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ENVIRONMENTAL IMPACTS OF RENEWABLE ENERGY SOURCES

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

Reda Nujoom[1] · Ahmed Mohammed[1,2] · Qian Wang[1]

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

Keywords Sustainable manufacturing systems · Energy consumption · CO_2 · Lean manufacturing · Environmental constraints · Multi-objective

Introduction

To design a sustainable manufacturing system, manufacturing system designers need to not merely rely on applying traditional methods for improving efficiency and productivity of manufacturing systems but also examine the environmental impact on the developed system (Heilala et al. 2008). The traditional manufacturing system design is involved in the determination, analysis and optimization of, for example, system capacities, material flow, material-handling methods, production methods, system flexibilities, operations, and shop-floor layouts. However, there are environmental aspects that also need to be addressed today as a new challenge for designers of manufacturing systems to create an effective approach incorporating environmental parameters or constraints (Paju et al. 2010). 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 (Taghdisian et al. 2014). The term

✉ Reda Nujoom
  Reda.Nujoom@port.ac.uk

[1] School of Engineering, University of Portsmouth, Portsmouth, UK

[2] Business School, Cardiff University, Aberconway Building, Colum Dr, Cardiff CF10 3EU, UK

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, 2016b). This concept has usually been implemented when environmental problems are to be taken as a completely separate objective in the process synthesis at the initial design stage. In this case study, each of the environmental aspects is considered as a separate objective together with other classical objectives in maximizing system productivity or efficiency and/or minimizing the cost of the manufactured product; this forms a multi-objective optimization (MOO) problem (Taghdisian et al. 2014; Nujoom et al. 2016a, 2016b).

Development of a sustainable manufacturing system design may also apply lean methods as 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, 2016b). 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, the traditional lean manufacturing method does not consider environmental wastes of such as energy and CO_2 emissions which also need to be considered as these wastes add no value on manufactured products (Nujoom et al. 2016a, 2016b; Wang et al. 2009). Consequently, it is important to optimize the traditional lean manufacturing system design to achieve 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 impact on manufacturing systems design. 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 known as the process integration (PI) method that was used for evaluating CO_2 emissions for the steel industry. Branham et al. (2008) used the quantitative thermodynamic analysis for measuring the amount of energy to be used by various categories in manufacturing systems. Guillén-Gosálbez and Grossmann (2009) developed a mathematical model named as the 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 chain 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 2017a, b). Li et al. (2009) used a multi-objective mixed-integer non-linear model incorporating environmental and economic factors for the design and optimization of chemical processes. Abdallah et al. (2010) 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 the 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 the supply chain design in terms of minimization of the annual cost with a due consideration over environmental effect. Shaw et al. (2012) presented an integrated approach for selecting the appropriate supplier in the supply chain through the development of a fuzzy multi-objective linear programming that addresses the minimization of ordered quantity to the supplier and the minimization of the total carbon emissions for sourcing of material. Moreover, in the real world, some input parameters such as purchasing cost and demands are normally subject to uncertainty. Thus, uncertainty in terms of input parameters should also be measured in a manufacturing design (Mohammed et al. 2016). Fuzzy logic is one of the main approaches that were used to handle the uncertainty in a given data.

This paper presents an investigation into a sustainable manufacturing system design under multiple uncertainties through the 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) the number of machines involved in each process in the manufacturing system, (2) the number of air conditioning units and number of bulbs involved in each process, (3) the 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. Afterwards, the developed multi-objective model was re-developed towards a fuzzy multi-objective model to cope with the uncertainties in a number of parameters, i.e. raw material cost, demands, and CO_2 emissions. 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: the "Problem statement and model formulation" section gives an

explanation of the problem description and model formulation. The "Optimization approaches" section presents the optimization approach used for this study. Application and evaluation of the model is presented in the "Evaluation: a real case study" section, and finally, the paper sums up the findings in the "Conclusion" section.

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 the compressed air to some machines. Energy and CO_2 emissions are generated directly by combusting fossil fuels or 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 and 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 the total investment cost for establishing the manufacturing system (Eq. 1), minimization of the total energy consumed by the manufacturing system (Eq. 2), and minimization of the total amount of CO_2 emissions (Eq. 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 need to be involved in the sustainable manufacturing system and (ii) quantity of material flows through the operation machines that need to be involved in the manufacturing system.

