The International Journal of Advanced Manufacturing Technology (2018) 96:2539–2558
https://doi.org/10.1007/s00170-018-1649-y

ORIGINAL ARTICLE

Optimisation of a sustainable manufacturing system design using the multi-objective approach

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

Received: 2 May 2017 / Accepted: 15 January 2018 / Published online: 23 February 2018

Abstract

A sustainable manufacturing system design can be defined as a process aimed at minimising the negative aspect of both economic and ecological costs. This may be partially achieved through the implementation of lean manufacturing methods in order to reduce production wastes, increase efficiency of manufacturing systems and minimise operational costs. Nevertheless, the concept of lean methods does not include environmental considerations in terms of such as energy consumption and CO_2 (carbon dioxide) emissions, which are also important factors today for developing a sustainable manufacturing system. This paper addresses these issues involved in modelling a sustainable manufacturing system allowing an evaluation in energy consumption and CO_2 emissions against the total cost using the multi-objective approach. In this work, a multi-objective mathematical model was developed based on a manufacturing system incorporating its economic and ecological parameters towards a minimisation of the total cost, the total energy consumption and CO_2 emissions associated with relevant machines, air-conditioning units and lighting bulbs involved in each manufacturing process and material flow. The model was coded using LINGO^{11} to help gain optimal solutions using the ε-constraint approach and the LP-metrics approach, respectively. The best solution among obtained optimal results was revealed using the max-min approach. Applicability of the proposed method was also examined using collected data from a real case study. The study concluded that the multi-objective mathematical model was useful as an aid for optimizing the manufacturing system design under the economic and ecological constraints.

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

1 Introduction

In the past decade, there has been an increasing awareness in development of sustainable manufacturing processes or systems as governments in many countries have been enforcing ever-stricter environmental policies and regulations in industry by promoting energy-saving and low-emission manufacturing activities. Thus, system designers need not merely to apply traditional methods to improve system efficiency and productivity but also to examine the environmental impact on the developed system by incorporating economic and ecological constraints into their manufacturing systems design [1]. In practice, a sustainable manufacturing system may be designed or implemented by addressing the environmental considerations as constraints or enforcing legislations that aim to mitigate environmental impacts by dealing with the environmental issues at an early stage. In this case, the environmental aspect is considered as a separate objective, together with other classical objectives such as system productivity, efficiency and costs to form a multi-objective optimisation (MOO) problem [2]. Development of a sustainable manufacturing system design may also be achieved by applying lean methods to improve system efficiency and productivity without significantly additional investments. Lean manufacturing is a systematic approach to eliminate non-value added wastes in various forms and it enables continuous improvement. These wastes are identified as overproduction, waiting for parts to arrive, unnecessary movement of materials, overprocessing, unnecessary inventory, excess motion and rework [3]. Nevertheless, the traditional lean manufacturing concept does not consider environmental wastes particularly in terms of energy consumption and CO_2 emissions for such as manufacturing system design and evaluation; these wastes add no values on manufactured products and need also to be identified [4, 5].

✉ Reda Nujoom
Reda.Nujoom@port.ac.uk

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

[2] Business School, Cardiff University, Cardiff, UK

There are a few studies in considering environmental aspects relating to sustainable manufacturing systems design. The concept of manufacturing sustainability may be defined as the creation of manufactured products by minimizing the negative environmental impact on usage of energy or other natural resources [5]. Manufacturing companies ought to improve system efficiency and productivity without sacrificing the environment as return to achieve these goals [6]. Heilala et al. [4] suggested 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 manufacturing processes or systems. Rodger and George [7] proposed a sustainable economic model under the triple bottom line (TBL) or the three pillars approach; which is the interdependencies between economic sectors, with national social and environmental concerns to construct a model in which financial aspects of performance can be expressed. The model preserves the positive dynamics of capitalism and accounting principles while improving collaboration between industry, landowners and environmentalists to optimise return on profits for companies, it provides royalties to landowners, and satisfies the environmental concerns. The study is very much in line with our model in terms of economic and ecological considerations. The measures for economic performance are manufacturing cost, quality, responsiveness and flexibility. The environmental performance is all about how well an organisation manages the environmental aspects of its activities, products and services. The measures considered for environmental aspect of sustainability are material usage, energy usage, water usage, waste and emissions. Social performance assesses how well an organisation has translated its social goals into practice. Social performance can be evaluated in terms of the impact of organisation's decisions and activities on society that contribute towards sustainable development including health and welfare of society, stakeholder's expectations, compliance with applicable law and integration throughout the organisation. The contrasting between their paper and our paper is a social performance outcomes, which is the third part of the TBL accounting. The present study focuses on two of the three pillars of sustainable development: economic and environmental considerations (the social pillar is not addressed in this paper) as two of the most important strategies to improve sustainability in manufacturing is to reduce the adverse environmental impacts of energy consumed and CO_2 emissions during the manufacturing phase as energy consumption directly impacts economic progress ([8, 9, 10, 11]). Pishvaee and Razmi [12] established a multi-objective fuzzy model for optimizing a green supply chain design in minimizing total costs as well as environmental impact. Gielen and Moriguchi [13] developed a new linear programming model (namely the steel environmental strategy assessment program) to analyse and reduce the impact of CO_2 emissions in the life cycle of iron and steel in Japan for the next three decades. Hidalgo et al. [14] created a simulation model aimed to analyse the evolution of the world energy outlook for steel and iron industry from 1997 to 2030. Koç and Kaplan [15] presented an investigation on energy consumption for a particular ring-type yarn manufacturing system. Wang et al. [16] proposed a process integration (PI) technique that was used for evaluating CO_2 emissions for a steel industry. Li et al. [17] used a multi-objective mixed integer non-linear mathematical model incorporating environmental considerations in terms of material flow and energy consumption into the chemical process synthesis at the initial design stage. Mohammed et al. [18] applied a fuzzy tri-criterion programming model for minimisation of the warehouse total cost, maximisation of the warehouse capacity utilisation and minimisation of the travel time of products from storage racks to collection points. Jamshidi et al. [19] developed a multi-objective mathematical model considering the annual cost minimisation and the effect of NO_2, CO and volatile organic particles produced by facilities and transportation in the supply chain. Alçada-Almeida et al. [20] developed a multi-objective programming approach used for investigating the locations and capacities of hazardous material burning facilities under the social, economic and environmental constraints. Wang et al. [21] studied a multi-objective optimisation model used for determining the trade-off decision between the total cost and the amount of CO_2 emissions released from the supply chain facilities. Abdallah et al. [22] applied a multi-objective optimisation method for minimizing carbon emissions and investment cost of the supply chain network facilities. Shaw et al. [23] selected the appropriate suppliers in the supply chain network using a fuzzy multi-objective linear programming approach that addresses the minimisation of ordered quantity to the supplier and the total carbon emissions for sourcing of material. Zhou et al. [24] selected suitable materials to develop sustainable products using a multi-objective approach with genetic algorithms. Hamdy et al. [25] applied a multi-objective optimisation method to minimise the CO_2 emissions and the investment cost for a two-storey house and its heating/cooling system. Pinto-Varela et al. [26] developed a fuzzy linear programming and a mixed integer linear programming for designing supply chain structures for annual profit maximisation, while considering environmental aspects. Fesanghary et al. [27] developed a multi-objective programming approach to minimise the life cycle cost and CO_2 emissions of the residential buildings. Sharafi and ELMekkawy [28] proposed a novel approach for optimal design of hybrid renewable energy systems (HRES) including various generators and storage devices to minimise simultaneously the total cost of the system, unmet load and fuel emissions. Sahar et al. [29] proposed a multi-objective optimisation model of a two-layer dairy supply chain aimed at minimizing CO_2 emissions of transportation and the total cost for product distribution. Bortolini et al. [30] proposed a three-objective distribution planner to tackle the tactical optimisation issue of a fresh food distribution network. The optimisation objectives

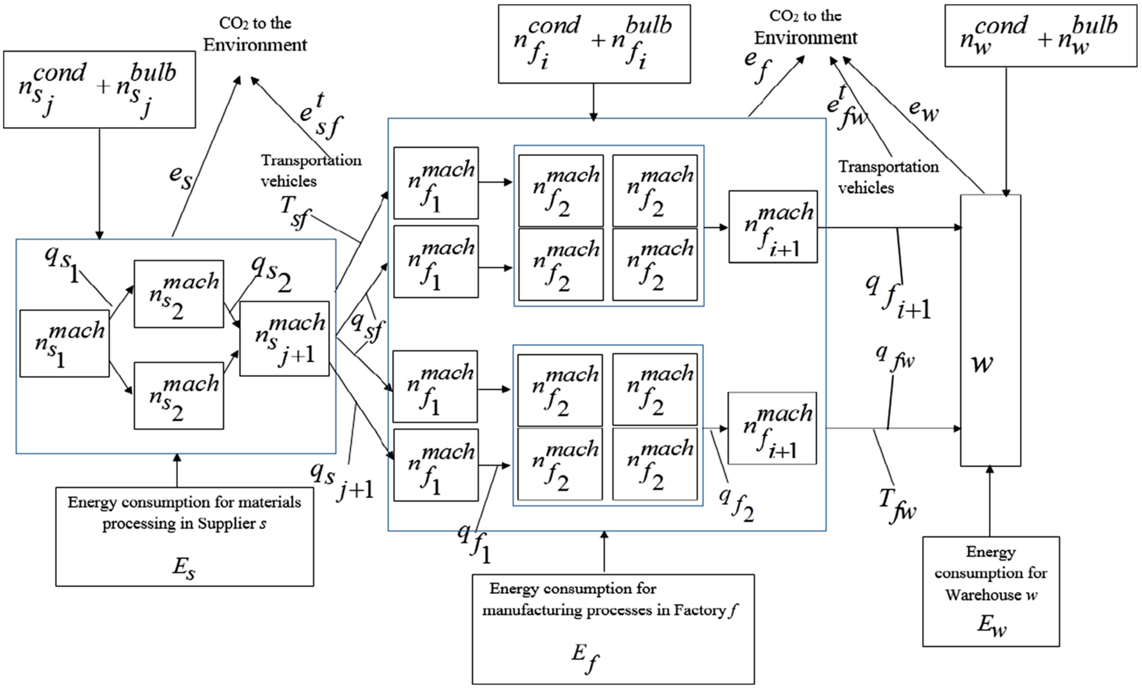


Fig 1 A sustainable manufacturing system design

were to minimise operating cost, carbon footprint and delivery time; the work, however, did not consider other costs and the effect of uncertainty that may occur. Paksoy et al. [31] provided a fuzzy multi-objective model for designing a green closed-loop supply chain network aimed at minimizing all the transportation costs for the supply chain's forward and reverse logistics and total CO_2 emissions. Harris et al. [32] proposed a multi-objective optimisation approach for solving a facility location–allocation problem for a supply chain network where financial costs and CO_2 emissions are considered as objectives.

This paper presents an investigation into a sustainable manufacturing system design through the development of a multi-objective optimisation model seeking a compromised solution based on a number of conflicting objectives. These objectives are aimed at minimizing the total investment cost, the amount of energy consumption and CO_2 emissions. The developed model was coded using LINGO^{11} in which optimal solutions were obtained using the ε-constraint approach and the LP-metrics approach, respectively. The best solution was determined using the max-min approach. Applicability of the proposed method was also examined through a real case study.

