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

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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 CO₂ (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 CO₂ emissions against the total cost using the multi-objective approach. This a novel approach proposed in this study which has not 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 CO₂ 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 minimization of the total cost, the total energy consumption and CO₂ 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 LINGO¹¹ 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 obtain 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.

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 CO₂ (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 CO₂ 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 minimization of the total cost, the total energy consumption and CO₂ emissions associated with relevant machines, air conditioning units and lighting bulbs involved in each manufacturing process and material flow. The model was coded using LINGO¹¹ 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, CO₂, 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 (Lind *et al.*, 2008). 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 optimization (MOO) problem (Taghdisian *et al.*, 2015). 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 (Wang *et al.*, 2009). Nevertheless, the traditional lean manufacturing concept does not consider environmental wastes particularly in terms of energy consumption and CO₂ emissions for such as manufacturing system design and evaluation; these wastes add no values on manufactured products and need also to be identified (Heilala *et al.*, 2008; Nujoom *et al.*, 2016a).

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 (Nujoom *et al.*, 2016a). Manufacturing companies ought to improve system efficiency and productivity without sacrificing the environment as return to achieve these goals (Pagell *et al.*, 2004). Heilala *et al.*, (2008) 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 (2017) 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 optimize return on profits for companies, it provide royalties to landowners, and satisfy the planet's environmental concerns. The study is very much in line with our model in term 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 organization 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 organization has translated its social goals into practice. Social performance can be evaluated in terms of the impact of organization'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 organization. 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 CO₂ emissions during the manufacturing phase as energy consumption directly impacts economic progress (Jayal *et al.*, 2010., Nishant *et al.*, 2014., Pusavec *et al.*, 2010 and Jawahir *et al.*, 2011). Pishvae and Razmi (2012) 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 (2002) developed a new linear programming model (namely the steel environmental strategy assessment program) to analyse and reduce the impact of CO₂ emissions in the life cycle of iron and steel in Japan for the next three decades. Hidalgo *et al.*, (2005) created a simulation model aimed to analyse the evolution of the world energy outlook for steel and iron industry from 1997 to 2030. Koc and Kaplan (2007) presented an investigation on energy consumption for a particular ring type yarn manufacturing system. Wang *et al.*, (2008) proposed a process integration (PI) technique that was used for evaluating CO₂ emissions for a steel industry. Li *et al.*, (2009) 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.*, (2016) applied a fuzzy tri-criterion programming model for minimization of the warehouse total cost, maximization of the warehouse capacity utilization, and minimization of the travel time of products from storage racks to collection points. Jamshidi *et al.*, (2012) developed a multi-objective mathematical model considering the annual cost minimization and the effect of NO₂, CO and volatile organic particles produced by facilities and transportation in the supply chain. Alçada-Almeida *et al.* (2009) 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.*, (2011) studied a multi-objective optimization model used for determining the trade-off decision between the total cost and the amount of CO₂ emissions released from the supply chain facilities. Abdallah *et al.*, (2010) applied a multi-objective optimization method for minimizing carbon emissions and investment cost of the supply chain network facilities. Shaw *et al.*, (2012) selected the appropriate suppliers in the supply chain network using a fuzzy multi-objective linear programming approach that addresses the minimization of ordered quantity to the supplier and the total carbon emissions for sourcing of material. Zhou *et al.*, (2009) selected suitable materials to develop sustainable products using a multi-objective approach with genetic algorithms. Hamdy *et al.*, (2011) applied a multi-objective optimization method to minimize the CO₂ emissions and the investment cost for a two-storey house and its Heating/cooling system. Pinto *et al.*, (2011) developed a fuzzy linear programming and a mixed integer linear programming for designing supply chain structures for annual profit maximization, while considering environmental aspects. Fesanghary *et al.*, (2012) developed a multi-objective programming approach to minimize the life cycle cost and CO₂ emissions of the residential buildings. Sharafi and ELMekkawy (2014) proposed a novel approach for optimal design of hybrid renewable energy systems (HRES) including various generators and storage devices to minimize simultaneously the total cost of the system, unmet load, and fuel emissions. Sahar *et al.*, (2014) proposed a multi-objective optimization model of a two-layer dairy supply chain aimed at minimizing CO₂ emissions of transportation and the total cost for product distribution. Bortolini *et al.*, (2016) proposed a three-objective distribution planner to

tackle the tactical optimization issue of a fresh food distribution network. The optimization objectives were to minimize 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.*, (2012) 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 CO₂ emissions. Harris *et al.*, (2014) proposed a multi-objective optimization approach for solving a facility location–allocation problem for a supply chain network where financial costs and CO₂ emissions are considered as objectives.

This paper presents an investigation into a sustainable manufacturing system design through the development of a multi-objective optimization 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 CO₂ emissions. The developed model was coded using LINGO¹¹ 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 CO₂ 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 CO₂ emissions of facilities in a manufacturing system, a multi-objective optimization model was formulated based on the proposed sustainable manufacturing system design. The model was used for obtaining a trade-off decision towards the minimization of the total investment cost for establishing the manufacturing system, the total energy consumption by the manufacturing system, and the total amount of CO₂ 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.