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 $i \in \{1, 2, \ldots, m_{MS}\}$

Parameters

C_{MS}^{Fixed}	Fixed cost (GBP) of the manufacturing system
$C_{SUPP.MS}^{R}$	Raw materials cost (GBP)
C_{SUPP}^{R}	Unit raw material cost (GBP) in a supplier
$C_{MS.W}^{MP}$	Manufactured product cost (GBP)
C_{MS}^{MP}	Unit manufactured product cost (GBP)
$C_{MS.W}^{I}$	Inventory cost (GBP) from a manufacturing system to a warehouse
C_{w}^{I}	Unit inventory cost (GBP) in a warehouse
$C_{SUPP.MS}^{T.R}$	Transportation cost (GBP) of raw materials from supplier to a manufacturing system
$C_{SUPP}^{T.R}$	Unit transportation cost (GBP) per mile of raw materials from a supplier to a manufacturing system
$C_{MS.W}^{T.MP}$	Transportation cost (GBP) of manufacturing products from a manufacturing system to a warehouse
$C_{MS}^{T.MP}$	Unit transportation cost (GBP) per mile of manufacturing products from a manufacturing system to a 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
$E_{MS_i}^{machin}$	Energy consumption (kWh) for the machines involved in process i in a manufacturing system, where, $i \in \{1, 2, \ldots, m_{MS}\}$
$E_{MS_i}^{air\ comp}$	Energy consumption (kWh) of compressed air needed for the machines involved in process i
$E_{MS_i}^{cond}$	Energy consumption (kWh) for the air conditioning units involved in process i
$E_{MS_i}^{bulb}$	Energy consumption (kWh) for the lighting bulbs involved in process i
$N_{MS_i}^{machin}$	Installed power (kw) for a machine involved in process i
$N_{MS_i}^{cond}$	Installed power (Kw) for an air conditioning unit involved in process i
$N_{MS_i}^{bulb}$	Installed power (Kw) for an illumination bulb involved in process i
$N_{MS_i}^{air\ comp}$	Installed power for a compressor involved in process i
$\mathfrak{R}_{MS_i}^{machin}$	Manufacturing rate (kg/h) for a machine involved in process i
$\tau_{MS_i}^{machin}$	Operating time (hr) for a machine involved in process i
$\mu_{MS_i}^{machin}$	Efficiency (%) for a machine involved in process i
G_{MS}^{month}	Mass production (kg) per month for the manufacturing system
$\Psi_{MS_i}^{machin}$	Total waste ratio (%) for a machine involved in process i
$\upsilon_{MS_i}^{air\ comp}$	Compressed air (m^3/h) used for the machines involved in process i
$\rho_{MS_i}^{air\ comp}$	Capacity of compressed air (m^3/h) of a compressor

Fig. 1 Structure of a sustainable manufacturing system design
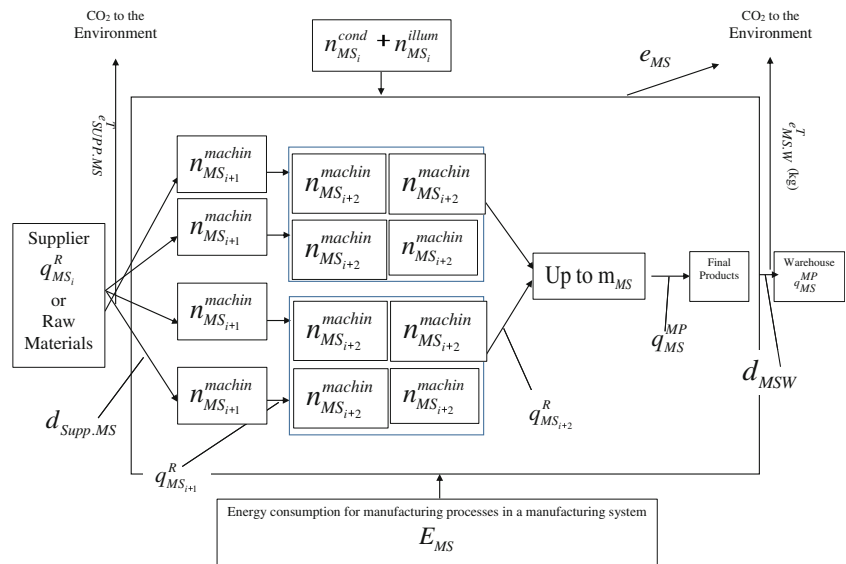
$\Phi_{MS_i}^{cond}$ Covering rate per air conditioning unit that services machines involved in process i