2 Problem statement and model formulation

Energy and CO_2 emissions are generated often by using combusting fossil fuels or renewable resources that produce such as thermal heat or electricity used by facilities in a manufacturing system. Figure 1 illustrates the sustainable manufacturing system design in which three facilities were considered: these are supplier *s*, factory *f* and warehouse *w*. The facility may consist of operation machines, air-conditioning units, lighting bulbs and other supportive equipment such as compressors that supply compressed air to some operation machines. Between facilities, there are transportation vehicles to be used. In order to quantify energy consumption and CO_2 emissions of facilities in a manufacturing system, a multi-objective optimisation model was formulated based on the proposed sustainable manufacturing system design. The model was used for obtaining a trade-off decision towards the minimisation of the total investment cost for establishing the manufacturing system, the total energy consumption by the manufacturing system and the total amount of CO_2 emissions. These objectives are in conjunction with (i) numbers of operation machines, air-conditioning units and lighting bulbs and (ii) quantity of materials flows in the manufacturing system.

The model was formulated based on the following assumptions:

- Supplier *s* must satisfy all demands of a factory *f* and a warehouse *w* at any time.
- The potential locations of a supplier or a factory are known.
- Supplier and factory have a certain capacity.
- Breakdown is not considered for all facilities used in this case study.

- Compressor system, air-conditioning units and illumination bulbs are powered by electricity.

2.1 Notations

Sets, parameters and decision variables are used as follows:

Sets	
s	Set of supplier $(1\ldots s\ldots S)$
f	Set of factory $(1\ldots f\ldots F)$
w	Set of warehouse $(1\ldots s\ldots W)$
Π_s and Π_f	Number of manufacturing processes involved in supplier s and in factory f, respectively.
Parameters	
C_l^{es}	Cost required (GBP) for establishing facility l, where$l \in \{s, f, w\}$
C_s^{mach} and C_f^{mach}	Cost of machines (GBP) involved in process j in facility s and involved in process i in facility f, respectively, where $j \in \{1, 2, \ldots., \Pi_s\}andi \in \{1, 2, \ldots., \Pi_f\}$
C_l^{cond}	Cost of an air-conditioning unit (GBP) involved in facility l
C_l^{bulp}	Cost of a lighting bulb (GBP) involved in facility l
C_s^r	Unit raw materials cost (GBP) at supplier s
C_{sf}^r	Total raw materials cost (GBP) from supplier s to factory f
C_f^{mp}	Unit manufacturing product cost (GBP) at factory f
C_{fw}^{mp}	Total manufacturing product cost (GBP) from factory f to warehouse w
C_w^I	Unit inventory cost (GBP) per product at warehouse w
C_{fw}^I	Total inventory cost (GBP) from factory f to warehouse w
C_l^t	Unit transportation cost (GBP) of transportation raw materials and product per mile between facilities l
C_{sf}^t and C_{fw}^t	Total transportation cost (GBP) of raw material and products per mile from supplier s to factory f and from factory f to warehouse w, respectively
C_l^t	The total cost of transportation of raw materials and manufacturing products per mile between facilities l, where $l \in \{s, f, w\}$
T_{sf} and T_{fw}	Distance (miles) from supplier s to factory f and from factory f to warehouse w
Ca_l	Maximum operations capacity (kg) of facility l
D_f and D_w	Minimum demand (kg) of factory f and warehouse w
E_s, E_f and E_w	Total energy consumption (kWh) for supplier s, for factory f and for warehouse w, respectively
$E_{s_j}^{mach}$ and $E_{f_i}^{mach}$	Energy consumption (kWh) for a machine involved in process j at supplier s and in process i at factory f respectively, where $j \in \{1, 2, \ldots., \Pi_s\}$ and $i \in \{1, 2, \ldots., \Pi_f\}$
$E_{s_j}^{cond}$ and $E_{f_i}^{cond}$	Energy consumption (kWh) for the air-conditioning units involved in process j at supplier s and in process i at factory f, respectively
$E_{s_j}^{bulb}$ and $E_{f_i}^{bulb}$	Energy consumption (kWh) for the lighting bulbs involved in process j at supplier s and in process i at factory f, respectively
$E_{s_j}^{comp}$ and $E_{f_i}^{comp}$	Energy consumption (kWh) of compressed air needed for a machine involved in process j at supplier s and in process i at factory f, respectively
E_w^{cond} and E_w^{bulb}	Energy consumption (kWh) for the air-conditioning units and lighting bulbs at warehouse w, respectively
$N_{s_j}^{mach}$ and $N_{f_i}^{mach}$	Installed power (kw) for a machine involved in process j at supplier s and in process i at factory f, respectively
$\mathfrak{R}_{s_j}$ and $\mathfrak{R}_{f_i}$	Manufacturing rate (kg/h) for a machine involved in process j at supplier s and in process i at factory f, respectively
τ_{s_j} and τ_{f_i}	Operating time (h) for a machine involved in process j at supplier s and in process i at factory f, respectively
μ_{s_j} and μ_{f_i}	Efficiency (%) for a machine involved in process j at supplier s and in process i at factory f, respectively
$N_{s_j}^{cond}$ and $N_{f_i}^{cond}$	Installed power (kw) for an air-conditioning unit involved in process j at supplier s and in process i at factory f, respectively
$N_{s_j}^{bulb}$ and $N_{f_i}^{bulb}$	Installed power (kW) for a lighting bulb involved in process j at supplier s and in process i at factory f, respectively
$N_{s_j}^{comp}$ and $N_{f_i}^{comp}$	Installed power (kw) for a compressor at supplier s and at factory f, respectively
$\wp_s$, $\wp_f$ and $\wp_w$	Mass production (kg/month) from supplier s, from factory f and stored at warehouse w, respectively
Ψ_{s_j} and Ψ_{f_i}	Total waste ratio (%) for a machine involved in process j at supplier s and in process i at factory f, respectively
$\upsilon_{s_j}^{comp}$ and $\upsilon_{f_i}^{comp}$	Compressed air (m^3/h) used for a machine involved in process j at supplier s and in process i at factory f, respectively
ρ_s^{comp} and ρ_f^{comp}	The capacity of a compressor (m^3/h) at supplier s and at factory f, respectively
$\Phi_{s_j}^{cond}$ and $\Phi_{f_i}^{cond}$	Covering rate per air-conditioning unit (unit) that serves machines involved in

	process *j* at supplier *s* and in process *i* at factory *f*, respectively
$\varphi_{s_j}^{bulb}$ and $\varphi_{f_i}^{bulb}$	Covering rate of lighting bulbs (unit) per one machine involved process *j* at supplier *s* and in process *i* at factory *f*, respectively
Γ_w^{cond}	Covering rate per air-conditioning unit (kg) that services quantity of products in warehouse *w*
λ_w^{bulb}	Covering rate per lighting bulb (kg) that services quantity of products in warehouse *w*
$e_{s_j}^{mach}$ and $e_{f_i}^{mach}$	Amount of CO_2 emissions (kg) released from the machines involved in process *j* of supplier *s* and in process *i* of factory *f*, respectively
$e_{s_j}^{cond}$ and $e_{f_i}^{cond}$	Amount of CO_2 emissions (kg) released from the air-conditioning units involved in process *j* of supplier *s* and in process *i* of factory *f*, respectively
$e_{s_j}^{bulb}$ and $e_{f_i}^{bulb}$	Amount of CO_2 emissions (kg) released from the lighting bulbs involved in process *j* of supplier *s* and in process *i* of factory *f*, respectively
$e_{s_j}^{comp}$ and $e_{f_i}^{comp}$	Amount of CO_2 emissions (kg) released from a compressor system involved in process *j* of supplier *s* and in process *i* of factory *f*, respectively
e_w^{cond} and e_w^{bulb}	Amount of CO_2 emissions (kg) released from air-conditioning units and the lighting bulbs involved in warehouse *w*
e_{sf}^t and e_{fw}^t	Amount of CO_2 emissions (kg) released for transportation from supplier *s* to factory *f* and from factory *f* to warehouse *w*, respectively
e_s	The total amount of CO_2 emissions (kg) released from supplier *s*
e^t	The total amount of CO_2 emissions (kg) released from transportation vehicles duo to transferring materials from supplier *s* to factory *f* and shipped the products from factory *f* to warehouse *w*
e_f	The total amount of CO_2 emissions (kg) released from factory *f*
e_w	The total amount of CO_2 emissions (kg) released from warehouse *w*
V	Capacity (units) per vehicle
ω_{s_j}, ω_{f_i} and ω_w	CO_2 emission factor (kg/kWh) at supplier *s*, at factory *f* and warehouse *w*, respectively
ω_{sf}^t and ω_{fw}^t	CO_2 emission factor (kg/mile) released for transportation from supplier *s* to factory *f* and from factory *f* to warehouse *w*, respectively
Decision variables	
$q_{s_j}^r$ and $q_{f_i}^r$	Mass of material (kg) involved in process *j* in supplier *s* and in process *i* in factory *f*, respectively, where $j \in \{1, 2, \ldots, \Pi_s\}$ and $i \in \{1, 2, \ldots, \Pi_f\}$
$q_{s_{(j+1)}}^r$ and $q_{f_{(i+1)}}^r$	Mass of material (kg) transferred from the machines involved in process *j* in supplier *s* and in process *i* in factory *f*, respectively
q_{sf}^r and q_{fw}^{mp}	Mass of material (kg) transported from supplier *s* to factory *f* and products transported from factory *f* to warehouse *w*
$n_{s_j}^{mach}$ and $n_{f_i}^{mach}$	Number of machines (unit) involved in process *j* in supplier *s* and in process *i* in factory *f*, respectively
$n_{s_j}^{cond}$, $n_{f_i}^{cond}$ and n_w^{cond}	Number of air-conditioning units (unit) involved in process *j* in supplier *s*, in process *i* in factory *f* and in warehouse *w*, respectively
$n_{s_j}^{bulb}$, $n_{f_i}^{bulb}$ and n_w^{bulb}	Number of lighting bulbs (unit) involved in process *j* in supplier *s*, in process *i* in factory *f* and in warehouse *w*, respectively

Thus, the multi-objective mathematical model is formulated as follows:

2.1.1 Objective function 1: minimisation of total investment cost Λ_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 Λ_1 can be minimised as follows:

$$\text{Min } \Lambda_1 = C_l^{es} + C_s^{mach} + C_f^{mach} + C_s^{cond} + C_f^{cond} + C_w^{cond} + C_s^{bulp} + C_f^{bulp} + C_w^{bulp} + C_{sf}^r + C_{fw}^{mp} + C_l^t + C_{fw}^I \tag{1}$$

where the total cost required for establishing facility l C_l^{es}, where $l \in \{s, f, w\}$ is given as below:

$$C_l^{es} = C_s^{es} + C_f^{es} + C_w^{es} \tag{2}$$

Cost required for establishing supplier *s*, factory *f* and warehouse *w* (C_s^{es}, C_f^{es} and C_w^{es}) is given respectively as follows:

$$C_s^{es} = C_s^{land} + C_s^{building} + C_s^{equipment} + C_s^{services} + C_s^{saleries} \tag{3}$$

$$C_f^{es} = C_f^{land} + C_f^{building} + C_f^{equipment} + C_f^{services} + C_f^{saleries} \tag{4}$$

$$C_w^{es} = C_w^{land} + C_w^{building} + C_w^{equipment} + C_w^{services} + C_w^{saleries} \tag{5}$$