Figure 1. A sustainable manufacturing system design

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... s ... S)
f	set of factory (1... f ... F)
w	set of warehouse (1... w ... 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, $j \in \{1, 2, \dots, \Pi_s\}$ and $i \in \{1, 2, \dots, \Pi_f\}$
C_l^{cond}	cost of an air-conditioning unit (GBP) involved in facility l
C_l^{bulb}	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_{sj}^{mach} and E_{fi}^{mach}	energy consumption (kWh) for a machine involved in process j at supplier s and in process i at factory f respectively, where $j \in \{1, 2, \dots, \Pi_s\}$ and $i \in \{1, 2, \dots, \Pi_f\}$
E_{sj}^{cond} and E_{fi}^{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_{sj}^{bulb} and E_{fi}^{bulb}	energy consumption (kWh) for the lighting bulbs involved in process j at supplier s and in process i at factory f respectively
E_{sj}^{comp} and E_{fi}^{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_{sj}^{mach} and N_{fi}^{mach}	installed power (kw) for a machine involved in process j at supplier s and in process i at factory f respectively
$\Re_{sj}$ and $\Re_{fi}$	manufacturing rate (kg/h) for a machine involved in process j at supplier s and in process i at factory f respectively
τ_{sj} and τ_{fi}	operating time (hr) for a machine involved in process j at supplier s and in process i at factory f respectively
μ_{sj} and μ_{fi}	efficiency (%) for a machine involved in process j at supplier s and in process i at factory f respectively
N_{sj}^{cond} and N_{fi}^{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_{sj}^{bulb} and N_{fi}^{bulb}	installed power (kW) for a lighting bulb involved in process j at supplier s and in process i at factory f respectively
N_{sj}^{comp} and N_{fi}^{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_{sj} and Ψ_{fi}	total waste ratio (%) for a machine involved in process j at supplier s and in process i at factory f respectively
v_{sj}^{comp} and v_{fi}^{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
Φ_{sj}^{cond} and Φ_{fi}^{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
ϕ_{sj}^{bulb} and ϕ_{fi}^{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_{sj}^{mach} and e_{fi}^{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_{sj}^{cond} and e_{fi}^{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_{sj}^{bulb} and e_{fi}^{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_{sj}^{comp} and e_{fi}^{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_{sj} , ω_{fi} 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

CO₂ emission factor (kg/mile) released for transportation from supplier s to factory f and from factory f to warehouse w respectively

Decision variables

q_{sj}^r and q_{fi}^r

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

$q_{s(j+1)}^r$ 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_{sj}^{mach} and n_{fi}^{mach}

number of machines (unit) involved in process j in supplier s and in process i in factory f respectively.

n_{sj}^{cond} , n_{fi}^{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_{sj}^{bulb} , n_{fi}^{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:

Objective function 1: Minimization 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:

$$\begin{aligned} \text{Min } \Lambda_1 = & C_l^{es} + C_s^{mach} + C_f^{mach} + C_s^{cond} + C_f^{cond} + C_w^{cond} \\ & + C_s^{bulb} + C_f^{bulb} + C_w^{bulb} + C_{sf}^r + C_{fw}^{mp} + C_l^t + C_{fw}^I \end{aligned} \quad (1)$$

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

$$C_l^{es} = C_s^{es} + C_f^{es} + C_w^{es} \quad (2)$$

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:

$$\begin{aligned} C_s^{es} = & C_s^{land} + C_s^{building} \\ & + C_s^{equipment} + C_s^{services} + C_s^{saleries} \end{aligned} \quad (3)$$

$$C_f^{es} = C_f^{land} + C_f^{building} + C_f^{equipment} + C_f^{services} + C_f^{saleries} \quad (4)$$

$$C_w^{es} = C_w^{land} + C_w^{building} + C_w^{equipment} + C_w^{services} + C_w^{saleries} \quad (5)$$

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:

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

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

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:

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

$$C_f^{cond} = \sum_{i=1}^{\Pi_f} \left(C_{fi}^{cond} n_{fi}^{cond} \right) \quad (9)$$

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

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:

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

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

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

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

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

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

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

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

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

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

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

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

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

Hence, equation (1) can be expressed as follows:

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

Objective function 2: Minimization of total energy consumption Λ_2

The total energy consumption can be minimized as follows:

$$\text{Min } \Lambda_2 = E_s + E_f + E_w \quad (19)$$

Where, total energy consumption E_s for supplier s is given by:

$$E_s = \sum_{j=1}^{\Pi_s} \left[E_{s,j}^{mach} + E_{s,j}^{cond} + E_{s,j}^{bulb} + E_{s,j}^{comp} \right], \text{ where } j \in \{1, 2, \dots, \Pi_s\} \quad (20)$$

