligned}Max\ Z_1 &= C_{MS}^{Land}+C_{MS}^{Building}+C_{MS}^{Equipment}\\ &+C_{MS}^{Services}+C_{MS}^{Saleries}+C_{SUPP}^{R}q_{SUPP.MS}^{R}\\ &+C_{MS}^{MP}q_{MS.W}^{MP}+C_{w}^{I}q_{MS.W}\\ &+C_{SUPP.MS}^{T.R}\frac{q_{SUPP.MS}^{R}}{V}d_{SUPP.MS}\\ &+C_{MS.W}^{T.MP}\frac{q_{MS.W}^{MP}}{V}d_{MS.W}\end{aligned} \tag{40}$$

$$Max\ Z_2=\sum_{i=1}^{m_{MS}}\left(\begin{array}{l}E_{MS_i}^{machin}+E_{MS_i}^{air\ comp}\\ +E_{MS_i}^{cond}+E_{MS_i}^{bulb}\end{array}\right) \tag{41}$$

$$Max\ Z_3=\sum_{i=1}^{m_{MS}}\left[\begin{array}{l}\omega_{MS_i}E_{MS_i}^{machin}q_{MS_i}+\omega_{MS_i}E_{MS_i}^{air\ comp}\\ +\omega_{MS_i}E_{MS_i}^{cond}+\omega_{MS_i}E_{MS_i}^{bulb}\\ +\left(\dfrac{{\omega_{SUPP.MS}^{T}}^{pes}+2{\omega_{SUPP.MS}^{T}}^{mos}+{\omega_{SUPP.MS}^{T}}^{opt}}{4}\right)\\ \dfrac{q_{SUPP.MS}}{V}d_{SUPP.MS}\\ +\left(\dfrac{{\omega_{MS.MS}^{T}}^{pes}+2{\omega_{MS.MS}^{T}}^{mos}+{\omega_{MS.MS}^{T}}^{opt}}{4}\right)\\ \dfrac{q_{MS.W}}{V}d_{MS.W}\end{array}\right] \tag{42}$$

III. OPTIMISATION APPROACHES

Optimization of a manufacturing system design based on design criteria towards multiple and possibly conflicting objectives is a multi-objective problem. In this case, it is useful to find out an optimum solution for the manufacturing system design with a lowest cost, a lowest amount of energy consumption and CO_2 emissions simultaneously based on the developed multi-objective model. There are several approaches for multi-objective optimization; this includes the ε -constraint method, the weighted-sum method, the LP-metrics method, the weighted tchebycheff method and so on (Nurjanni et al. 2014). In this paper, ε-constraint approache was utilized to gain the optimal solutions. Moreover, an optimal solution was determined using the max-min approach.

3.1 ε -constraint approach

In this approach, the multi-objective model is converted into a single-objective aiming to reveal the non-inferior solutions under constraints. The higher priority is given to minimization of the total energy consumption in this study as the single objective function (equation. 43); the other two objective functions (total cost and total CO_2 emissions) are shifted to be the ε - based constraints; i.e. equation. 44 restricts the value of the objective function one 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. 45). Equation. 46 restricts objective function three 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. 47) (Amin and Zhang 2013) and (Mohammed and Wang 2016). The equivalent solution formula Z is presented as follows:

$$Min Z_2 = \sum_{i=1}^{m_{MS}} \left(\begin{array}{l} \frac{q^R_{MS_i}}{\Re_{MS_i} \mu_{MS_i}} N^{mach}_{MS_i} n^{mach}_{MS_i} \\ + \frac{q^R_{MS_i}}{\Re_{MS_i} \mu_{MS_i}} \frac{N^{air\ comp}_{MS_i}}{\rho^{air\ comp}_{MS_i}} v^{air\ comp}_{MS_i} n^{mach}_{MS_i} \\ + N^{cond}_{MS_i} n^{cond}_{MS_i} \frac{q^R_{MS_{i+1}}}{G_{MS}} + N^{bulb}_{MS_i} n^{bulb}_{MS_i} \frac{q^R_{MS_{i+1}}}{G_{MS}} \end{array} \right) \tag{43}$$