$\varphi_{MS_i}^{bulb}$ Covering rate of lighting bulbs per one machine involved in process i

$N_{MS_i}^{air\ comp}$ Installed power (kWh) for a compressor

e_{MS} Amount of CO_2 emissions (kg) released from the manufacturing system for manufacturing the products

e^T Amount of CO_2 emissions (kg) released from transportation vehicles to transfer materials from a supplier to a manufacturing system and shipped the products from a manufacturing system to a warehouse

$e_{MS_i}^{machin}$ Amount of CO_2 emissions (kg) released from the machines involved in process i

$e_{MS_i}^{air\ comp}$ Amount of CO_2 emissions (kg) released from a compressor system involved in process i

$e_{MS_i}^{cond}$ Amount of CO_2 emissions (kg) released from the air conditioning units involved in process i

$e_{MS_i}^{bulb}$ Amount of CO_2 emissions (kg) released from the illumination bulbs involved in process i

$e_{SUPP.MS}^{T}$ Amount of CO_2 emissions (kg) released for transportation from a supplier to a manufacturing system

$e_{MS.W}^{T}$ Amount of CO_2 emissions (kg) released for transportation from a manufacturing system to a warehouse

ω_{MS_i} CO_2 emission factor (kg/kWh) Based on the source of energy used by the manufacturing system

$\omega_{SUPP.MS,}$ CO_2 emission factor (kg/mile) released for
$MS.W^T$ transportation from a supplier to a manufacturing system and from a manufacturing system to a warehouse

Decision variables

$q_{SUPP.MS}^{R}$ Mass of material (kg) transported from a supplier to a manufacturing system

$q_{MS_i}^{R}$ Mass of materials (kg) involved in process i

$q_{MS_{i+1}}^{R}$ Mass of materials (kg) transferred from a machine involved in process i

q_{MS}^{MP} Mass of material (kg)shipped as final products to a warehouse

$n_{MS_i}^{machin}$ Number of machines (unit) involved in process i

$n_{MS_i}^{cond}$ Number of air conditioning units (unit) involved in process i

$n_{MS_i}^{bulb}$ Number of lighting bulbs (unit) involved in process i

$q_{MS.W}$ Mass of material (kg) transported from a manufacturing system to a 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 the 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 minimized as follows:

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

where the fixed cost $C_{M.S}^{Fixed}$ of establishing the manufacturing system is given as below:

$$C_{MS}^{Fixed} = C_{MS}^{Land} + C_{MS}^{Building} \\ + C_{MS}^{Equipment} + C_{MS}^{Services} + C_{MS}^{Salaries} \tag{2}$$

The cost of unit raw materials $C_{SUPP.MS}^{R}$ is calculated as follows:

$$C_{SUPP.MS}^{R} = C_{SUPP}^{R} q_{SUPP.MS}^{R} \tag{3}$$

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

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

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

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

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

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

The cost of transportation of manufactured products from a manufacturing system to a 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, Eq. (1) will be as follows:

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

Objective function 2: Total energy consumption Z_2

$$Min \ Z_2 = \sum_{i=1}^{m_{MS}} \begin{pmatrix} E_{MS_i}^{machin} + E_{MS_i}^{air \ comp} \\ + E_{MS_i}^{cond} + E_{MS_i}^{bulb} \end{pmatrix} \tag{8}$$

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:

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

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, Eq. 8 is given as follows:

$$Min Z_2 = \sum_{i=1}^{m_{M.S}} \begin{pmatrix} \frac{q_{MS_i}^{R}}{\Re_{MS_i} \mu_{MS_i}} N_{MS_i}^{mach} n_{MS_i}^{mach} \\ + \frac{q_{MS_i}^{R}}{\Re_{MS_i} \mu_{MS_i}} \frac{N_{MS_i}^{air \ comp}}{\rho_{MS_i}^{air \ comp}} \nu_{MS_i}^{air \ comp} n_{MS_i}^{mach} \\ + N_{MS_i}^{cond} n_{MS_i}^{cond} \frac{q_{MS_{i+1}}^{R}}{G_{MS}} + N_{MS_i}^{bulb} n_{MS_i}^{bulb} \frac{q_{MS_{i+1}}^{R}}{G_{MS}} \end{pmatrix}$$