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 are given respectively by:

$$E_{s,j}^{mach} = \sum_{j=1}^{\Pi_s} \left(\frac{q_{s,j}^r}{\Re_{s,j} \mu_{s,j}} N_{s,j}^{mach} n_{s,j}^{mach} \right) \quad (21)$$

$$E_{s,j}^{cond} = \sum_{j=1}^{\Pi_s} \left(N_{s,j}^{cond} n_{s,j}^{cond} \frac{q_{s(j+1)}^r}{\phi_s} \right) \quad (22)$$

$$E_{s,j}^{bulb} = \sum_{j=1}^{\Pi_s} \left(N_{s,j}^{bulb} n_{s,j}^{bulb} \frac{q_{s(j+1)}^r}{\phi_s} \right) \quad (23)$$

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

$$E_{s,j}^{comp} = \sum_{j=1}^{\Pi_s} \left(\frac{q_{s,j}^r}{\Re_{s,j} \mu_{s,j}} \frac{N_{s,j}^{comp}}{\rho_{s,j}^{comp}} v_{s,j}^{comp} n_{s,j}^{mach} \right) \quad (24)$$

Total energy consumption E_f for factory f is given by:

$$E_f = \sum_{i=1}^{\Pi_f} \left[E_{f,i}^{mach} + E_{f,i}^{cond} + E_{f,i}^{bulb} + E_{f,i}^{comp} \right], \text{ where, } i \in \{1, 2, \dots, \Pi_f\} \quad (25)$$

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:

$$E_{fi}^{mach} = \sum_{i=1}^{\Pi f} \left(N_{fi}^{mach} n_{fi}^{mach} \frac{q_{fi}^r}{\Re_{fi} \mu_{fi}} \right) \quad (26)$$

$$E_{fi}^{cond} = \sum_{i=1}^{\Pi f} \left(N_{fi}^{cond} n_{fi}^{cond} \frac{q_{f(i+1)}^r}{\wp_f} \right) \quad (27)$$

$$E_{fi}^{bulb} = \sum_{i=1}^{\Pi f} \left(N_{fi}^{bulb} n_{fi}^{bulb} \frac{q_{f(i+1)}^r}{\wp_f} \right) \quad (28)$$

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

$$E_{fi}^{comp} = \sum_{i=1}^{\Pi f} \left(\frac{q_{fi}^r}{\Re_{fi} \mu_{fi}} \frac{N_{fi}^{comp}}{\rho_{fi}^{comp}} v_{fi}^{comp} n_{fi}^{mach} \right) \quad (29)$$

Total energy consumption E_w for warehouse w is given by:

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

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

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

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

Hence, equation (19) is given as follows:

$$\begin{aligned}
 Min Z_2 = & \sum_{j=1}^{\Pi_s} \left(\frac{q_{sj}^r}{\Re_{sj} \mu_{sj}} N_{sj}^{mach} n_{sj}^{mach} + N_{sj}^{cond} n_{sj}^{cond} \frac{q_{s(j+1)}^r}{\wp_s} + N_{sj}^{bulb} n_{sj}^{bulb} \frac{q_{s(j+1)}^r}{\wp_s} \right) \\
 & + \frac{q_{sj}^r}{\Re_{sj} \mu_{sj}} \frac{N_{sj}^{comp}}{\rho_{sj}^{comp}} v_{sj}^{comp} n_{sj}^{mach} \\
 & + \sum_{i=1}^{\Pi_f} \left(\frac{q_{fi}^r}{\Re_{fi} \mu_{fi}} N_{fi}^{mach} n_{fi}^{mach} + N_{fi}^{cond} n_{fi}^{cond} \frac{q_{f(i+1)}^r}{\wp_f} + N_{fi}^{bulb} n_{fi}^{bulb} \frac{q_{f(i+1)}^r}{\wp_f} \right) \\
 & + \frac{q_{fi}^r}{\Re_{fi} \mu_{fi}} \frac{N_{fi}^{comp}}{\rho_{fi}^{comp}} v_{fi}^{comp} n_{fi}^{mach} \\
 & + \sum_{w=1}^W \left(N_w^{cond} n_w^{cond} \frac{q_w^{mp}}{\wp_w} + N_w^{bulb} n_w^{bulb} \frac{q_w^{mp}}{\wp_w} \right)
 \end{aligned}$$

Objective function 3: Minimization of total CO₂ emissions Λ_3

The total amount of CO₂ emissions can be minimized below:

$$Min \Lambda_3 = e_s + e^t + e_f + e_w \quad (33)$$

Where, the total amount of CO₂ emissions e_s released from supplier s is calculated as follows:

$$e_s = \sum_{j=1}^{\Pi_s} \left[e_{sj}^{mach} + e_{sj}^{cond} + e_{sj}^{bulb} + e_{sj}^{comp} \right] \quad (34)$$

Amount of CO₂ emissions e_{sj}^{mach} , e_{sj}^{cond} and e_{sj}^{bulb} released from the machines, air-conditioning units and lighting bulbs involved in process j at supplier s , is respectively given by:

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

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

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

Amount of CO₂ emissions e_{sj}^{comp} released from a compressor system involved in process j of supplier s as below:

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

The total amount of CO₂ emissions e^t which are released for transportation from supplier s to factory f and from factory f to warehouse w , is given below:

$$e^t = e_{sf}^t + e_{fw}^t \quad (39)$$

Where, amount of CO₂ 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:

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

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

The total amount of CO₂ emissions e_f released from factory f is calculated as below:

$$e_f = \sum_{i=1}^{\Pi_f} \left[e_{fi}^{mach} + e_{fi}^{cond} + e_{fi}^{bulb} + e_{fi}^{comp} \right] \quad (42)$$

Amount of CO₂ emissions e_{fi}^{mach} , e_{fi}^{cond} and e_{fi}^{bulb} released from the machines, air-conditioning units and lighting bulbs involved in process i at factory f is given respectively by:

$$e_{fi}^{mach} = \sum_{i=1}^{\Pi_f} \left(\omega_{fi} \frac{q_{fi}^r}{\Re_{fi} \mu_{fi}} N_{fi}^{mach} n_{fi}^{mach} \right) \quad (43)$$

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

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

Amount of CO₂ emissions e_{fi}^{comp} released from a compressor system involved in process i at factory f as below:

$$e_{f_i}^{comp} = \sum_{i=1}^{\Pi_f} \left(0.689 \frac{q_{f_i}^r}{\Re_{f_i} \mu_{f_i}} \frac{N_{f_i}^{comp}}{\rho_{f_i}^{comp}} v_{f_i}^{comp} n_{f_i}^{mach} \right) \quad (46)$$

Where 0.689 is the emission factor for the electricity

Amount of CO₂ emissions e_w released from warehouse w is calculated as below:

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

Thus, equation (32) is given as follows:

$$\begin{aligned} Min Z_3 = & \sum_{j=1}^{\Pi_s} \left[\omega_{s_j} \frac{q_{s_j}^r}{\Re_{s_j} \mu_{s_j}} N_{s_j}^{mach} n_{s_j}^{mach} \right. \\ & \left. + 0.689 \left(N_{s_j}^{cond} n_{s_j}^{cond} \frac{q_{s(j+1)}^r}{\wp_s} + N_{s_j}^{bulb} n_{s_j}^{bulb} \frac{q_{s(j+1)}^r}{\wp_s} + N_{s_j}^{bulb} n_{s_j}^{bulb} \frac{q_{s(j+1)}^r}{\wp_s} \right) \right] \\ & + \sum_{s=1}^S \sum_{f=1}^F \left(\omega_{sf}^t \frac{q_{sf}^r}{V} T_{sf} \right) + \sum_{f=1}^F \sum_{w=1}^W \left(\omega_{fw}^t \frac{q_{fw}^{mp}}{V} T_{fw} \right) \\ & + \sum_{i=1}^{\Pi_f} \left[\omega_{f_i} \frac{q_{f_i}^r}{\Re_{f_i} \mu_{f_i}} N_{f_i}^{mach} n_{f_i}^{mach} \right. \\ & \left. + 0.689 \left(N_{f_i}^{cond} n_{f_i}^{cond} \frac{q_{f(i+1)}^r}{\wp_f} + N_{f_i}^{bulb} n_{f_i}^{bulb} \frac{q_{f(i+1)}^r}{\wp_f} + \frac{q_{f_i}^r}{\Re_{f_i} \mu_{f_i}} \frac{N_{f_i}^{comp}}{\rho_{f_i}^{comp}} v_{f_i}^{comp} n_{f_i}^{mach} \right) \right] \\ & + 0.689 \sum_{w=1}^W \left(N_w^{cond} n_w^{cond} \frac{q_{fw}^{mp}}{\wp_w} + N_w^{bulb} n_w^{bulb} \frac{q_{fw}^{mp}}{\wp_w} \right) \end{aligned}$$

Where, the CO₂ emission factor ω_{s_j} , ω_{f_i} , ω_w and ω_{sf}^t is shown in Table 1 (EPA, 2008; Nujoom *et al.*, 2016b).

Table.1. Amount CO₂ emission factor per kWh and per mile

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

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.

$$q_{sf}^r \leq Ca_s \quad (48)$$

$$q_{fw}^{mp} \leq Ca_f \quad (49)$$

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

$$q_{sf}^r \geq D_f \quad (50)$$

$$q_{fw}^{mp} \geq D_w \quad (51)$$

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.

$$(1 - \Psi_{sj})q_{sj}^r \geq q_{s(i+1)}^r \quad (52)$$

$$(1 - \Psi_{fi})q_{fi}^r \geq q_{f(i+1)}^r \quad (53)$$

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.

$$\Phi_{sj}^{cond} n_{sj}^{cond} \geq n_{sj}^{mach} \quad (54)$$

$$\Phi_{fi}^{cond} n_{fi}^{cond} \geq n_{fi}^{mach} \quad (55)$$

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.

$$n_{sj}^{bulb} \geq \phi_{sj}^{bulb} n_{sj}^{mach} \quad (56)$$

$$n_{fi}^{bulb} \geq \phi_{fi}^{bulb} n_{fi}^{mach} \quad (57)$$

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.

$$\Gamma_w^{cond} n_w^{cond} \geq q_{fw}^{mp} \quad (58)$$

$$\lambda_w^{bulb} n_w^{bulb} \geq q_{fw}^{mp} \quad (59)$$

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 .