Equation. (43) is subject to the following constrains:

$$Z_1 \le \varepsilon_1 \tag{44}$$

$$(Z_1)^{\min} \le \varepsilon_1 \le (Z_1)^{\max} \tag{45}$$

$$Z_3 \le \varepsilon_2 \tag{46}$$

$$(Z_3)^{\min} \le \varepsilon_2 \le (Z_3)^{\max} \tag{47}$$

And additional constraints are included equations. 22-30

3.2 The Max-Min approach

The Max-Min approach is normally applied for selecting the compromised solution x in a non-inferior set based on the objective function Z using a satisfaction value ϑ_{Z_x} . For further details about this approach, it may refer to (Lai and Hwang 1992). The Max-Min approach formula is presented as follows:

$$\begin{aligned} & \underset{x}{Max} \left\{ \min \left\{ \vartheta_{Z_x} - \vartheta^{ref}_{Z_x} \right\} \right\} \\ & = \underset{x}{Max} \left\{ \min \left\{ \left(\frac{Z_x^{\max} - Z(x)}{Z_x^{\max} - Z_x^{\min}} \right) - \vartheta^{ref}_{Z_x} \right\} \right\} \end{aligned} \tag{48}$$

$$\text{s.t.} \left\{ \vartheta_{Z_x} = \begin{cases} 1 & Z(x) \le Z_x^{\min} \\ \left(\frac{Z_x^{\max} - Z(x)}{Z_x^{\max} - Z_x^{\min}} \right) & Z_x^{\min} \le Z(x) \le Z_x^{\max} \\ 0 & Z(x) \ge Z_x^{\max} \end{cases} \right. \tag{49}$$

Where $Z_x^{\max}$ is the maximum value and $Z_x^{\min}$ is the minimum value, which are obtained based on the objective function Z_x, respectively. In the non-inferior set, $\vartheta^{ref}_{Z_x}$ is a minimal accepted satisfaction value for objective function, Z_x which is assigned by manufacturing designers in consonance to their needs.

IV. EVALUATION: A REAL CASE STUDY

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 production line consist of 8 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, release amount of CO_2 emissions and has mass inputs with different specifications. Table II shows the manufacturing processes in which the symbols represent process task i that involved in the manufacturing process to produce plastic and woven sacks in a woven sacks factory. Table III shows the data collected from the real production line at the woven sacks company. In this case, the production line is powered by three deferent source of energy (oil as direct energy source to generate thermal energy, oil as indirect energy source to generate electricity and solar as indirect energy source to generate electricity) in order to find which is the efficient source for designing the sustainable manufacturing system. LINGO[11] software was used for computing results based on the developed fuzzy multi-objective mathematical model aiming to seek the optimization solutions.

TABLE II. 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 smoothes	C
S	Film sewn into bag	K
B	End product compressed using baling machines	S

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

C_{MS}^{Fixed} (GBP): 6000000, C_{SUPP}^{R} (GBP/kg): 2, C_{MS}^{MP} (GBP/unit): 3, C_{w}^{I} (GBP/unit): 2, $C_{SUPP}^{T.R}$ (GBP):2, $C_{MS}^{T.MP}$ (GBP):2, $d_{SUPP.MS}$ (mile):50, $d_{MS.W}$ (mile):10, V (kg): = 20000
Ca_{MS} (kg/month): 990,000, Ca_{W} (kg/month): 900000,, D_{MS} (kg/month): 850000, D_{W} (kg/month): 850000
$m_{MS_i} = 8$, $\Re_{MS_i}^{machin}$ (kg/h): 1852, 1815, 1742, 1716, 1699, 1665, 1660, 1643, where $i \in \{1, 2, ..., m_{MS}\}$, $\mu_{MS_i}^{machin}$ (%): 80, $\Psi_{MS_i}^{machin}$ (%):0.02, 0.04, 0.015, 0.01, 0.02, 0.003, 0.01,0
$N_{MS_i}^{machin}$ (Kw): 200, 20, 7, 40, 7, 0, 0.8, 4, $N_{MS_i}^{air\ comp}$ (Kw):200, $\rho_{MS_i}^{air\ comp}$ (m³/h): 666, $\upsilon_{MS_i}^{air\ comp}$ (m³/h): 5, 4, 13, 0, 7, 5, 20 and 0
$N_{MS_i}^{cond}$ (kw):2., $N_{MS_i}^{bulb}$ (Kw): 0.4, $\Phi_{MS_i}^{cond}$ (unit):2, $\varphi_{MS_i}^{bulb}$ (unit):15
G_{MS}^{month} (Kg): 831540, ω_{MS_i} (kg/kwh): 0.05, $\omega_{SUPP.MS,\ MS.W}^{T}$ (kg/mile):0.420