Objective function 3: Total CO$_2$ emissions Z_3

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

where the amount of CO_2 emissions released from the manufacturing system is calculated as follows:

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

The amount of CO_2 emissions $e_{MS_i}^{machin}$ released from the machines involved in process i is calculated as follows:

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

The amount of CO_2 emissions $e_{MS_i}^{air\ comp}$ released from a compressor system involved in process i calculated as follows:

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

The amount of CO_2 emissions $e_{MS_i}^{cond}$ released from the air conditioning units involved in process i is calculated as follows:

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

The amount of CO_2 emissions $e_{MS_i}^{bulb}$ released from the illumination bulbs involved in process i is calculated as follows:

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

The amount of CO_2 emissions e^T released from transportation vehicles to transfer materials from a supplier to the manufacturing system and ship the manufactured products from a manufacturing system to a warehouse is calculated by:

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

where the amount of CO_2 emissions $e_{SUPP.MS}^{T.R}$ per one unit in distance (mile in this study), which is released for transportation from a supplier to a manufacturing system, is given below:

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

The amount of CO_2 emissions $e_{MS.W}^{T.MS}$ per one unit in distance (mile in this study), which is released for transportation from a manufacturing system to a warehouse, is given as below:

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

Hence, Eq. 13 is given as follows:

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

where the CO_2 emission factor ω_{MS_i} and $\omega_{SUPP.MS,MS.W}^{T}$ are shown in Table 1 (Nujoom et al. 2016a, 2016b; EPA. 2008).

Constraints:

Equations 22 and 23 ensure that the quantity of raw material, which is shipped to the manufacturing system and warehouse, respectively, cannot be greater than their capacity.

$$q_{SUPP.MS}^{R} \leq Ca_{MS} \quad (22)$$

$$q_{MS.W}^{MP} \leq Ca_{W} \quad (23)$$

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

$$q_{SUPP.MS}^{R} \geq D_{MS} \quad (24)$$

$$q_{MS.W}^{MP} \geq D_{W} \quad (25)$$

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

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

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 a supplier to a manufacturing system and from a manufacturing system to a 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 $(i + 1)$.

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

where, Eqs. 22, 23, 24, 25, 26, and 29 are quantity constraints and Eqs. 27, 28, and 30 are constraints in the numbers

Table 1 Amount of CO$_2$ 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	

of manufactured machines, air conditioning units, and illumination bulbs.

Treating the uncertainty

In the real world, some data for analysis and usage are subject to uncertainty. Decision makers, however, must incorporate 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 López et al. 2007; Mohammed and Wang a, 2017b):

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

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

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

s.t.

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

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

in addition to Eqs. 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 López et al. 2007).

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

$$\mu_b = \begin{cases} 1 & if\ A_b \leq Max_b \\ \frac{Max_b - A_b}{Max_b - Min_b} & if\ Min_b \leq A_b \leq Max_b \\ 0 & if\ A_b \geq Min_b \end{cases} \quad (36)$$

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

$$Min\ Z_1 = C_{MS}^{Land} + C_{MS}^{Building} + C_{MS}^{Equipment}$$
$$+ C_{MS}^{Services} + C_{MS}^{Saleries} + C_{SUPP}^R q_{SUPP.MS}^R$$
$$+ C_{MS}^{MP} q_{MS.W}^{MP} + C_w^I q_{MS.W}$$
$$+ C_{SUPP.MS}^{T.R} \frac{q_{SUPP.MS}^R}{V} d_{SUPP.MS} \quad (37)$$
$$+ C_{MS.W}^{T.MP} \frac{q_{MS.W}^{MP}}{V} d_{MS.W}$$

$$Min \, Z_2 = \sum_{i=1}^{m_{MS}} \begin{pmatrix} E_{MS_i}^{machin} + E_{MS_i}^{air \, comp} \\ + E_{MS_i}^{cond} + E_{MS_i}^{bulb} \end{pmatrix} \quad (38)$$