$$q_{sj}^r, q_{sf}^r, q_{fi}^r, q_{fw}^{mp} \geq 0 \quad (60)$$

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.

$$\Re_{sj} n_{sj}^{mach} \geq q_{s(i+1)}^r \quad (61)$$

$$\Re_{fi} n_{fi}^{mach} \geq q_{f(i+1)}^r \quad (62)$$

Where, equations (48), (49), (50), (51), (52), (53) and (60) are quantity constraints; and equations (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 CO₂ emissions based on the developed multi-objective model. There are several approaches for multi-objective optimization; this includes the ε -constraint method, the weighted-sum method, the LP-metrics method, the weighted tchebycheff method (Nurjanni, *et al* 2014). 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 minimization of the total energy consumption in this study as the single objective function (equation. 63); the other two objective functions (total cost and total CO₂ emissions) are shifted to be ε -based constraints; i.e., equation 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 (equation 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 (equation 67) (Amin and Zhang, 2013; Mohammed and Wang, 2016). Thus, the equivalent solution formula Λ is expressed as follows:

$$\text{Min } \Lambda_2 \quad (63)$$

Equation 63 is subject to the following constraints:

$$\Lambda_1 \leq \varepsilon_1 \quad (64)$$

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

$$\Lambda_3 \leq \varepsilon_2 \quad (66)$$

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

And additional constraints are included equations 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 objectives model into a modular-objective function using the following equation

$$\text{Min } \Lambda = \left[y_1 \frac{\Lambda_1 - \Lambda_1^*}{\Lambda_1^*} + y_2 \frac{\Lambda_2 - \Lambda_2^*}{\Lambda_2^*} + y_3 \frac{\Lambda_3 - \Lambda_3^*}{\Lambda_3^*} \right] \quad (68)$$

Subject to equations 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:

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

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

Subject to equations 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 g_{Λ_x} . For further details about this approach, it may refer to

Lai and Hwang, 1992). The Max-Min approach formula is described as follows:

$$\begin{aligned} & \text{Max}_x \left\{ \min \left\{ g_{\Lambda_x} - g_{\Lambda_x}^{ref} \right\} \right\} \\ & = \text{Max}_x \left\{ \min \left\{ \left(\frac{\Lambda_x^{\max} - \Lambda(x)}{\Lambda_x^{\max} - \Lambda_x^{\min}} \right) - g_{\Lambda_x}^{ref} \right\} \right\} \end{aligned} \quad (71)$$

$$\text{s.t. } \begin{cases} g_{\Lambda_x} = \begin{cases} 1 & \Lambda(x) \leq \Lambda_x^{\min} \\ \left(\frac{\Lambda_x^{\max} - \Lambda(x)}{\Lambda_x^{\max} - \Lambda_x^{\min}} \right) & \Lambda_x^{\min} \leq \Lambda(x) \leq \Lambda_x^{\max} \\ 0 & \Lambda(x) \geq \Lambda_x^{\max} \end{cases} \end{cases} \quad (72)$$

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, $g_{\Lambda_x}^{ref}$ 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 warehouse w), the energy consumption and the amount of CO₂ 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 1 supplier, 1 factory and 1 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 using oil as source of energy. LINGO¹¹ was used for computing results aiming to seek the optimization solutions.

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

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

Facilities		
Supplier s	Factory f	Warehouse w
C_s^{es} (GBP): 100000	C_f^{es} (GBP): 100000	C_w^{es} (GBP): 55000
C_{sj}^{mach} (GBP): 7000, 7000, 7000, 7000, where $j \in \{1, 2, \dots, \Pi_s\}$	C_{fi}^{mach} (GBP): 5000, 3000, 4000, 3000, 3000, 100, 200, 2000, where $i \in \{1, 2, \dots, \Pi_f\}$	-----
C_{sj}^{cond} (GBP): 1000, 1000, 1000, 1000	C_{fi}^{cond} (GBP): 1000, 1000, 1000, 1000, 1000, 1000, 1000, 1000, 1000	C_w^{cond} (GBP): 700
C_{sj}^{bulp} (GBP): 50, 50, 50, 50	C_{fi}^{bulp} (GBP): 50, 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^l (GBP/kg): 2
C_{sf}^t (GBP/mile): 2	C_{fw}^t (GBP/mile): 2	-----
T_{sf} (mile): 50, V (kg): 20000	T_{fw} (mile): 10, $V = 20000$	-----
Ca_s (kg/month): 1000000	Ca_f (kg/month): 990,000	Ca_w (kg/month): 900000
-----	D_f (kg/month): 850000	D_w (kg/month): 850000

$\Pi_s = 4$ process	$\Pi_f = 8$ process	-----
$\Re_{s_j}$ (kg/h): 1976, 1936, 1932 and 1929, where $j \in \{1, 2, \dots, \Pi_s\}$	$\Re_{f_i}$ (kg/h): 1852, 1815, 1742, 1716, 1699, 1665, 1660 and 1643, where $i \in \{1, 2, \dots, \Pi_f\}$	-----
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	-----
$v_{s_j}^{comp}$ (m ³ /h): 0	$v_{f_i}^{comp}$ (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): 950000	$\wp_f$ (kg): 840000	$\wp_w$ (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	-----

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 optimized 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 CO₂ emissions of 17.9×10^9 kg.