Cost of the machines C_s^{mach} and C_f^{mach} involved in process *j* at supplier *s* and in process *i* at factory *f* is given respectively as follows:

$$C_s^{mach} = \sum_{j=1}^{\Pi_s} \left(C_{s_j}^{mach} n_{s_j}^{machin} \right) \tag{6}$$

$$C_f^{mach} = \sum_{i=1}^{\Pi_f} \left(C_{f_i}^{mach} n_{f_i}^{machin} \right) \tag{7}$$

Cost of an air-conditioning unit C_s^{cond}, C_f^{cond} and C_w^{cond} involved in process j at supplier s, involved in process i at factory f and involved in warehouse w is given respectively by the following equations:

$$C_s^{cond} = \sum_{j=1}^{\Pi_s} \left(C_{s_j}^{cond} n_{s_j}^{cond} \right) \tag{8}$$

$$C_f^{cond} = \sum_{j=1}^{\Pi_f} \left(C_{f_i}^{cond} n_{f_i}^{cond} \right) \tag{9}$$

$$C_w^{cond} = \sum_{w \in W} \left(C_w^{cond} n_w^{cond} \right) \tag{10}$$

Cost of a lighting bulb C_s^{bulp}, C_f^{bulp} and C_w^{bulp} involved in process j at supplier s, involved in process i at factory f and involved in warehouse w is given respectively by the following equations:

$$C_s^{bulp} = \sum_{j=1}^{\Pi_s} \left(C_{s_j}^{bulp} n_{s_j}^{bulb} \right) \tag{11}$$

$$C_f^{bulp} = \sum_{i=1}^{\Pi_f} \left(C_{f_i}^{bulp} n_{f_i}^{bulb} \right) \tag{12}$$

$$C_w^{bulb} = \sum_{w \in W} \left(C_w^{bulb} n_w^{bulb} \right) \tag{13}$$

The total cost of raw materials at supplier s C_{sf}^r is calculated as below:

$$C_{sf}^r = \sum_{s=1}^{S} \sum_{f=1}^{F} C_s^r q_{sf}^r \tag{14}$$

The total cost of manufacturing products at factory f C_{fw}^{mp} is given by the following equation:

$$C_{fw}^{mp} = \sum_{f=1}^{F} \sum_{w=1}^{W} C_f^{mp} q_{fw}^{mp} \tag{15}$$

The total cost of transportation of raw materials per mile between s and f C_{sf}^t is given as follows:

$$C_{sf}^t = \sum_{s=1}^{S} \sum_{f=1}^{F} C_{sf}^t \frac{q_{sf}^r}{V} T_{sf} \tag{16}$$

The total cost of transportation of products per mile between f and w C_{fw}^t is given as follows:

$$C_{sf}^t = \sum_{s=1}^{S} \sum_{f=1}^{F} C_{sf}^t \frac{q_{sf}^r}{V} T_{sf} \tag{17}$$

Total cost of inventory C_{fw}^I at warehouse w is determined as below:

$$C_{fw}^I = \sum_{f=1}^{F} \sum_{w=1}^{W} C_w^I q_{fw}^{mp} \tag{18}$$

Hence, Eq. (1) can be expressed as follows:

$$\begin{aligned}
Min\ Z_1 = {} & C_s^{land} + C_s^{building} + C_s^{equipment} + C_s^{services} + C_s^{saleries} \\
& + C_f^{land} + C_f^{building} + C_f^{equipment} + C_f^{services} + C_f^{saleries} + C_w^{land} \\
& + C_w^{building} + C_w^{equipment} + C_w^{services} + C_w^{saleries} + \sum_{j=1}^{\Pi_s} \left(C_{s_j}^{mach} n_{s_j}^{mach} \right) \\
& + \sum_{i=1}^{\Pi_f} \left(C_{f_i}^{mach} n_{f_i}^{mach} \right) + \sum_{j=1}^{\Pi_s} \left(C_{s_j}^{cond} n_{s_j}^{cond} \right) + \sum_{j=1}^{\Pi_f} \left(C_{f_i}^{cond} n_{f_i}^{cond} \right) \\
& + \sum_{w=1}^{W} \left(C_w^{cond} n_w^{cond} \right) + \sum_{j=1}^{\Pi_s} \left(C_{s_j}^{bulp} n_{s_j}^{bulb} \right) + \sum_{i=1}^{\Pi_f} \left(C_{f_i}^{bulp} n_{f_i}^{bulb} \right) \\
& + \sum_{w=1}^{W} \left(C_w^{bulp} n_w^{bulb} \right) + \sum_{s=1}^{S} \sum_{f=1}^{F} C_s^r q_{sf}^r + \sum_{f=1}^{F} \sum_{w=1}^{W} C_f^{mp} q_{fw}^{mp} \\
& + \sum_{s=1}^{S} \sum_{f=1}^{F} C_{sf}^t \frac{q_{sf}^r}{V} T_{sf} + \sum_{f=1}^{F} \sum_{w=1}^{W} C_{fw}^t \frac{q_{fw}^{mp}}{V} T_{fw} + \sum_{f=1}^{F} \sum_{w=1}^{W} C_w^I q_{fw}^{mp}
\end{aligned}$$

2.1.2 Objective function 2: minimisation of total energy consumption Λ_2

The total energy consumption can be minimised as follows:

$$\text{Min } \Lambda_2 = E_s + E_f + E_w \tag{19}$$

where the total energy consumption E_s for supplier s is given by the following:

$$E_s = \sum_{j=1}^{\Pi_s} \left[E_{s_j}^{mach} + E_{s_j}^{cond} + E_{s_j}^{bulb} + E_{s_j}^{comp} \right], \quad where j \in \{1, 2, \ldots., \Pi_s\} \tag{20}$$

Energy consumption $E_{s_j}^{mach}$, $E_{s_j}^{cond}$ and $E_{s_j}^{bulb}$ for machines, air-conditioning units and lighting bulbs involved in process j at supplier s is given respectively by the following:

$$E_{s_j}^{mach} = \sum_{j=1}^{\Pi_s} \left(\frac{q_{s_j}^r}{\mathfrak{R}_{s_j} \mu_{s_j}} N_{s_j}^{mach} n_{s_j}^{mach} \right) \tag{21}$$

$$E_{s_j}^{cond} = \sum_{j=1}^{\Pi_s} \left(N_{s_j}^{cond} n_{s_j}^{cond} \frac{q_{s_{(j+1)}}^r}{\wp_s} \right) \tag{22}$$

$$E_{s_j}^{bulb} = \sum_{j=1}^{\Pi_s} \left(N_{s_j}^{bulb} n_{s_j}^{bulb} \frac{q_{s_{(j+1)}}^r}{\wp_s} \right) \tag{23}$$

Energy consumption of compressed air $E_{s_j}^{comp}$ which is needed for machines involved in process j at supplier s is calculated by the following:

$$E_{s_j}^{comp} = \sum_{j=1}^{\Pi_s}\left(\frac{q_{s_j}^{r}}{\mathfrak{R}_{s_j}\mu_{s_j}}\frac{N_{s_j}^{comp}}{\rho_{s_j}^{comp}}\upsilon_{s_j}^{comp}n_{s_j}^{mach}\right) \tag{24}$$

Total energy consumption E_f for factory f is given by the following:

$$E_f = \sum_{i=1}^{\Pi_f}\left[E_{f_i}^{mach}+E_{fi}^{cond}+E_{f_i}^{bulb}+E_{f_i}^{comp}\right], \quad where, \quad i\in\{1,2,....,\Pi_f\} \tag{25}$$

Energy consumption $E_{f_i}^{mach}$, $E_{f_i}^{cond}$ and $E_{f_i}^{bulb}$ for machines, air-conditioning units and lighting bulbs involved in process i at factory f is given respectively by the following:

$$E_{f_i}^{mach} = \sum_{i=1}^{\Pi_f}\left(N_{f_i}^{mach}n_{fi}^{mach}\frac{q_{f_i}^{r}}{\mathfrak{R}_{f_i}\mu_{f_i}}\right) \tag{26}$$

$$E_{f_i}^{cond} = \sum_{i=1}^{\Pi_f}\left(N_{f_i}^{cond}n_{f_i}^{cond}\frac{q_{f_{(i+1)}}^{r}}{\wp_f}\right) \tag{27}$$

$$E_{f_i}^{bulb} = \sum_{i=1}^{\Pi_f}\left(N_{f_i}^{bulb}n_{f_i}^{bulb}\frac{q_{f_{(i+1)}}^{r}}{\wp_f}\right) \tag{28}$$

Energy consumption of compressed air $E_{f_i}^{comp}$ needed for machines involved in process i at factory f is calculated by the following:

$$E_{f_i}^{comp} = \sum_{i=1}^{\Pi_f}\left(\frac{q_{f_i}^{r}}{\mathfrak{R}_{f_i}\mu_{f_i}}\frac{N_{f_i}^{comp}}{\rho_{f_i}^{comp}}\upsilon_{f_i}^{comp}n_{f_i}^{mach}\right) \tag{29}$$

Total energy consumption E_w for warehouse w is given by the following:

$$E_w = \sum_{w=1}^{W}\left(E_w^{cond}+E_w^{bulb}\right) \tag{30}$$

Energy consumption E_w^{cond} and E_w^{bulb} for air-conditioning units and lighting bulbs at warehouse w is given by the following:

$$E_w^{cond} = \sum_{w=1}^{W}\left(N_w^{cond}n_w^{cond}\frac{q_{fw}^{mp}}{\wp_w}\right) \tag{31}$$

$$E_w^{bulb} = \sum_{w=1}^{W}\left(N_w^{bulb}n_w^{bulb}\frac{q_{fw}^{mp}}{\wp_w}\right) \tag{32}$$

Hence, Eq. (19) is given as follows:

$$\begin{aligned}\text{Min } Z_2 = &\sum_{j=1}^{\Pi_s}\left(\begin{array}{l}\frac{q_{s_j}^{r}}{\mathfrak{R}_{s_j}\mu_{s_j}}N_{s_j}^{mach}n_{s_j}^{mach}+N_{s_j}^{cond}n_{s_j}^{cond}\frac{q_{s_{(j+1)}}^{r}}{\wp_s}+N_{s_j}^{bulb}n_{s_j}^{bulb}\frac{q_{s_{(j+1)}}^{r}}{\wp_s}\\+\frac{q_{s_j}^{r}}{\mathfrak{R}_{s_j}\ \mu_{s_j}}\frac{N_{s_j}^{comp}}{\rho_{s_j}^{comp}}\upsilon_{s_j}^{comp}n_{s_j}^{mach}\end{array}\right)\\&+\sum_{i=1}^{\Pi_f}\left(\begin{array}{l}\frac{q_{f_i}^{r}}{\mathfrak{R}_{f_i}\mu_{f_i}}N_{f_i}^{mach}n_{f_i}^{mach}+N_{f_i}^{cond}n_{f_i}^{cond}\frac{q_{f_{(i+1)}}^{r}}{\wp_f}+N_{f_i}^{bulb}n_{f_i}^{bulb}\frac{q_{f_{(i+1)}}^{r}}{\wp_f}\\+\frac{q_{f_i}^{r}}{\mathfrak{R}_{f_i}\ \mu_{f_i}}\frac{N_{f_i}^{comp}}{\rho_{f_i}^{comp}}\upsilon_{f_i}^{comp}n_{f_i}^{mach}\end{array}\right)\\&+\sum_{w=1}^{W}\left(N_w^{cond}n_w^{cond}\frac{q_w^{mp}}{\wp_w}+N_w^{bulb}n_w^{bulb}\frac{q_{fw}^{mp}}{\wp_w}\right)\end{aligned}$$