4.1. Computational results and discussion

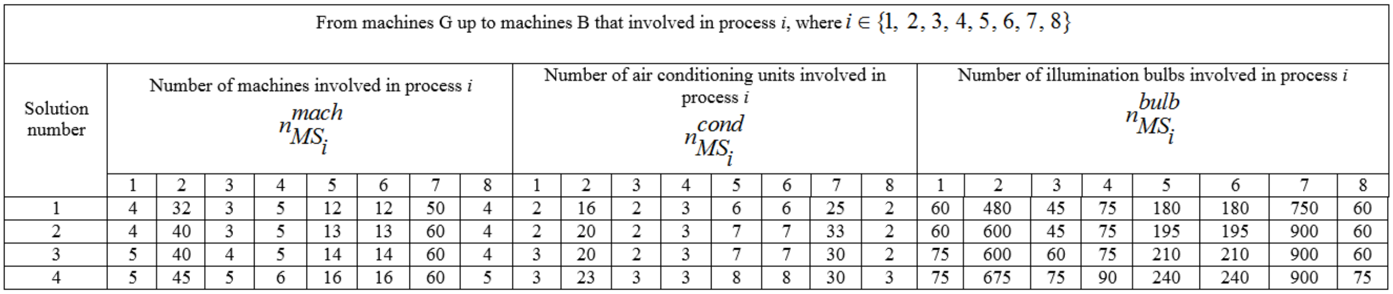
In this work, because of the multi-objective nature of the developed fuzzy multi-objective model formulated in section 2.1, the ε-constraint method was employed for optimising the three objectives simultaneously.

Table IV, illustrates the non-inferior solutions that were obtained by an assignment of ε-values from 10210000 to 16360000 for objective (1) and from 155×10^9 to 169×10^9 for objective (3) using oil as a direct energy source to generate thermal energy, from 215.66×10^9 to 230.98×10^9 using oil as indirect energy source to generate electricity and from 12.679×10^6 to 22.5×10^6 using solar as indirect energy source to generate electricity. It can be noted in Table IV that the values of objective (1) and (3) are highly 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, solution 1 obtained by an assignment of $\varepsilon_1 = 10210000$, and ($\varepsilon_2 = 155\times10^9$ using oil as direct energy source, 215.66×10^9 using oil as indirect energy source to generate electricity and 12.679×10^6 using solar as indirect energy source to generate electricity) accordingly, the minimum total cost for establishing the manufacturing system is 10210000 GBP, the minimum total amount of energy consumed by the manufacturing system is 1036639 kWh and the minimum total amount of CO_2 emissions released from the manufacturing system based on deferent source of energy (oil as direct energy source, oil as indirect energy source to generate electricity and solar as indirect energy source to generate electricity) is 155×10^9 kg 215.66×10^9 kg and 12.679×10^6 kg respectively. As shown in Table V, each solution has a potential group of number of machines, number of air conditioning units and number of bulbs that is involved in process task *i* in the manufacturing system. For instance, in solution 1, number of machines involved in process task *i* in a manufacturing system $n_{MS_i}^{mach}$ where $i \in \{1, 2, 3, 4, 5, 6, 7, 8\}$ are (4, 32, 3, 5, 12, 12, 50, 4), number of air conditioning units involved in process task *i* $n_{MS_i}^{cond}$ are (2, 16, 2, 3, 6, 6, 25, 2) and number of bulbs $n_{MS_i}^{bulb}$ are (60, 480, 45, 75, 180, 180, 750, 60).

TABLE IV. NON-INFERIOR SOLUTIONS OBTAINED BY USING THE Ɛ-CONSTRAINT APPROACH

Solution number	α-level	ε-values				Objective function solutions				
		ε_1	ε_2			Min Z_1 (GBP)	Min Z_2 (kWh)	Min Z_3 (kg)		
								Source of energy		
			Oil as direct energy source	Oil as indirect energy source to generate electricity	Solar as indirect energy source to generate electricity			Oil as direct energy	Oil as indirect energy to generate electricity	Solar as indirect energy to generate electricity
1	0.3	10210000	155×10^9	215.66×10^9	12.679×10^6	10210000	1036639	155×10^9	215.66×10^9	12.679×10^6
2	0.5	11747500	158×10^9	217×10^9	15.134×10^6	12260000	1400000	160×10^9	220×10^9	15.679×10^6
3	0.7	13285000	161.5×10^9	220×10^9	17.589×10^6	14310000	1763000	164.88×10^9	225×10^9	19.2×10^6
4	0.9	14822500	165×10^9	225×10^9	20×10^6	16360000	1998000	169×10^9	230.98×10^9	22.5×10^6