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

By comparison as shown in Table 4, 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 CO₂ emissions of 18.2×10^9 kg.

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

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 ($n_{s_j}^{mach}$) where $j \in \{1, 2, 3, 4\}$ is (2, 2, 1, 1), the group in numbers of air conditioning units ($n_{s_j}^{cond}$) is (1, 1, 1, 1) and the group in numbers of lighting bulbs ($n_{s_j}^{bulb}$) 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 ($n_{f_i}^{mach}$) 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 ($n_{f_i}^{cond}$) is (2, 20, 2, 3, 7, 7, 30, 2) and the group in numbers of lighting bulbs ($n_{f_i}^{bulb}$) is (60, 600, 45, 75, 195, 195, 900, 60). Table 7 also shows that solution 1 requires 832 air conditioning units (n_w^{cond}) and 1664 lighting bulbs (n_w^{bulb}) that need to be installed in warehouse w .

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_{sj}^{mach} Where $j \in \{1, 2, 3, 4\}$.				Numbers of air-conditioning units involved in process j n_{sj}^{cond} Where $j \in \{1, 2, 3, 4\}$.				Numbers of bulbs involved in process j n_{sj}^{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_{fi}^{mach}								Number of air-conditioning units involved process i in factory f , n_{fi}^{cond}			
	n_{f1}	n_{f2}	n_{f3}	n_{f4}	n_{f5}	n_{f6}	n_{f7}	n_{f8}	n_{f1}	n_{f2}	n_{f3}	n_{f4}
1	4	40	3	5	13	13	60	4	2	20	2	3
2	5	40	4	5	14	14	60	4	3	20	2	3
3	5	45	5	6	16	16	60	5	3	23	3	3
4	5	50	6	6	16	16	65	5	3	25	3	3
5	5	50	6	7	17	17	65	6	3	25	3	4
6	6	55	6	8	17	17	67	6	3	28	3	4
7	6	56	6	8	18	18	67	7	3	28	3	4
8	6	56	7	9	18	18	68	7	3	28	4	

Number of lighting bulbs involved process i in factory f										Number of air-conditioning units in warehouse w		Number of lighting bulbs in warehouse w	
										n_w^{cond}		n_w^{bulb}	
n_{j5}	n_{j6}	n_{j7}	n_{j8}	n_{j1}	n_{j2}	n_{j3}	n_{j4}	n_{j5}	n_{j6}	n_{j7}	n_{j8}		
7	7	30	2	60	600	45	75	195	195	900	60	832	1664
7	7	30	2	75	600	60	75	210	210	900	60	847	1694
8	8	30	3	75	675	75	90	240	240	900	75	865	1729
8	8	33	3	75	750	90	90	240	240	975	75	881	1762
9	9	33	3	75	750	90	105	255	255	975	90	881	1762
9	9	34	3	90	825	90	120	255	255	1005	90	788	1575
9	9	34	4	90	840	90	120	270	270	1005	105	861	1722
9	9	34	4	90	840	105	135	270	270	1020	105	880	1760

Table 8 shows the obtained results of solution 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 ($n_{s_j}^{mach}$) where $j \in \{1, 2, 3, 4\}$; the group (1, 1, 1, 1) in numbers of air conditioning units ($n_{s_j}^{cond}$) and the group (30, 30, 30, 15) in numbers of lighting bulbs ($n_{s_j}^{bulb}$). 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 ($n_{f_i}^{mach}$) 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 ($n_{f_i}^{cond}$) is (2, 23, 2, 3, 7, 7, 30, 2) and the group in numbers of lighting bulbs ($n_{f_i}^{bulb}$) 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

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_{sj}^{mach} Where $j \in \{1, 2, 3, 4\}$.				Numbers of air conditioning units involved in process j n_{sj}^{cond} Where $j \in \{1, 2, 3, 4\}$.				Numbers of bulbs involved in process j n_{sj}^{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

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_{fi}^{mach}								Number of air-conditioning units involved process i in factory f , n_{fi}^{cond}			
	Where, $i \in \{1, 2, 3, 4, 5, 6, 7, 8\}$								n_{f1}	n_{f2}	n_{f3}	n_{f4}
1	4	45	4	5	14	14	60	4	2	23	2	3
2	6	45	4	5	14	14	60	4	3	23	2	3
3	6	45	5	6	16	16	60	5	3	23	3	3
4	6	50	6	6	16	16	65	5	3	25	3	3
5	7	50	7	7	17	17	65	6	4	25	4	4
6	7	55	7	8	17	17	67	6	4	28	4	4
7	7	56	7	8	18	18	67	7	4	28	4	4
8	7	56	7	9	19	19	68	7	4	28	4	5