2.1.3 Objective function 3: minimisation of total CO$_2$ emissionsΛ_3

The total amount of CO$_2$ emissions can be minimised below:

$$\text{Min } \Lambda_3 = e_s + e^t + e_f + e_w \tag{33}$$

where the total amount of CO$_2$ emissions e_s released from supplier s is calculated as follows:

$$e_s = \sum_{j=1}^{\Pi_s}\left[e_{s_j}^{mach} + e_{s_j}^{cond} + e_{s_j}^{bulb} + e_{s_j}^{comp}\right] \tag{34}$$

Amount of CO$_2$ emissions $e_{s_j}^{mach}$, $e_{s_j}^{cond}$ and $e_{s_j}^{bulb}$ released from the machines, air-conditioning units and lighting bulbs involved in process j at supplier s is respectively given by the following:

$$e_{s_j}^{mach} = \sum_{j=1}^{\Pi_s}\left(\omega_{s_j} E_{s_j}^{mach}\, q_{s_j}^r\right) \tag{35}$$

$$e_{s_j}^{cond} = \sum_{j=1}^{\Pi_s}\left(0.689 E_{s_j}^{cond}\right) \tag{36}$$

$$e_{s_j}^{bulb} = \sum_{j=1}^{\Pi_s}\left(0.689 E_{s_j}^{bulb}\right) \tag{37}$$

Amount of CO$_2$ emissions $e_{s_j}^{comp}$ released from a compressor system involved in process j at supplier s is given below:

$$e_{s_j}^{comp} = \sum_{j=1}^{\Pi_s}\left(0.689 E_{s_j}^{comp}\right), \quad \textit{where } 0.689 \textit{ is the emission factor for the electricity} \tag{38}$$

The total amount of CO$_2$ emissions e^t which are released for transportation from supplier s to factory f and from factory f to warehouse w is given below:

$$e^t = e_{sf}^t + e_{fw}^t \tag{39}$$

where the amount of CO$_2$ emissions e_{sf}^t and e_{fw}^t which are released for transporting raw material from supplier s to factory f and products from factory f to warehouse w respectively is given below:

$$e_{sf}^t = \sum_{s=1}^{S}\sum_{f=1}^{F}\left(\omega_{sf}^t \frac{q_{sf}^r}{V} T_{sf}\right) \tag{40}$$

$$e_{fw}^t = \sum_{f=1}^{F}\sum_{w=1}^{W}\left(\omega_{fw}^t \frac{q_{fw}^{mp}}{V} T_{fw}\right) \tag{41}$$

The total amount of CO$_2$ emissions e_f released from factory f is calculated as below:

$$e_f = \sum_{i=1}^{\Pi_f}\left[e_{f_i}^{mach} + e_{f_i}^{cond} + e_{f_i}^{bulb} + e_{f_i}^{comp}\right] \tag{42}$$

Amount of CO$_2$ emissions $e_{f_i}^{mach}$, $e_{f_i}^{cond}$ and $e_{f_i}^{bulb}$ released from the machines, air-conditioning units and lighting bulbs involved in process i at factory f is given respectively by the following:

$$e_{f_i}^{mach} = \sum_{i=1}^{\Pi_f}\left(\omega_{f_i} \frac{q_{f_i}^r}{\mathfrak{R}_{f_i}\mu_{f_i}} N_{f_i}^{mach} n_{fi}^{mach}\right) \tag{43}$$

$$e_{f_i}^{cond} = \sum_{i=1}^{\Pi_f}\left(0.689 N_{f_i}^{cond} n_{f_i}^{cond} \frac{q_{f_{(i+1)}}^r}{\wp_f}\right) \tag{44}$$

$$e_{f_i}^{bulb} = \sum_{i=1}^{\Pi_f}\left(0.689 N_{f_i}^{bulb} n_{f_i}^{bulb} \frac{q_{f_{(i+1)}}^r}{\wp_f}\right) \tag{45}$$

Amount of CO$_2$ emissions $e_{f_i}^{comp}$ released from a compressor system involved in process i at factory f is given below:

$$e_{f_i}^{comp} = \sum_{i=1}^{\Pi_f}\left(0.689 \frac{q_{f_i}^r}{\mathfrak{R}_{f_i}\mu_{f_i}} \frac{N_{f_i}^{comp}}{\rho_{f_i}^{comp}} \upsilon_{f_i}^{comp} n_{f_i}^{mach}\right) \tag{46}$$

where 0.689 is the emission factor for the electricity.

Amount of CO$_2$ emissions e_w released from warehouse w is calculated as below:

$$e_w = 0.989 \sum_{w=1}^{W}\left(N_w^{cond} n_w^{cond} \frac{q_{fw}^{mp}}{\wp_w} + N_w^{bulb} n_w^{bulb} \frac{q_{fw}^{mp}}{\wp_w}\right) \tag{47}$$

Thus, Eq. (32) is given as follows:

$$\begin{aligned}\text{Min } Z_3 = \sum_{j=1}^{\Pi_s}&\left[\begin{array}{l}\omega_{s_j}\dfrac{q^r_{s_j}}{\Re_{s_j}\mu_{s_j}}N^{mach}_{s_j}n^{mach}_{s_j}\\ +0.689\left(N^{cond}_{s_j}n^{cond}_{s_j}\dfrac{q^r_{s(j+1)}}{\wp_s}+N^{bulb}_{s_j}n^{bulb}_{s_j}\dfrac{q^r_{s(j+1)}}{\wp_s}+N^{bulb}_{s_j}n^{bulb}_{s_j}\dfrac{q^r_{s(j+1)}}{\wp_s}\right)\end{array}\right]\\ &+\sum_{s=1}^{S}\sum_{f=1}^{F}\left(\omega^t_{sf}\frac{q^r_{sf}}{V}T_{sf}\right)+\sum_{f=1}^{F}\sum_{w=1}^{W}\left(\omega^t_{fw}\frac{q^{mp}_{fw}}{V}T_{fw}\right)\\ +\sum_{i=1}^{\Pi_f}&\left[\begin{array}{l}\omega_{f_i}\dfrac{q^r_{f_i}}{\Re_{f_i}\mu_{f_i}}N^{mach}_{f_i}n^{mach}_{fi}\\ +0.689\left(N^{cond}_{f_i}n^{cond}_{f_i}\dfrac{q^r_{f(i+1)}}{\wp_f}+N^{bulb}_{f_i}n^{bulb}_{f_i}\dfrac{q^r_{f(i+1)}}{\wp_f}+\dfrac{q^r_{f_i}}{\Re_{f_i}\mu_{f_i}}\dfrac{N^{comp}_{f_i}}{\rho^{comp}_{f_i}}\upsilon^{comp}_{f_i}n^{mach}_{f_i}\right)\end{array}\right]\\ &+0.689\sum_{w=1}^{W}\left(N^{cond}_{w}n^{cond}_{w}\frac{q^{mp}_{fw}}{\wp_w}+N^{bulb}_{w}n^{bulb}_{w}\frac{q^{mp}_{fw}}{\wp_w}\right)\end{aligned}$$

where the CO$_2$ emission factor ω_{s_j}, ω_{f_i}, ω_w and ω^t_{sf} is shown in Table 1 [33, 34].

2.1.4 Constraints

Equations (48) and (49) ensure that the quantity of raw material shipped to factory *f* and warehouse *w* cannot be greater than their capacity.

$$q^r_{sf}\le Ca_s \tag{48}$$

$$q^{mp}_{fw}\le Ca_f \tag{49}$$

Equations (50) and (51) ensure that the demands of factory *f* and warehouse *w* are fulfilled, respectively.

$$q^r_{sf}\ge D_f \tag{50}$$

$$q^{mp}_{fw}\ge D_w \tag{51}$$

Equations (52) and (53) ensure that quantity of materials of the first process task *j* and *i* must be bigger than or equal to the quantity of materials of the next process task (*j*+1) and (*i*+1) in supplier *s* and factory *f*, respectively.

$$\left(1-\Psi_{s_j}\right)q^r_{s_j}\ge q^r_{s_{(i+1)}} \tag{52}$$

$$\left(1-\Psi_{f_i}\right)q^r_{f_{(i+1)}}\ge q^r_{f_{(i+1)}} \tag{53}$$

Equations (54) and (55) are defined that the number of machines involved in process task *j* in supplier *s* and process task *i* in factory *f* (being served by one air-conditioning unit) must be less than or equal to the number of air-conditioning units involved in this process, respectively.

$$\Phi^{cond}_{s_j}n^{cond}_{s_j}\ge n^{mach}_{s_j} \tag{54}$$

$$\Phi^{cond}_{f_i}n^{cond}_{f_i}\ge n^{mach}_{f_i} \tag{55}$$

Equations (56) and (57) is defined that the number of light bulbs, which serve all the machines involved in process task *j* in supplier *s* and process task *i* in factory *f*, must be greater than or equal to the number of machines involved in this process, respectively.

$$n^{bulb}_{s_j}\ge\varphi^{bulb}_{s_j}n^{mach}_{s_j} \tag{56}$$

$$n^{bulb}_{f_i}\ge\varphi^{bulb}_{f_i}n^{mach}_{f_i} \tag{57}$$

Equations (58) and (59) are defined as the quantity of products being served by one air-conditioning unit and one lighting bulb in warehouse *w*, respectively.

$$\Gamma^{cond}_{w}n^{cond}_{w}\ge q^{mp}_{fw} \tag{58}$$

$$\lambda^{bulb}_{w}n^{bulb}_{w}\ge q^{mp}_{fw} \tag{59}$$

Equation (60) is a non-negativity constraint for the quantity of materials shipped from supplier *s* to factory *f* and for products shipped from factory *f* to warehouse *w*.

$$q^r_{s_j},q^r_{sf},q^r_{f_i},q^{mp}_{fw}\ge 0 \tag{60}$$

Equations (61) and (62) are defined that the manufacturing rate of process task *j* and *i* in supplier *s* and factory *f* must be greater than or equal to the quantity of materials involved in the next process task (*j*+1) and (*i*+1) in supplier *s* and factory *f*, respectively.

$$\Re_{s_j}n^{mach}_{s_j}\ge q^r_{s_{(i+1)}} \tag{61}$$

$$\Re_{f_i}n^{mach}_{f_i}\ge q_{f_{(i+1)}} \tag{62}$$

Table 1 Amount CO_2 emission factor per kWh and per mile

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

where Eqs. (48), (49), (50), (51), (52), (53) and (60) are quantity constraints and Eqs. (54)–(59), (61) and (62) are constraints on numbers of machines, air-conditioning units and lighting bulbs.

3 Optimisation approaches

A manufacturing system design towards an optimisation of multiple and possibly conflicting objectives forms a multi-objective optimisation 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 based on the developed multi-objective model. There are several approaches for multi-objective optimisation; this includes the ε-constraint method, the weighted-sum method, the LP-metrics method and the weighted tchebycheff method [35]. In this paper, two approaches are used to gain the optimal solutions: these are the ε-constraint method and the LP-metrics method. Moreover, an optimal solution was determined using the max-min approach.