TABLE V. NUMBER OF MACHINES, AIR CONDITIONING UNITS AND NUMBER OF BULBS INVOLVED IN PROCESS *I* IN A MANUFACTURING SYSTEM



From machines G up to machines B 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* $n^{mach}_{MS_i}$								Number of air conditioning units involved in process *i* $n^{cond}_{MS_i}$								Number of illumination bulbs involved in process *i* $n^{bulb}_{MS_i}$							
	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	32	3	5	12	12	50	4	2	16	2	3	6	6	25	2	60	480	45	75	180	180	750	60
2	4	40	3	5	13	13	60	4	2	20	2	3	7	7	33	2	60	600	45	75	195	195	900	60
3	5	40	4	5	14	14	60	4	3	20	2	3	7	7	30	2	75	600	60	75	210	210	900	60
4	5	45	5	6	16	16	60	5	3	23	3	3	8	8	30	3	75	675	75	90	240	240	900	75

A pairwise comparison in a relationship between two of the three conflicting objectives is illustrated in Figure 2a and 2b. The results shown in this Figure indicate that the non-inferior solution 1, which has less total investment cost, the machines involved in process task *i* consumed less energy and the total amount of CO_2 emissions using different source of energy are less compared to the other solutions. Moreover, as shown in Table VI, based on solution 1, the number of machines, air conditioning units and illumination bulbs involved in process task *i* in a manufacturing system are less compared to the other solutions. By balancing the three objectives with ε_1 = 10210000, and ε_2 = 155×10^9, 215.66×10^9 and 12.679×10^6 using (oil as direct energy source, oil as indirect energy source to generate electricity and solar as indirect energy source to generate electricity, respectively), it leads to compromise solution 1, which includes an installation of machines (4, 32, 3, 5, 12, 12, 50, 4), air conditioning units (2, 16, 2, 3, 6, 6, 25, 2) and illumination bulbs (60, 480, 45, 75, 180, 180, 750, 60) for processes task (1, 2, 3, 4, 5, 6, 7, 8) in the manufacturing system. This solution gives a total amount of energy consumption 1036639 kWh, the total amount of CO_2 emissions using oil as direct energy 155×10^9 kg, using oil as indirect energy source to generate electricity 215.66×10^9 kg and using solar as indirect energy source to generate electricity 12.679×10^6 kg and the total investment cost 10210000 GBP.