Number of lighting bulbs involved process i in factory f										Number of air-conditioning units in warehouse w		Number of lighting bulbs in warehouse w	
n_{fi}^{bulb}										n_w^{cond}		n_w^{bulb}	
Where, $i \in \{1, 2, 3, 4, 5, 6, 7, 8\}$													
n_{j5}	n_{j6}	n_{j7}	n_{j8}	n_{j1}	n_{j2}	n_{j3}	n_{j4}	n_{j5}	n_{j6}	n_{j7}	n_{j8}		
7	7	30	2	60	675	60	75	210	210	900	60	832	1664
7	7	30	2	90	675	60	75	210	210	900	60	847	1694
8	8	30	3	90	675	75	90	240	240	900	75	865	1729
8	8	33	3	90	750	90	90	240	240	975	75	881	1762
9	9	33	3	105	750	105	105	255	255	975	90	881	1762
9	9	34	3	105	825	105	120	255	255	1005	90	788	1575
9	9	34	4	105	840	105	120	270	270	1005	105	861	1722
10	10	34	4	105	840	105	135	285	285	1020	105	880	1760

Figures 2a, 2b and 2c illustrate 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 figures 2a and 2b 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 CO₂ 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 total energy consumption under the LP-metrics approach (3,335,765 kWh) and the minimum total CO₂ 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 CO₂ emissions released from the manufacturing system and the transportation vehicles, under the LP-metrics approach (18.2×10^9 kg).

Figure 2. Comparative solutions obtained using the ϵ -constraint approach and the LP-metrics approach, respectively

Figures 3a, 3b, 3c, 3d, 3e and 3f show 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 Figures 3a and 3b 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 number of lighting bulbs are 15 bulbs while the number of machines needed to be established under LP-metrics approach are 2 machines, number of air-conditioning units are 1 units and number of lighting bulbs are 30 bulbs. The results in Figures 3c and 3d 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). Figures 3e and 3f indicate 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.

(a)

(b)

(c)

(d)

Figure 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

In practice, based on the obtained solutions using the two optimization 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 $g_{\Lambda_1}^{ref} = 0, g_{\Lambda_2}^{ref} = 0.5$ and $g_{\Lambda_3}^{ref} = 0.5$), solution 1, which is obtained using the ε -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) in supplier s are 980000 kg, 978040 kg, 976084 kg, 937040 kg, 937040 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 831540 kg to warehouse w for storing the final products.

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

Supplier s									
Solution number	q_{sj}^r where $j \in \{1, 2, 3, 4\}$				q_{sf}^r	-	-	-	-
	q_{s1}	q_{s2}	q_{s3}	q_{s4}		-	-	-	-
1	1000000	980000	978040	976084	937040	-	-	-	-
2	1020000	1002000	996100	994084	955150	-	-	-	-
3	1045000	1027000	1009000	991100	973050	-	-	-	-
4	1066000	1048000	1033000	1015000	997040	-	-	-	-
5	1083000	1065000	1047050	1029100	1014100	-	-	-	-
6	1100000	1067000	1045660	1043568	887033	-	-	-	-
7	1120000	1086400	1053808	1022193	991527	-	-	-	-
8	1145000	1110650	1077330	1045010	1013660	-	-	-	-
Factory f									Warehouse w
Solution number	q_{fi}^r where $i \in \{1, 2, 3, 4, 5, 6, 7, 8\}$								q_{fw}^{mp}
	q_{f1}	q_{f2}	q_{f3}	q_{f4}	q_{f5}	q_{f6}	q_{f7}	q_{f8}	
1	937040	918299	889824	868344	850660	840467	835940	831540	7483860 Sacks
2	955150	928300	904824	883344	865660	855467	850940	846540	7618860

									Sacks
3	973050	940200	919700	898400	883660	870500	868940	864499	7780491 Sacks
4	997040	955100	934824	919344	901660	888399	886950	880550	7924950 Sacks
5	1014100	968188	952824	931344	916660	906467	904940	880555	7924995 Sacks
6	887033	869292	834520	822002	813782	797507	795114	787163	7084471 Sacks
7	991528	971697	952263	933218	914553	896262	878337	860770	7746936 Sacks
8	1013660	993386	973519	954048	934967	916268	897942	879984	7919857 Sacks

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 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 CO₂ of 17.9×10^9 kg

Table 10. 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_{sj}^{machin} (units)	Number of air conditioning units involved in process j n_{sj}^{cond} (units)	Number of bulbs involved in process j n_{sj}^{bulb} (units)	Quantity of materials involved in process j q_{sj} (kg)
1	2	1	30	980000
2	2	1	30	978040
3	1	1	15	976084
4	1	1	15	937040
The optimal solution for factory f				
Process number i	Number of machines involved in process i n_{fi}^{machin} (units)	Number of air conditioning units involved in process i n_{fi}^{cond} (units)	Number of bulbs involved in process i n_{fi}^{bulb} (units)	Quantity of materials involved in process i q_{fi} (kg)
1	4	2	60	937040
2	40	20	600	918299
3	3	2	45	889824
4	5	3	75	868344
5	13	7	195	850660
6	13	7	195	840467
7	60	30	900	835940
8	4	2	60	831540
The optimal solution for warehouse w				
Process number	Number of machines involved in process	Number of air conditioning units n_w^{cond} (units)	Number of bulbs n_w^{bulb} (units)	Number of manufacturing products q_{fw} (units)
-	-	832	1663	7,483,860 sacks

Figure 4. An optimal sustainable manufacturing system design

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 optimization 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 CO₂ 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 (Wang and Chatwin, 2005). Thus, an integrated method incorporating environmental parameters for a discrete even simulation model is recommended as part of this study, which is under the development.