3.1 The 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 minimisation of the total energy consumption in this study as the single-objective function (Eq. 63); the other two objective functions (total cost and total CO_2 emissions) are shifted to be ε-based constraints; i.e. Eq. 64 restricts the first objective function to be less than or equal to ε_1 between the minimum value and the maximum value for objective function one (Eq. 65). Equation 66 restricts the third objective function to be less than or equal to ε_2 which gradually varies between the minimum value and the maximum value for objective function three (Eq. 67) ([36, 37]). Thus, the equivalent solution formula Λ is expressed as follows:

$$\mathrm{Min}\ \Lambda_2 \tag{63}$$

Equation 63 is subject to the following constrains:

$$\Lambda_1 \leq \varepsilon_1 \tag{64}$$

$$(\Lambda_1)^{\min} \leq \varepsilon_1 \leq (\Lambda_1)^{\max} \tag{65}$$

$$\Lambda_3 \leq \varepsilon_2 \tag{66}$$

$$(\Lambda_3)^{\min} \leq \varepsilon_2 \leq (\Lambda_3)^{\max} \tag{67}$$

And additional constraints are included (Eqs. 48–62).

3.2 The LP-metrics approach

The solution procedure of the LP-metrics method is described as below:

1. Obtain the optimal value for each individual objective by optimizing them individually (Λ_1^*, Λ_2^* and Λ_3^*)

2. Convert the three-objective model into a modular-objective function using the following equation

$$\mathrm{Min}\ \Lambda = \left[y_1 \frac{\Lambda_1 - \Lambda_1^*}{\Lambda_1^*} + y_2 \frac{\Lambda_2 - \Lambda_2^*}{\Lambda_2^*} + y_3 \frac{\Lambda_3 - \Lambda_3^*}{\Lambda_3^*} \right] \tag{68}$$

subject to Eqs. 48–62.

3. Determine the importance of each objective function based on decision makers' preferences. The weight formula for the three-objective functions is given as below:

$$\sum_{b=1}^{3} y_b,\ where\ y_b \geq 0\ (b = 1, 2, 3) \tag{69}$$

$$\mathrm{Min}\ \Lambda = \left(\sum_{a=1}^{3} l_a \left| \Lambda_a - \Lambda_a^* \right|^p \right)^{\frac{1}{p}} \tag{70}$$

Subject to Eqs. 48–62. It is noticed that the values of the objective functions are dependent on the value of p. Usually, the value of p is either 1 or 2. In this work, the value of p is set as 1.

3.3 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 ϑ_{Λ_x}. For further details about this approach, it may refer to Lai and Hwang [38]. The max-min approach formula is described as follows:

$$\begin{aligned} &\underset{x}{\mathrm{Max}} \left\{ \min \left\{ \vartheta_{\Lambda_x} - \vartheta_{\Lambda_x}^{\mathrm{ref}} \right\} \right\} \\ &= \underset{x}{\mathrm{Max}} \left\{ \min \left\{ \left(\frac{\Lambda_x^{\max} - \Lambda(x)}{\Lambda_x^{\max} - \Lambda_x^{\min}} \right) - \vartheta_{\Lambda_x}^{\mathrm{ref}} \right\} \right\} \end{aligned} \tag{71}$$

Table 2 Manufacturing processes tasks for producing plastic and woven sacks

Tasks	Description	Predecessors
A	Gas phase	None
B	Converted the gas to liquid	A
D	Converted the liquid to powder	B
H	Converted powder to pellets	D
R.M	Raw material (polypropylene)	G
G	Extruding the polypropylene to make stands	R.M
W	Weaving the stands into rolls of sacks	K
L	Laminating the rolls	H
P	Printing and branding	L
C	Cutting the rolls into bags	P
K	Inserts and smoothest out blown film into the bags	C
S	Blown film is sewn into bag	M
Z	End product compressed	Y
W	Store the products in warehouse	Z

$$\text{s.t.}\left\{\vartheta_{\Lambda_x}=\begin{cases}1 & \Lambda(x)\le\Lambda_x^{\min}\\ \left(\dfrac{\Lambda_x^{\max}-\Lambda(x)}{\Lambda_x^{\max}-\Lambda_x^{\min}}\right) & \Lambda_x^{\min}\le\Lambda(x)\le\Lambda_x^{\max}\\ 0 & \Lambda(x)\ge\Lambda_x^{\max}\end{cases}\right. \tag{72}$$

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

4 Application and evaluation

In this section, a case study was used for the applicability of the developed models and the proposed optimisation methods as described above. The study was carried out for analysing the total cost for establishing the facilities (supplier s, factory f and

Table 3 Data collected from a plastic and woven sacks company

Facilities		
Supplier s	Factory f	Warehouse w
C_s^{es} (GBP), 100,000	C_f^{es} (GBP), 100,000	C_w^{es} (GBP), 55,000
$C_{s_j}^{mach}$ (GBP), 7000, 7000, 7000, 7000, where $j\in\{1,2,\ldots.,\Pi_s\}$	$C_{f_i}^{mach}$ (GBP), 5000, 3000, 4000, 3000, 3000, 100, 200, 2000, where $i\in\{1,2,\ldots.,\Pi_f\}$	–
$C_{s_j}^{cond}$ (GBP),1000, 1000, 1000, 1000	$C_{f_i}^{cond}$ (GBP), 1000, 1000, 1000, 1000, 1000, 1000, 1000, 1000	C_w^{cond} (GBP), 700
$C_{s_j}^{bulp}$ (GBP), 50, 50, 50, 50	$C_{f_i}^{bulp}$ (GBP), 50, 50, 50, 50, 50, 50, 50, 50	C_w^{bulb} (GBP), 50
C_s^r (GBP/ kg), 2	C_f^{mp} (GBP/kg), 3	C_w^I (GBP/kg), 2
C_{sf}^t (GBP/mile), 2	C_{fw}^t (GBP/mile), 2	–
T_{sf} (mile), 50; V (kg), 20,000	T_{fw} (mile), 10; $V=20{,}000$	–
Ca_s (kg/month), 1,000,000	Ca_f (kg/month), 990,000	Ca_w (kg/month), 900,000
–	D_f (kg/month), 850,000	D_w (kg/month), 850,000
$\Pi_s=4$ process	$\Pi_f=8$ process	–
$\mathfrak{R}_{s_j}$ (kg/h), 1976, 1936, 1932 and 1929, where $j\in\{1,2,\ldots.,\Pi_s\}$	$\mathfrak{R}_{f_i}$ (kg/h), 1852, 1815, 1742, 1716, 1699, 1665, 1660 and 1643, where $i\in\{1,2,\ldots.,\Pi_f\}$	–
μ_{s_j} (%), 80 for all machines	μ_{f_i} (%), 80 for all machines	–
Ψ_{s_j} (%), 0.03, 0.02, 0.002, 0.15	Ψ_{f_i} (%),0.02, 0.04, 0.015, 0.01, 0.02, 0.003, 0.01, 0	–
$N_{s_j}^{mach}$ (kw), 700, 500, 300, 600	$N_{f_i}^{mach}$ (kw), 200, 20, 7, 40, 7, 0, 0.8, 4	–
$N_{s_j}^{comp}$ (kw), 0	$N_{f_i}^{comp}$ (kw), 200	–
$\rho_{s_j}^{comp}$ (m^3/h), 0	$\rho_{f_i}^{comp}$ (m^3/h), 666	–
$\upsilon_{s_j}^{comp}$ (m^3/h), 0	$\upsilon_{f_i}^{comp}$ (m^3/h), 5, 4, 13, 0, 7, 5, 20, 0, 0, 0	–
$N_{s_j}^{cond}$ (kw), 3.5	$N_{f_i}^{cond}$ (kw), 3.5	N_w^{cond} (kw), 3.5
$N_{s_j}^{bulb}$ (kw), 2.5	$N_{f_i}^{bulb}$ (kw), 2.5	N_w^{bulb} (kw), 2.5
$\Phi_{s_j}^{cond}$ (units), 2; $\varphi_{s_j}^{bulb}$ (units), 15	$\Phi_{f_i}^{cond}$ (units), 2; $\varphi_{f_i}^{bulb}$ (units), 15	Γ_w^{cond} (kg),1000; λ_w^{bulb} (kg), 500
$\wp_s$ (kg), 950,000	$\wp_f$ (kg), 840,000	$\wp_w$ (units), 9,032,258
ω_{s_j} (kg/kWh), 0.6895	ω_{f_i} (kg/kWh), 0.6895	ω_w (kg/kWh), 0.6895
ω_{sf}^t (kg/mile), 0.420	ω_{fw}^t (kg/mile), 0.420	–

Table 4 The non-inferior solutions obtained by using the ε-constraint approach

Solution number	Assigned ε values		Objective function solutions		
	ε_1	ε_2	Min Λ_1 (cost) (GBP)	Min Λ_2 (energy) (kWh/month)	Min Λ_3 (CO_2) (kg/month)
1	23,239,639	17.9×10^9	23,239,639	2,842,852	17.9×10^9
2	24,808,211	18.35×10^9	24,640,700	3,128,510	18.3×10^9
3	26,150,354	18.66×10^9	26,000,000	3,414,168	18.6×10^9
4	27,492,497	18.9×10^9	27,370,000	3,699,826	18.9×10^9
5	28,800,000	19.5×10^9	28,800,000	3,998,500	19.4×10^9
6	29,990,000	19.75×10^9	29,600,000	4,200,000	19.7×10^9
7	30,895,000	20.2×10^9	30,550,000	4,450,000	20.1×10^9
8	30,990,000	20.4×10^9	30,990,000	4,820,000	20.4×10^9

Table 5 Non-inferior solutions obtained using the LP-metrics approach

Solution number	Objectives weights			Objective function solutions		
	y_1	y_2	y_3	Min Λ_1 (cost) (GBP)	Min Λ_2 (energy) (kWh/month)	Min Λ_3 (CO_2) (kg/month)
1	0	1	0	23,365,022	3,335,765	18.2×10^9
2	0.05	0.9	0.05	24,788,014	3,640,480	18.5×10^9
3	0.1	0.8	0.1	26,200,100	3,960,210	18.8×10^9
4	0.15	0.7	0.15	27,500,088	4,299,935	19×10^9
5	0.2	0.6	0.2	28,848,050	4,489,654	19.5×10^9
6	0.25	0.5	0.25	29,690,000	4,950,000	19.8×10^9
7	0.3	0.4	0.3	30,590,000	5,380,000	20.3×10^9
8	0.35	0.3	0.35	31,000,000	5,750,000	20.8×10^9

warehouse *w*), the energy consumption and the amount of CO_2 emissions towards a sustainable manufacturing design. Table 2 shows the manufacturing process with the symbols representing each task of a manufacturing process for the production of plastic and woven sacks inside supplier *s* and factory *f*. Table 3 shows the relevant parameters and their values used for the case study; it includes one supplier, one factory and one warehouse. All the parameters were taken from a real manufacturing system, which produces plastic and woven sacks. In this case, the production line is powered by electricity which is generated

Table 6 Numbers of machines, air-conditioning units and bulbs involved in process *j* in supplier *s* under the ε-constraint approach