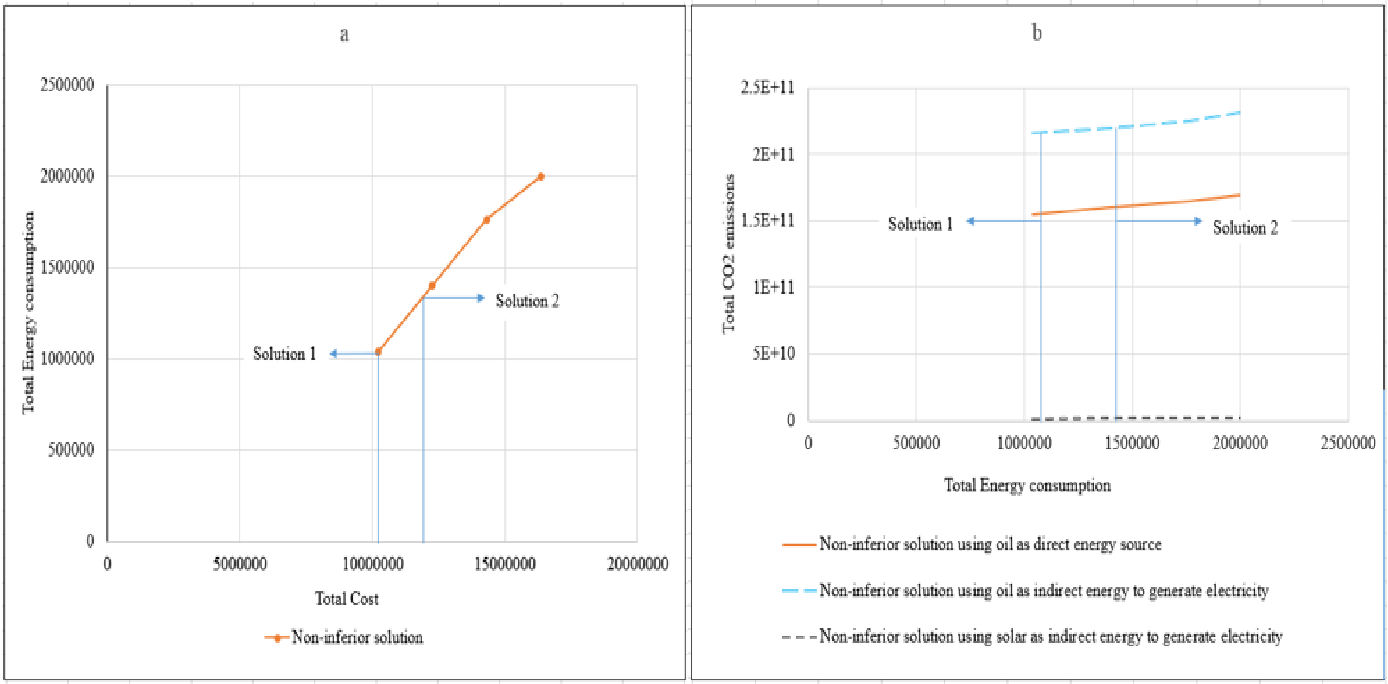


Fig. 2. Comparison between solutions obtained

It can be seen in figure 2b a comparison among the three deferent source of energy. The results in figure 2b indicates that the production line which is powered by solar source of energy is released less amount of CO_2 emissions compared to the other sources followed by oil as direct energy source to generate thermal energy and oil as indirect energy source to generate electricity. As a result, the solar source of energy is more efficient source for designing the sustainable manufacturing system.

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 (Lai and Hwang 1992., Mohammed 2016). Based on this Max-Min approach, solution 2 is determined as the best solution as it has the minimal distance 3.45 to the value of the ideal solution.

Furthermore, this solution shows the optimum delivery plan of the input quantity of materials $q_{MS_i}^{R}$, quantity of materials flow between the machines involved in process task *i* $q_{MS_{i+1}}^{R}$ and then shipped as a final product q_{MS}^{MP} . As shown in Table VI, based on solution 2 the optimal decisions in quantity of materials flows through the machines involved in process task 1, 2, 3, 4, 5, 6, 7, 8 are 980000 kg, 978040 kg, 976084 kg, 937040 kg, 918299 kg, 889824 kg, 868344 kg, 850660 kg , respectively before being shipped to warehouse as a final products as 9146881 sacks per month.

Table VII 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 sustainable manufacturing system design based on solution 2

TABLE VI. THE QUANTITY OF MATERIAL FLOW BETWEEN THE PROCESSES INSIDE A SUSTAINABLE MANUFACTURING SYSTEM

$n_{MS_i}^{R}$ (kg), where $i \in \{1, 2, 3, 4, 5, 6, 7, 8\}$										q_{MS}^{MP} (unit)
Solution number	0	1	2	3	4	5	6	7	8	
1	985500	965200	963040	960084	935805	909227	881567	853478	842344	9057462 sacks
2	1000000	980000	978040	976084	937040	918299	889824	868344	850660	9146881 sacks
3	1020000	1002000	996100	994084	955150	928300	904824	883344	865660	9308172 sacks
4	1045000	1027000	1009000	991100	973050	940200	919700	898400	883660	9501720 sacks

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

The best solution for a sustainable manufacturing system design					
Number of process task *i*	Number of machines involved in process *i* from process G up to process B $n_{MS_i}^{mach}$	Number of air conditioning units involved in process *i* $n_{MS_i}^{cond}$	Number of bulbs involved in process *i* $n_{MS_i}^{bulb}$	Quantity of materials involved in process *i* $n_{MS_i}^{R}$	
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	33	900	898344	
8	4	2	60	850660	
Number of manufacturing products q_{MS}^{MP} units				9,146,881 sack	

Finally, Figure 3 shows the optimal sustainable manufacturing system design model based on the determined solution 2, which is obtained with ε_1 =11747500, and ε_2 = 15.134×10^5 that yields a minimum total cost of 12260000 GBP with the minimum total amount of energy consumption of 1400000 kWh and the minimum total amount of CO_2 emissions of 15.679×10^6 kg using solar as direct energy source to generate electricity.