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

For the maximum values:

$$Max \, Z_1 = C_{MS}^{Land} + C_{MS}^{Building} + C_{MS}^{Equipment} \\ + C_{MS}^{Services} + C_{MS}^{Saleries} + C_{SUPP}^{R} q_{SUPP.MS}^{R} \\ + C_{MS}^{MP} q_{MS.W}^{MP} + C_w^{I} q_{MS.W} \\ + C_{SUPP.MS}^{T.R} \dfrac{q_{SUPP.MS}^{R}}{V} d_{SUPP.MS} \\ + C_{MS.W}^{T.MP} \dfrac{q_{MS.W}^{MP}}{V} d_{MS.W} \quad (40)$$

$$Max \, Z_2 = \sum_{i=1}^{m_{MS}} \begin{pmatrix} E_{MS_i}^{machin} + E_{MS_i}^{air \, comp} \\ + E_{MS_i}^{cond} + E_{MS_i}^{bulb} \end{pmatrix} \quad (41)$$

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

Optimization 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 the lowest cost and the 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; these include the ε-constraint method, the weighted-sum method, the LP-metrics method, and the weighted Tchebycheff method

(Nurjanni et al. 2014). In this paper, the ε-constraint approach was utilized to gain the optimal solutions. Moreover, an optimal solution was determined using the max-min approach.

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 (Eq. 43); the other two objective functions (total cost and total CO_2 emissions) are shifted to be the ε-based constraints, i.e., Eq. 44 restricts the value of the objective function 1 to be less than or equal to ε_1 which gradually varies between the minimum value and the maximum value for objective function 1 (Eq. 45). Equation 46 restricts objective function 3 to be less than or equal to ε_2 which gradually varies between the minimum value and the maximum value for objective function 3 (Eq. 47) (Amin and Zhang 2013; Mohammed and Wang 2017a, b). The equivalent solution formula Z is presented as follows:

$$Min Z_2 = \sum_{i=1}^{m_{MS}} \begin{pmatrix} \dfrac{q_{MS_i}^{R}}{\Re_{MS_i} \mu_{MS_i}} N_{MS_i}^{mach} n_{MS_i}^{mach} \\ + \dfrac{q_{MS_i}^{R}}{\Re_{MS_i} \mu_{MS_i}} \dfrac{N_{MS_i}^{air \, comp}}{\rho_{MS_i}^{air \, comp}} \nu_{MS_i}^{air \, comp} n_{MS_i}^{mach} \\ + N_{MS_i}^{cond} n_{MS_i}^{cond} \dfrac{q_{MS_{i+1}}^{R}}{G_{MS}} + N_{MS_i}^{bulb} n_{MS_i}^{bulb} \dfrac{q_{MS_{i+1}}^{R}}{G_{MS}} \end{pmatrix} \quad (43)$$

Equation (43) is subject to the following constrains:

$$Z_1 \leq \varepsilon_1 \quad (44)$$

$$(Z_1)^{min} \leq \varepsilon_1 \leq (Z_1)^{max} \quad (45)$$

$$Z_3 \leq \varepsilon_2 \quad (46)$$

$$(Z_3)^{min} \leq \varepsilon_2 \leq (Z_3)^{max} \quad (47)$$

And additional constraints are included in Eqs. 22, 23, 26-30, 34 and 35.

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 Λ using a satisfaction value $\vartheta_{\Lambda x}$. For further details about this approach, one may refer to Lai and Hwang (1992). The max-min approach formula is presented as follows:

$$Max_{x} \left\{ \min \left\{ \vartheta_{Z_x} - \vartheta_{Z_x}^{ref} \right\} \right\}$$

$$= Max_{x} \left\{ \min \left\{ \left(\frac{Z_x^{max} - Z(x)}{Z_x^{max} - Z_x^{min}} \right) - \vartheta_{Z_x}^{ref} \right\} \right\} \quad (48)$$

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

$$(49)$$

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, $\vartheta_{Z_x}^{ref}$ is a minimal accepted satisfaction value for the objective function Z_x which is assigned by manufacturing designers in consonance to their needs.