Solution number	Numbers of machines involved in process j, $n_{s_j}^{mach}$, where $j \in \{1, 2, 3, 4\}$				Numbers of air-conditioning units involved in process j, $n_{s_j}^{cond}$, where $j \in \{1, 2, 3, 4\}$				Numbers of bulbs involved in process j, $n_{s_j}^{bulb}$, where $j \in \{1, 2, 3, 4\}$			
	n_{s1}	n_{s2}	n_{s3}	n_{s4}	n_{s1}	n_{s2}	n_{s3}	n_{s4}	n_{s1}	n_{s2}	n_{s3}	n_{s4}
1	2	2	1	1	1	1	1	1	30	30	15	15
2	2	2	2	1	1	1	1	1	30	30	30	30
3	2	2	2	2	1	1	1	1	30	30	30	30
4	2	2	2	2	1	1	1	1	30	30	30	30
5	2	2	2	2	1	1	1	1	30	30	30	30
6	3	3	3	3	2	2	2	2	45	45	45	45
7	3	3	3	3	2	2	2	2	45	45	45	45
8	3	3	3	3	2	2	2	2	45	45	45	45

Table 7 Numbers of machines, air-conditioning units and bulbs involved in process i in factory f and warehouse w under the ε-constraint approach

Solution number	Number of machines involved process i in factory f, $n_{f_i}^{mach}$, where $i \in \{1,2,3,4,5,6,7,8\}$								Number of air-conditioning units involved process i in factory f, $n_{f_i}^{cond}$								Number of lighting bulbs involved process i in factory f $n_{f_i}^{bulb}$								Number of air-conditioning units in warehouse w n_w^{cond}	Number of lighting bulbs in warehouse w n_w^{bulb}
	*nf*1	*nf*2	*nf*3	*nf*4	*nf*5	*nf*6	*nf*7	*nf*8	*nf*1	*nf*2	*nf*3	*nf*4	*nf*5	*nf*6	*nf*7	*nf*8	*nf*1	*nf*2	*nf*3	*nf*4	*nf*5	*nf*6	*nf*7	*nf*8		
1	4	40	3	5	13	13	60	4	2	20	2	3	7	7	30	2	60	600	45	75	195	195	900	60	832	1664
2	5	40	4	5	14	14	60	4	3	20	2	3	7	7	30	2	75	600	60	75	210	210	900	60	847	1664
3	5	45	5	6	16	16	60	5	3	23	3	3	8	8	30	3	75	675	75	90	240	240	900	75	865	1729
4	5	50	6	6	16	16	65	5	3	25	3	3	8	8	33	3	75	750	90	90	240	240	975	75	881	1762
5	5	50	6	7	17	17	65	6	3	25	3	4	9	9	33	3	75	750	90	105	255	255	975	90	881	1762
6	6	55	6	8	17	17	67	6	3	28	3	4	9	9	34	3	90	825	90	120	255	255	1005	90	788	1575
7	6	56	6	8	18	18	67	7	3	28	3	4	9	9	34	4	90	840	90	120	270	270	1005	105	861	1722
8	6	56	7	9	18	18	68	7	3	28	4	5	9	9	34	4	90	840	105	135	270	270	1020	105	880	1760

Table 8 Solutions in numbers of machines, air-conditioning units and bulbs involved in process i in supplier s based on LP-metrics approach

Solution number	Numbers of machines involved in process j, $n_{s_j}^{mach}$, where $j \in \{1,2,3,4\}$				Numbers of air-conditioning units involved in process j, $n_{s_j}^{cond}$, where $j \in \{1,2,3,4\}$				Numbers of bulbs involved in process j, $n_{s_j}^{bulb}$, where $j \in \{1,2,3,4\}$			
	n_{s1}	n_{s2}	n_{s3}	n_{s4}	n_{s1}	n_{s2}	n_{s3}	n_{s4}	n_{s1}	n_{s2}	n_{s3}	n_{s4}
1	2	2	2	1	1	1	1	1	30	30	30	15
2	2	2	2	2	1	1	1	1	30	30	30	30
3	2	2	2	2	1	1	1	1	30	30	30	30
4	2	2	2	2	1	1	1	1	30	30	30	30
5	3	3	3	3	2	2	2	2	45	45	45	45
6	3	3	3	3	2	2	2	2	45	45	45	45
7	3	3	3	3	2	2	2	2	45	45	45	45
8	3	3	3	3	2	2	2	2	45	45	45	45

using oil as source of energy. LINGO[11] was used for computing results aiming to seek the optimisation solutions.

4.1 Computational results and discussion

Table 4 shows the solution results obtained using the ε-constraint approach; this includes eight epsilon values by assigning the incremental value of ε from 23,239,639 to 30,990,000 based on objective one and from 17.9×10^9 to 20.4×10^9 based on objective three. Table 5 shows the solution results using the LP-metrics method in which each objective was optimised individually to obtain the ideal value. As shown in Table 4, solution 1, as an example, was obtained by assigning $\varepsilon_1 = 23{,}239{,}639$ and $\varepsilon_2 = 17.9 \times 10^9$, respectively; it gives the minimum total cost of 23,239,639 GBP, the minimum total amount of energy of 2,842,852 kWh and the minimum total amount of CO_2 emissions of 17.9×10^9 kg.

By comparison as shown in Table 5, solution 1 was obtained using the LP-metrics approach by assigning $y_1 = 1$, $y_2 = 0$ and $y_3 = 0$; it gives the minimum total cost of 23,365,022 GBP, the minimum total amount of energy of 3,335,765 kWh and the minimum total amount of CO_2 emissions of 18.2×10^9 kg.

Tables 6, 7, 8 and 9 show the obtained solutions that contain potential groups in numbers of machines, air-conditioning units and lighting bulbs that should be established in the sustainable manufacturing system. These solutions were obtained using the ε-constraint approach and the LP-metrics approach, respectively. For instance, Table 6 shows the result for solution 1 using the ε-constraint approach which gives the group in numbers of machines involved in process j in supplier s $\left(n_{s_j}^{mach}\right)$ where $j \in \{1,2,3,4\}$ is (2, 2, 1, 1), the group in numbers of air-conditioning units $\left(n_{s_j}^{cond}\right)$ is (1, 1, 1, 1) and the

Table 9 Solutions in numbers of machines, air-conditioning units and bulbs involved in process *i* in factory *f* and warehouse *w* under the LP-metrics approach

Solution number	Number of machines involved process *i* in factory *f*, $n_{f_i}^{mach}$, where $i \in \{1, 2, 3, 4, 5, 6, 7, 8\}$								Number of air-conditioning units involved process *i* in factory *f*, $n_{f_i}^{cond}$								Number of lighting bulbs involved process *i* in factory *f*, $n_{f_i}^{bulb}$								Number of air-conditioning units in warehouse *w*, n_w^{cond}	Number of lighting bulbs in warehouse *w*, n_w^{bulb}
	*nf*1	*nf*2	*nf*3	*nf*4	*nf*5	*nf*6	*nf*7	*nf*8	*nf*1	*nf*2	*nf*3	*nf*4	*nf*5	*nf*6	*nf*7	*nf*8	*nf*1	*nf*2	*nf*3	*nf*4	*nf*5	*nf*6	*nf*7	*nf*8		
1	4	45	4	5	14	14	60	4	2	23	2	3	7	7	30	2	60	675	60	75	210	210	900	60	832	1664
2	6	45	4	5	14	14	60	4	3	23	2	3	7	7	30	2	90	675	60	75	210	210	900	60	847	1694
3	6	45	5	6	16	16	60	5	3	23	3	3	8	8	30	3	90	675	75	90	240	240	900	75	865	1729
4	6	50	6	6	16	16	65	5	3	25	3	3	8	8	33	3	90	750	90	90	240	240	975	75	881	1762
5	7	50	7	7	17	17	65	6	4	25	4	4	9	9	33	3	105	750	105	105	255	255	975	90	881	1762
6	7	55	7	8	17	17	67	6	4	28	4	4	9	9	34	3	105	825	105	120	255	255	1005	90	788	1575
7	7	56	7	8	18	18	67	7	4	28	4	4	9	9	34	4	105	840	105	120	270	270	1005	105	861	1722
8	7	56	7	9	19	19	68	7	4	28	4	5	10	10	34	4	105	840	105	135	285	285	1020	105	880	1760

group in numbers of lighting bulbs $\left(n_{s_j}^{bulb}\right)$ is (30, 30, 15, 15). Table 7 shows the result for solution 1 using the ε-constraint approach which gives the group in numbers of machines involved in process *i* in factory *f* $\left(n_{f_i}^{mach}\right)$ where $i \in \{1, 2, 3, 4, 5, 6, 7, 8\}$ is (4, 40, 3, 5, 13, 13, 60, 4), the group in numbers of air-conditioning units involved in process *i* $\left(n_{f_i}^{cond}\right)$ is (2, 20, 2, 3, 7, 7, 30, 2) and the group in numbers of lighting bulbs $\left(n_{f_i}^{bulb}\right)$ is (60, 600, 45, 75, 195, 195, 900, 60). Table 7 also shows that solution 1 requires 832 air-conditioning units $\left(n_w^{cond}\right)$ and 1664 lighting bulbs $\left(n_w^{bulb}\right)$ that need to be installed in warehouse *w*.

Table 8 shows the obtained results of solutions 1–8 using the LP-metrics approach. For instance, solution 1 gives the group (2, 2, 2, 1) in numbers of machines, which should be involved in process *j* in supplier *s* $\left(n_{s_j}^{mach}\right)$ where $j \in \{1, 2, 3, 4\}$; the group (1, 1, 1, 1) in numbers of air-conditioning units $\left(n_{s_j}^{cond}\right)$ and the group (30, 30, 30, 15) in numbers of lighting bulbs $\left(n_{s_j}^{bulb}\right)$. Table 9 shows the result for solution 1 using the LP-metrics approach which gives the group in numbers of machines that should be involved in process *i* in factory *f* $\left(n_{f_i}^{mach}\right)$ where $i \in \{1, 2, 3, 4, 5, 6, 7, 8\}$ is (4, 45, 4, 5, 14, 14, 60, 4), the group in numbers of air-conditioning units $\left(n_{f_i}^{cond}\right)$ is (2, 23, 2, 3, 7, 7, 30, 2) and the group in numbers of lighting bulbs $\left(n_{f_i}^{bulb}\right)$ is (60, 675, 60, 75, 210, 210, 900, 60). Solution 1 also gives 832 air-conditioning units (n_w^{cond}) and 1664 lighting bulbs (n_w^{bulb}) installed in warehouse *w*.