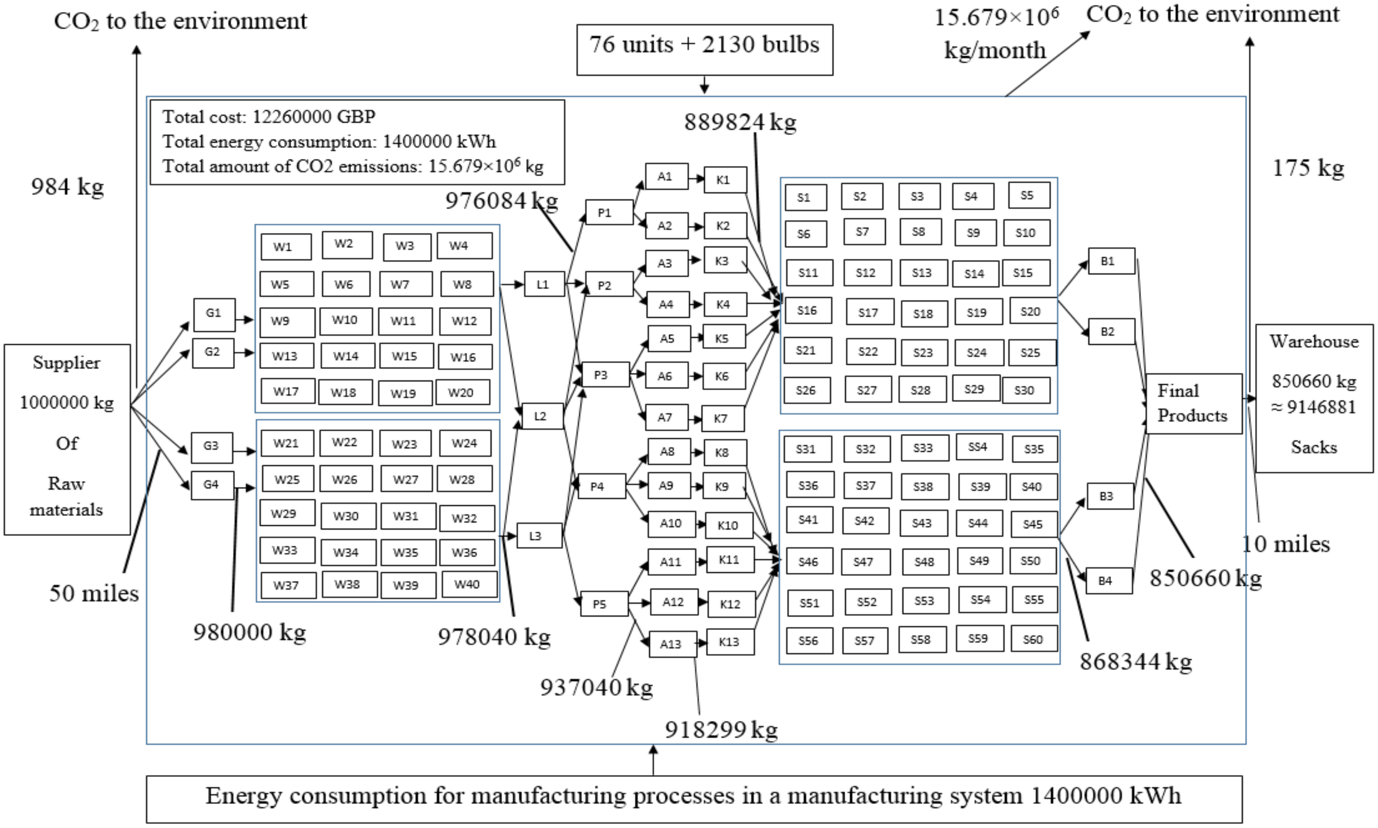


Fig. 3. An optimal sustainable manufacturing system design modeling

V. CONCLUSION

Whenever engineers take an initiate to design a manufacturing system, system designers used to emphasis on the key performance indicators in terms of system productivity and capacity; environmental considerations are often overlooked. This paper presents the development of a fuzzy three-objective mathematical model for optimizing a sustainable manufacturing system design which addresses environmental sustainability relating to manufacturing activities. The developed fuzzy 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 way as an aid for optimizing the traditional manufacturing system design in order to achieve the sustainability under the economic and ecological constraints. Nevertheless, mathematical or analytical modelling techniques might not be sufficient if a detailed analysis is required for a complex manufacturing system as the objective function may not be expressible as an explicit function of the input parameters. In some cases, one must resort to simulation even though in principle some systems are analytically tractable; this is because some performance measures of the system have values that can be observed only by running the computer-based simulation model (Wang and Chatwin 2005). Thus, an integrated method incorporating environmental parameters for a discrete even simulation model is recommended as part of this study, which is under the development.

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