Evaluation: A real case study

In order to examine the applicability and the validation of the developed multi-objective optimization model as described above, a real case study was applied. The production line consists of eight 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 CO_2 emissions, and has mass inputs with different specifications. Table 2 shows the manufacturing processes in which the symbols represent process task i involved in the manufacturing process to produce plastic and woven sacks in a woven sack factory. Table 3 shows the data collected from the real production line at the woven sack company. In this case, the production line is powered by three different sources of energy (oil as direct energy source to generate thermal energy, oil as indirect energy source to generate electricity,

Table 2 Manufacturing process 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 3 Data collected from a plastic and woven sacks company

C_{MS}^{Fixed} (GBP): 6,000,000, 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): = 20,000

$m_{MS_i} = 8$, $\mathfrak{R}_{MS_i}^{machin}$ (kg/h): 1852, 1815, 1742, 1716, 1699, 1665, 1660, 1643, where $i \in \{1, 2, ..., m_{MS}\}$, $\mu_{MS_i}^{machin}$ (%): 80

$N_{MS_i}^{machin}$ (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): 831,540, ω_{MS_i} (kg/kWh): 0.05, $\omega_{SUPP.MS,MS.W}^{T}$ (kg/mile):0.420

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 the results based on the developed multi-objective mathematical model aiming to seek the optimization solutions.

Computational results and discussion

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

Table 4 illustrates the non-inferior solutions that were obtained by an assignment of ε-values from 10,210,000 to 16,360,000 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 an indirect energy source to generate electricity, and from 12.679×10^6 to 22.5×10^6 using solar as an indirect energy source to generate electricity. It can be noted in Table 4 that the values of objectives (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 was obtained by an assignment of $\varepsilon_1 = 10,210,000$ and $\varepsilon_2 = 155 \times 10^9$ using oil as a direct energy source, 215.66×10^9 using oil as an indirect energy source to generate electricity, and 12.679×10^6 using solar as an indirect energy source to generate electricity accordingly; the minimum total cost for establishing the manufacturing system is 10,210,000 GBP; the minimum total amount of energy consumed by the manufacturing system is

Table 4 Non-inferior solutions obtained by using the ε-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 a direct energy source	Oil as an indirect energy source to generate electricity	Solar as an indirect energy source to generate electricity			Oil as a direct energy	Oil as an indirect energy to generate electricity	Solar as an indirect energy to generate electricity
1	0.3	10,210,000	155×10^9	215.66×10^9	12.679×10^6	10,210,000	1,036,639	155×10^9	215.66×10^9	12.679×10^6
2	0.5	11,747,500	158×10^9	217×10^9	15.134×10^6	12,260,000	1,400,000	160×10^9	220×10^9	15.679×10^6
3	0.7	13,285,000	161.5×10^9	220×10^9	17.589×10^6	14,310,000	1,763,000	164.88×10^9	225×10^9	19.2×10^6
4	0.9	14,822,500	165×10^9	225×10^9	20×10^6	16,360,000	1,998,000	169×10^9	230.98×10^9	22.5×10^6

1,036,639 kWh; and the minimum total amount of CO_2 emissions released from the manufacturing system based on different sources of energy (oil as a direct energy source, oil as an indirect energy source to generate electricity, and solar as an 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 5, 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, and 4; number of air conditioning units involved in process task i $n_{MS_i}^{cond}$ are 2, 16, 2, 3, 6, 6, 25, and 2; and number of bulbs $n_{MS_i}^{bulb}$ are 60, 480, 45, 75, 180, 180, 750, and 60.

A pairwise comparison in a relationship between two of the three conflicting objectives is illustrated in Fig. 2a, b. The results shown in this figure indicate that, for 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 sources of energy is less compared to the other solutions. Moreover, as shown in Table 6, based on solution 1, the numbers 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 $\varepsilon_1 = 10,210,000$ and $\varepsilon_2 = 155 \times 10^9$, 215.66×10^9, and 12.679×10^6 using oil as a direct energy source, oil as an indirect energy source to generate electricity, and solar as an 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 process tasks (1, 2, 3, 4, 5, 6, 7, 8) in the manufacturing system. This solution gives a total amount of energy consumption 1,036,639 kWh; the total amount of CO_2 emissions is 155×10^9 kg using oil as a direct energy, 215.66×10^9 kg using oil as an indirect energy source to generate electricity, and 12.679×10^6 kg using solar as an indirect energy source to generate electricity, and the total investment cost is 10,210,000 GBP.