Figure 2a–c illustrates a pairwise comparison in a relationship between two of the three conflicting objectives. Arguably, the two approaches performed well in generating the non-inferior solutions. However, the results shown in Fig. 2a, b indicate that the non-inferior solutions obtained using the ε-constraint approach; it gives values of the total cost and the total energy consumption less than those of the non-inferior solutions obtained using the LP-metrics approach. For instance, they indicate that the minimum total cost for establishing the manufacturing system under solution 1 using ε-constraint approach is 23,239,639 GBP which is less than the minimum total cost under the LP-metrics approach (23,365,022 GBP). Figure 2c also indicates that the non-inferior solutions obtained using the ε-constraint approach that gives values of the total energy consumption and the total CO_2 emissions less than those of the non-inferior solutions obtained using the LP-metrics approach. As an example, it indicates that the minimum total energy consumption by the manufacturing system under solution 1 using the ε-constraint approach is 2,842,852 kWh which is less than the minimum

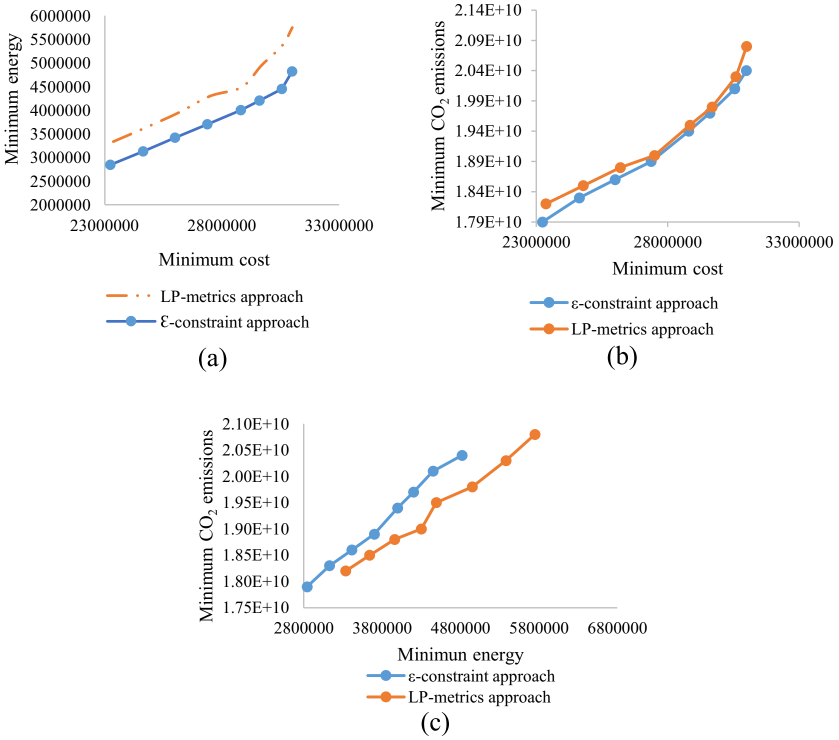


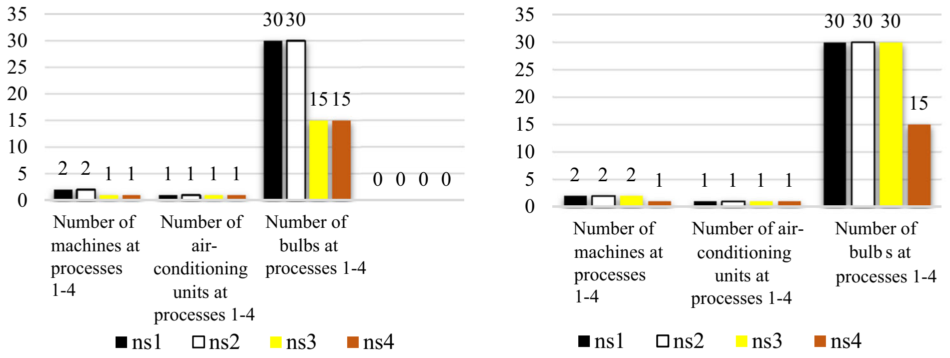
Fig. 2 Comparative solutions obtained using the ε-constraint approach and the LP-metrics approach: (**a**) Minimum cost VS Minimum Energy; (**b**) Minimum cost VS Minimum $\mathrm{CO_2}$ emission; and (**c**) Minimum Energy VS Minimum $\mathrm{CO_2}$ emission

total energy consumption under the LP-metrics approach (3,335,765 kWh) and the minimum total $\mathrm{CO_2}$ emissions released from the manufacturing system and the transportation vehicles, under the ε-constraint approach is 17.9×10^9 kg which is less than the minimum $\mathrm{CO_2}$ emissions released from the manufacturing system and the transportation vehicles, under the LP-metrics approach (18.2×10^9 kg).

Figure 3a–f shows a comparison among potential groups in numbers of machines, air-conditioning units and lighting bulbs that should be established in the manufacturing system based on solution 1 using the ε-constraint approach and the LP-metrics approach, respectively. The results in Fig. 3a, b indicate that the number of machines, air-conditioning units and lighting bulbs involved in process j in supplier s, where $j \in \{1, 2, 3, 4\}$ using the ε-constraint approach, is less than the results obtained using the LP-metrics approach. For instance, as shown in process task 3, the number of machines needed under ε-constraint approach is 1 machine, number of air-conditioning units is 1 unit and numbers of lighting bulbs are 15 bulbs while the numbers of machines needed to be established under LP-metrics approach are 2 machines, number of air-conditioning units is 1 unit and numbers of lighting bulbs are 30 bulbs. The results in Fig. 3c, d indicate that the number of machines, air-conditioning units and lighting bulbs involved in process i in factory f, where $i \in \{1, 2, 3, 4, 5, 6, 7, 8\}$ using the ε-constraint approach, is less than the results obtained using the LP-metrics approach. They indicate that the number of machines needed decreased for process task 3 from 4 to 3 and in process task 5 and 6 from 14 to 13, i.e. from (4, 45, 4, 5, 14, 14, 60, 4) to (4, 40, 3, 5, 13, 13, 60, 4); number of air-conditioning units needed decreased for process task 2 from 23 to 20, i.e. from (2, 23, 2, 3, 7, 7, 30, 2) to (2, 20, 2, 3, 7, 7, 30, 2) and the number of bulbs needed decreases for process task 2 from 675 to 600, process task 3 from 60 to 45, and process task 5 and 6 from 210 to 195, i.e. from (60, 675, 60, 75, 210, 210, 900, 60) to (60, 600, 45, 75, 195, 195, 900, 60). Figure 3e, f indicates that the numbers of air-conditioning units and lighting bulbs that need to be installed in warehouse w using the ε-constraint approach is the same number as using the LP-metrics approach, which is (832, 1664). Arguably, the two approaches performed well in generating the non-inferior solutions, but the solutions obtained by using the ε-constraint approach are more stable compared to the solutions obtained by using LP-metrics approach.

In practice, based on the obtained solutions using the two optimisation approaches, one of these solutions needs to be selected based on preferences of decision makers. Alternatively, it can be selected using the max-min approach. With the max-min approach (assuming $\vartheta^{\text{ref}}_{\Lambda_1} = 0, \vartheta^{\text{ref}}_{\Lambda_2} = 0.5 \textit{ and } \vartheta^{\text{ref}}_{\Lambda_3} = 0.5$), solution 1, which is obtained using the Ɛ-constraint approach, is determined as the best solution as it has the minimal distance in value of 3.45 to the ideal solution. Table 10 shows the optimal solutions in quantity of material flows (i) among the machines involved in process task j in supplier s, (ii) from supplier s to factory f, (iii) among the machines involved in process task i in factory f and (iv) from factory f to warehouse w. For instance, based on solution 4, the optimal decisions in quantity of material flows through the machines involved in process task (1, 2, 3, 4)

Fig. 3 Comparison between potential groups in numbers of machines, air-conditioning units and lighting bulbs obtained by using the ε-constraint approach and the LP-metrics approach based on solution 1 at supplier *s*, factory *f* and warehouse *w* respectively: (**a**) Minimum numbers of (machines, air-conditioning units and lighting bulbs) at processes 1-4 VS Numbers of (machines, air-conditioning units and lighting bulbs) at supplier s using ε-constraint approach; (**b**) Minimum numbers of (machines, air-conditioning units and lighting bulbs) at processes 1-4 VS Numbers of (machines, air-conditioning units and lighting bulbs) at supplier s using LP-metrics approach; (**c**) Minimum numbers of (machines, air-conditioning units and lighting bulbs) at processes 1-8 VS Numbers of (machines, air-conditioning units and lighting bulbs) at factory f using ε-constraint approach; (**d**) Minimum numbers of (machines, air-conditioning units and lighting bulbs) at processes 1-8 VS Numbers of (machines, air-conditioning units and lighting bulbs) at factory f using LP-metrics approach; (**e**) Minimum numbers of (air-conditioning units and lighting bulbs) VS Numbers of (air-conditioning units and lighting bulbs) at warehouse w using ε- constraint approach; (**f**) Minimum numbers of (air-conditioning units and lighting bulbs) VS Numbers of (air-conditioning units and lighting bulbs) at warehouse *w* using LP-metrics approach

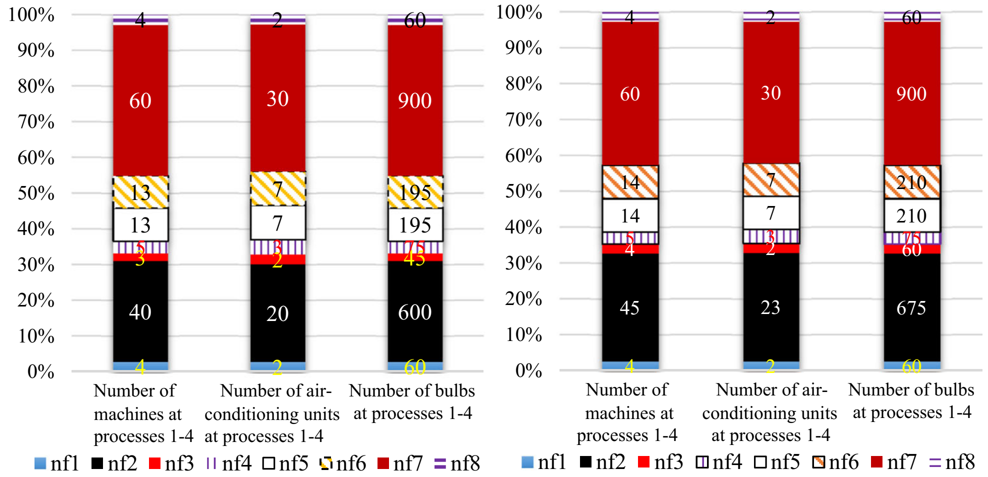


Solution 1 in supplier *s* using Ɛ- constraint approach

(a)

Solution 1 in supplier *s* using LP-metrics approach

(b)

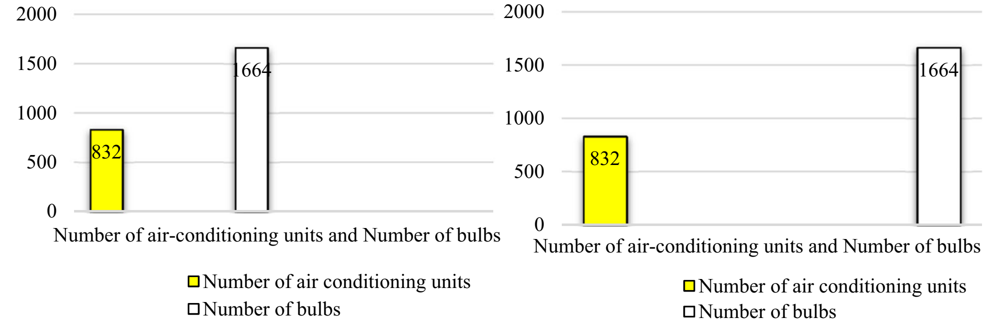


Solution 1 in factory *f* using Ɛ-constraint approach

(c)

Solution 1 in factory *f* using LP- metrics approach

(d)



Solution 1 in warehouse *w* using Ɛ- constraint approach

(e)

Solution 1 in warehouse *w* using LP-metrics approach

(f)

in supplier *s* are 980,000, 978,040, 976,084, 937,040, and 937,040 kg which are processed through the machines involved in process task (1, 2, 3, 4, 5, 6, 7, 8) in factory *f* before being shipped as 831,540 kg to warehouse *w* for storing the final products.