Table 5 Number of machines, air conditioning units and number of bulbs involved in process i in a manufacturing system

From machine G up to machine B involved in process i, where $\in \{1, 2, 3, 4, 5, 6, 7, 8\}$

Solution number	Number of machines involved in process i $n_{MS_i}^{mach}$								Number of air conditioning units involved in process i $n_{MS_i}^{cond}$								Number of illumination bulbs involved in process i $n_{MS_i}^{bulb}$							
	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	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	5	3	20	3	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
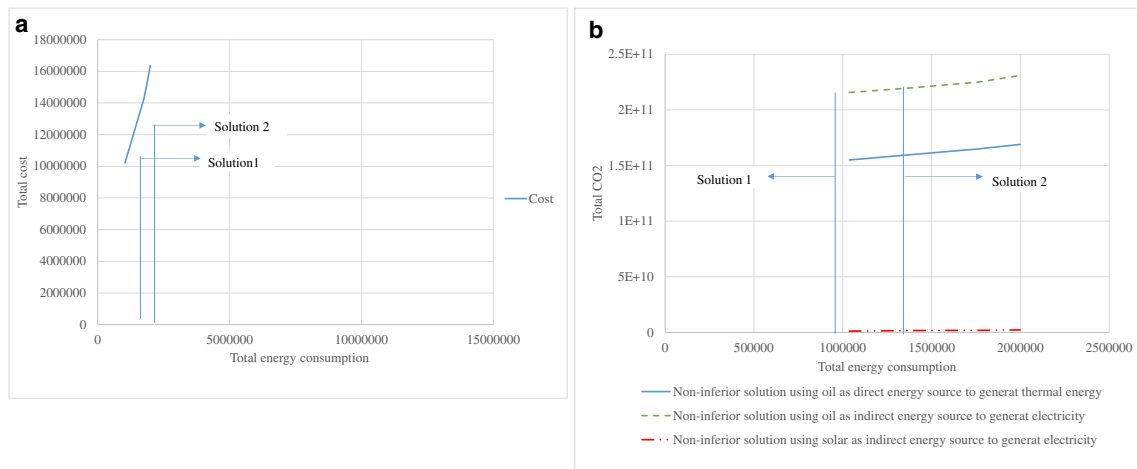
Fig. 2 Comparison between the solutions obtained

A comparison among the three different sources of energy can be seen in Fig. 2b. The results in Fig. 2b indicate that the production line which is powered by a solar source of energy released less amount of CO_2 emissions compared to the other sources followed by oil as a direct energy source to generate thermal energy and oil as an indirect energy source to generate electricity. As a result, the solar source of energy is a 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 a decision-making method such as the max-min approach (Lai and Hwang 1992., Mohammed et al. 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 $q_{MS_i}^R$ and quantity of material 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 6, based on solution 2, the optimal decisions in the quantity of material flows through the machines involved in process tasks 1, 2, 3, 4, 5, 6, 7, and 8 are 980,000, 978,040, 976,084, 937,040, 918,299, 889,824, 868,344, and 850,660 kg, respectively, before being shipped to a warehouse as final products as 9,146,881 sacks per month.

Table 7 shows the number of machines, the number of air conditioning units, the number of bulbs, and the quantity of materials that need to be involved in processes task i to achieve the sustainable manufacturing system design based on solution 2.

Finally, Fig. 3 shows the optimal sustainable manufacturing system design model based on the determined solution 2, which is obtained with $\varepsilon_1 = 11,747,500$ and $\varepsilon_2 = 15.134 \times 10^5$ that yields a minimum total cost of 12,260,000 GBP with the minimum total amount of energy consumption of 1,400,000 kWh and the minimum total amount of CO_2 emissions of 15.679×10^6 kg using solar as the direct energy source to generate electricity.

Table 6 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)
Number of solutions #	0	1	2	3	4	5	6	7	8	
1	985,500	965,200	963,040	960,084	935,805	909,227	881,567	853,478	842,344	9,057,462 sacks
2	1,000,000	980,000	978,040	976,084	937,040	918,299	889,824	868,344	850,660	9,146,881 sacks
3	1,020,000	1,002,000	996,100	994,084	955,150	928,300	904,824	883,344	865,660	9,308,172 sacks
4	1,045,000	1,027,000	1,009,000	991,100	973,050	940,200	919,700	898,400	883,660	9,501,720 sacks

Table 7 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	980,000
2	40	20	600	978,040
3	3	2	45	976,084
4	5	3	75	937,040
5	13	7	195	918,299
6	13	7	195	889,824
7	60	33	900	898,344
8	4	2	60	850,660
Number of manufacturing products q_{MS}^{MP} units				9,146,881 sacks

Conclusion

Whenever engineers took the initiative to design a manufacturing system, system designers used to emphasize on the key performance indicators in terms of such as system productivity and capacity, but environmental considerations were 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
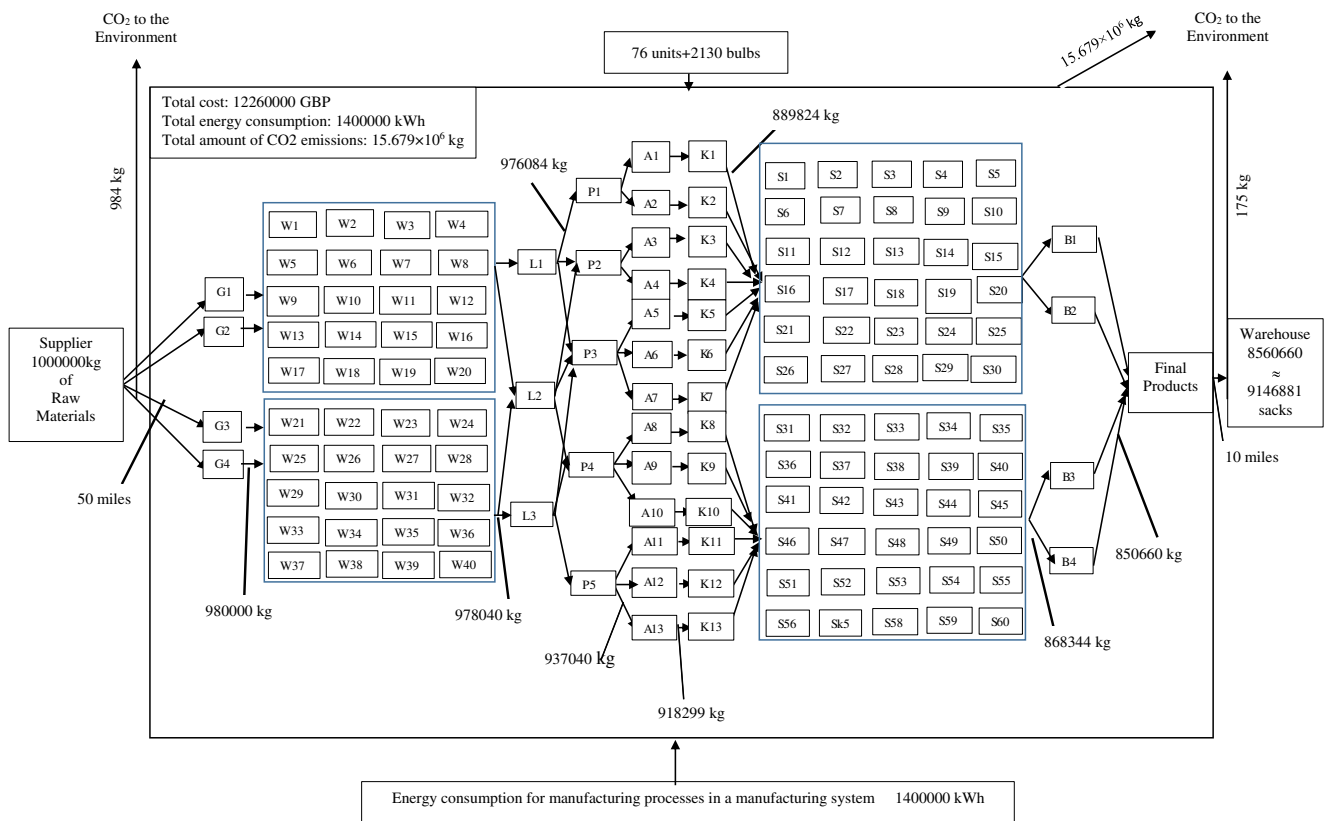
Fig. 3 An optimal sustainable manufacturing system design modelling

an aid for optimizing the traditional manufacturing system design towards 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 event simulation model is recommended as part of this study, which is under development.

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