Table 11 shows the result of solution 1 in terms of numbers of machines, air-conditioning units, lighting bulbs and the quantity of materials that need to be involved in the design of the sustainable manufacturing system. Figure 4 shows the optimal design of the sustainable manufacturing system based

Table 10 The optimal quantity of material flow for the sustainable manufacturing system design

Supplier *s*									
Solution number	$q^r_{s_j}$ where $j \in \{1, 2, 3, 4\}$				q^r_{sf}	–	–	–	–
	q_{s1}	q_{s2}	q_{s3}	q_{s4}		–	–	–	–
1	1,000,000	980,000	978,040	976,084	937,040	–	–	–	
2	1,020,000	1,002,000	996,100	994,084	955,150	–	–	–	–
3	1,045,000	1,027,000	1,009,000	991,100	973,050	–	–	–	–
4	1,066,000	1,048,000	1,033,000	1,015,000	997,040	–	–	–	–
5	1,083,000	1,065,000	1,047,050	1,029,100	1,014,100	–	–	–	–
6	1,100,000	1,067,000	1,045,660	1,043,568	887,033	–	–	–	–
7	1,120,000	1,086,400	1,053,808	1,022,193	991,527	–	–	–	–
8	1,145,000	1,110,650	1,077,330	1,045,010	1,013,660	–	–	–	–
Factory *f*									Warehouse *w*
Solution number	$q^r_{f_i}$ where $i \in \{1, 2, 3, 4, 5, 6, 7, 8\}$								q^{mp}_{fw}
	q_{f1}	q_{f2}	q_{f3}	q_{f4}	q_{f5}	q_{f6}	q_{f7}	q_{f8}	
1	937,040	918,299	889,824	868,344	850,660	840,467	835,940	831,540	7,483,860 sacks
2	955,150	928,300	904,824	883,344	865,660	855,467	850,940	846,540	7,618,860 sacks
3	973,050	940,200	919,700	898,400	883,660	870,500	868,940	864,499	7,780,491 sacks
4	997,040	955,100	934,824	919,344	901,660	888,399	886,950	880,550	7,924,950 sacks
5	1,014,100	968,188	952,824	931,344	916,660	906,467	904,940	880,555	7,924,995 sacks
6	887,033	869,292	834,520	822,002	813,782	797,507	795,114	787,163	7,084,471 sacks
7	991,528	971,697	952,263	933,218	914,553	896,262	878,337	860,770	7,746,936 sacks
8	1,013,660	993,386	973,519	954,048	934,967	916,268	897,942	879,984	7,919,857 sacks

Table 11 The optimal solution for a sustainable manufacturing system design

The optimal solution for supplier *s*				
Process number *j*	Number of machines involved in process *j*, $n^{machin}_{s_j}$ (units)	Number of air-conditioning units involved in process *j*, $n^{cond}_{s_j}$ (units)	Number of bulbs involved in process *j*, $n^{bulb}_{s_j}$ (units)	Quantity of materials involved in process *j*, q_{s_j} (kg)
1	2	1	30	980,000
2	2	1	30	978,040
3	1	1	15	976,084
4	1	1	15	937,040
The optimal solution for factory *f*				
Process number *i*	Number of machines involved in process *i*, $n^{machin}_{f_i}$ (units)	Number of air-conditioning units involved in process *i*, $n^{cond}_{f_i}$ (units)	Number of bulbs involved in process *i*, $n^{bulb}_{f_i}$ (units)	Quantity of materials involved in process *i*, q_{f_i} (kg)
1	4	2	60	937,040
2	40	20	600	918,299
3	3	2	45	889,824
4	5	3	75	868,344
5	13	7	195	850,660
6	13	7	195	840,467
7	60	30	900	835,940
8	4	2	60	831,540
The optimal solution for warehouse *w*				
Process number	Number of machines involved in process	Number of air-conditioning units, n^{cond}_{w} (units)	Number of bulbs, n^{bulb}_{w} (units)	Number of manufacturing products, q_{fw} (units)
–	–	832	1663	7,483,860 sacks

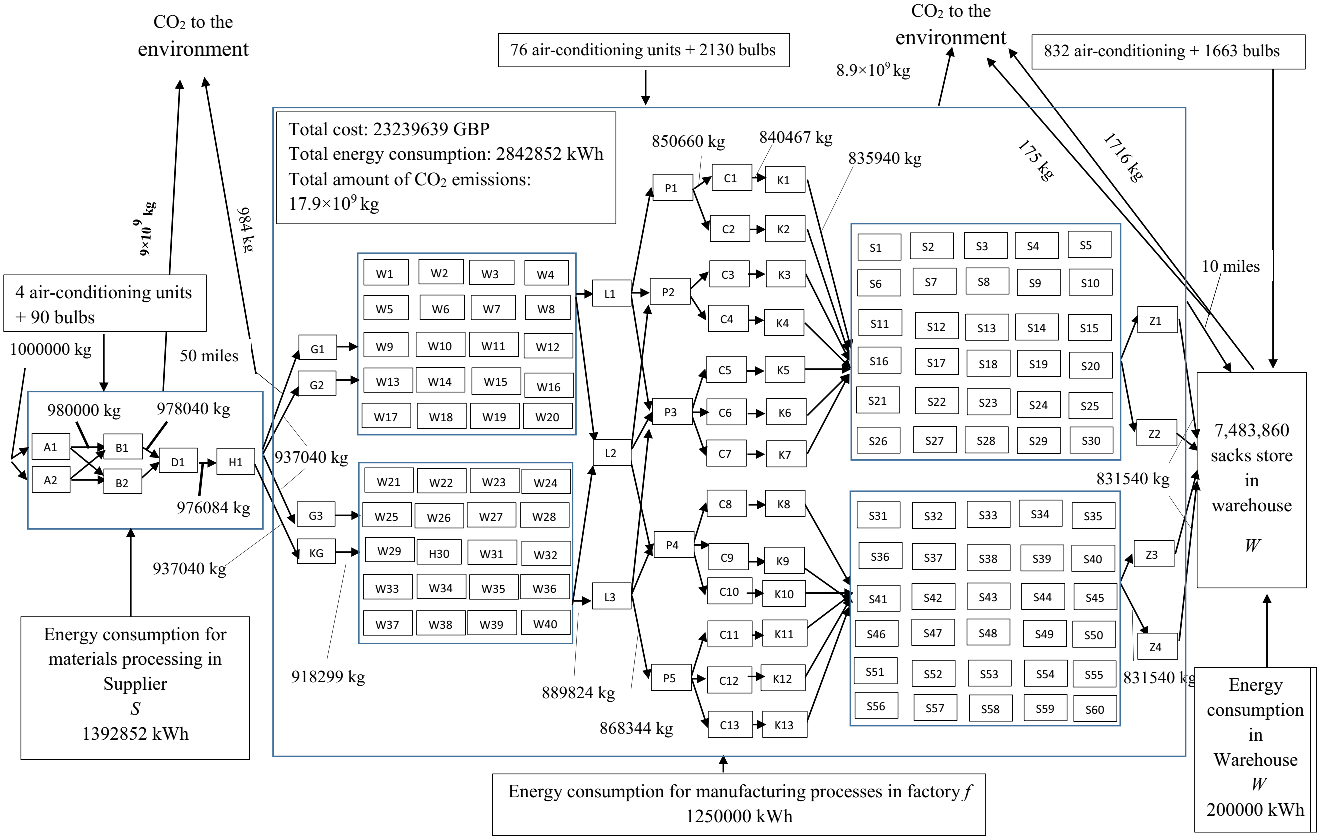


Fig. 4 An optimal sustainable manufacturing system design

on solution 1, which was obtained with $\varepsilon_1 = 23{,}239{,}639$ and $\varepsilon_2 = 17.9 \times 10^9$ that yields the optimal total cost of 23,239,639 GBP, the optimal total amount of energy consumption of 2,842,852 kWh and the optimal total amount of CO_2 of 17.9×10^9 kg.

5 Conclusion and discussion

In a traditional manufacturing system design, engineers used to focus on indicators of system performance in terms of output, capacity, efficiency and other production-related parameters; environmental considerations are often overlooked as part of manufacturing systems analysis, design and performance evaluation. This paper presents a study in developing a multi-objective optimisation model used as an aid for decision-makings of a sustainable manufacturing system, which includes the facilities of supplier *s*, factory *f* and warehouse *w*. The multi-objective model consists of three-objective functions aimed at minimizing the total cost, the total energy consumption and the amount of CO_2 emissions for establishing facilities and transportation vehicles within a manufacturing system. To reveal the non-inferior solutions, two approaches were investigated: these are the ε-constraint approach and the LP-metrics approach. The computational results are obtained and compared using the above approaches and the max-min approach was employed to determine the best solution. A real case study was used for examining the applicability of the developed mathematical model which supports manufacturing system designers to develop a sustainable manufacturing system.

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 [39]. 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.

Future work should focus on improving the developed model by considering a multi-period multi-objective model and formulating the end of life disposal of the products in terms of a closed-loop supply chain when configuring the SMS.

6 The main contributions of this research

1) The concept of lean methods does not include environmental considerations in terms of such as energy consumption and CO_2 (carbon dioxide) emissions, which are also important factors today for developing a sustainable manufacturing system. This research addresses these issues involved in modelling a sustainable manufacturing system allowing an evaluation in energy consumption and CO_2 emissions against the total cost using the multi-objective approach. This is a novel approach proposed in this study which has not been explored in the current literature.
2) This research presents a development of a multi-objective model of a sustainable manufacturing system design in which three facilities were considered: these are supplier *s*, factory *f* and warehouse *w* in order to option the optimal solution among conflicting objective including investment cost for establishing the manufacturing system, total energy consumption consumed by the manufacturing system and total CO_2 emissions released from it.
3) The developed model can be used for designing the sustainable manufacturing system by taking into account the economic and ecological parameters towards a minimisation of the total cost, the total energy consumption and CO_2 emissions associated with relevant machines, air-conditioning units and lighting bulbs involved in each manufacturing process and material flow.
4) The developed model was coded using LINGO^{11} in which optimal solutions were obtained using two different solution approaches which are the ε-constraint approach and the LP-metrics approach, respectively. Subsequently, the performances of these approaches were compared in terms of both the solution quality and run time required. The best solution then was determined using the max-min approach. This helps in obtaining the best sustainable manufacturing system design and it also reflects different prospects of decision makers or manufacturing system designers in different preferences.
5) Applicability of the developed model and proposed solution approaches was examined using collected data from a real case study.
6) The study concluded that the multi-objective mathematical model was useful as an aid for optimizing the manufacturing system design under the economic and ecological constraints.

Acknowledgements The authors would like to express their gratitude to the Ministry of Education in Saudi Arabia for the financial support in this study. Also, the authors would like to thank the anonymous referees whose thorough reviews and insightful comments made a valuable contribution to this article.

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