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.

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References

- Abdallah, T., Diabat, A., & Simchi-Levi, D. (2010). A carbon sensitive supply chain network problem with green procurement, proceedings of the 40th International Conference in Computers and Industrial Engineering (CIE), 1-6. IEEE.
- Alçada-Almeida, L., Coutinho-Rodrigues, J., & Current, J. (2009). A multi-objective modeling approach to locating incinerators, *Socio-Economic Planning Sciences*, 43, 111–120.
- Amin, S. H., & Zhang, G. (2013). A multi-objective facility location model for closed-loop supply chain network under uncertain demand and return, *Applied Mathematical Modelling*, 37(6), 416.
- Bortolini, M., Faccio, M., Ferrari, M., Gamberi, M. and Pilati, F. (2016). Fresh Food Sustainable Distribution: Cost, Delivery Time And Carbon Footprint Three-Objective Optimization. *Journal of Food Engineering*, 174, 56-67.
- EPA. (2008). The Lean and Environment Toolkit. U.S. Environmental Protection Agency, <http://www.epa.gov/lean/toolkit/index.htm> accessed June 26.
- Fesanghary, M., Asadi, S., & Geem, Z. W. (2012). Design of low-emission and energy-efficient residential buildings using a multi-objective optimization algorithm. *Building and environment*, 49, 245-250.
- Gielen, D., & Moriguchi, Y. (2002). CO₂ in the iron and steel industry: an analysis of Japanese emission reduction potentials, *Energy Policy*, 30, 349–363.
- Hamdy, M., Hasan, A., & Siren, K. (2011). Applying a multi-objective optimization approach for design of low-emission cost-effective dwellings. *Building and environment*, 46(1), 109-123.

- Harris, I., Mumford, C.L. and Naim, M.M. (2014). A hybrid multi-objective approach to capacitated facility location with flexible store allocation for green logistics modeling. *Transportation Research Part E: Logistics and Transportation Review*, 66, 1–22.
- Heilala, J., Vatanen, S., Tonteri, H., Montonen, J., Lind, S., Johansson, B., & Stahre, J. (2008). Simulation-based sustainable manufacturing system design, *Proceedings of the 2008 Winter Simulation Conference*. 1922-1930.
- Hidalgo, I., Szabo, L., Ciscar, C., & Soria, A. (2005) Technological prospects and CO₂ emission trading analyses in the iron and steel industry, a global model. *Energy*, 30, 583–610.
- Jamshidi, R., Ghomi, S. F., & Karimi, B. (2012). Multi-objective green supply chain optimization with a new hybrid memetic algorithm using the Taguchi method, *Scientia Iranica*, 19(6), 1876-1886.
- Jayal, A.D., Badurdeen, F., Dillon, J.r .O.W., Jawahir, I.S. (2010). Sustainable manufacturing modeling and optimization challenges at the product, pro-cess and system levels. *CIRP J Manuf Sci Technol* , 2, 144–52.
- Jawahir, I.S., Jayal, A.D. (2011). Product and process innovation for modeling of sustainable machining processes. In: Seliger G, Khraisheh MMK, Jawahir IS, editors. *Adv. Sustain. Manuf.* Berlin Heidelberg: Springer, 2011, 301–7.
- Koç, E., & Kaplan, E. (2007). An investigation on energy consumption in yarn production with special reference to ring spinning, *J. Fibr & Texti in Eas. Eur*, 4, 18-24.
- Lai, Y.L., & Hwang, C.L. (1992). *Fuzzy mathematical programming*, 1st ed., Springer: Berlin.
- Li, C., Zhang, X., Zhang, S., Suzuki, K. (2009). Environmentally conscious design of chemical processes and products, multi-optimization method. *Chem. Eng. Res. Des.* 87, 233-243.
- Lind, S., Krassi, B., Johansson, B., Viitaniemi, J., Heilala, J., Stahre, J., ... & Berlin, C. (2008). SIMTER: a production simulation tool for joint assessment of ergonomics, level of automation and environmental impacts. In *The 18th International Conference on Flexible Automation and Intelligent Manufacturing*.
- Mohammed, A., Wang, Q., Alyahya, S. and Bennett, N. (2016). Design and optimization of an RFID-enabled automated warehousing system under uncertainties: a multi-criterion fuzzy programming approach. *The International Journal of Advanced Manufacturing Technology*.
- Mohammed, A., & Wang, Q. (2016). The fuzzy multi-objective distribution planner for a green meat supply chain. *International Journal of Production Economics*.
- Nishant, R., Teo, T.S.H., Goh, M. (2014). Energy efficiency benefits: is technophilic optimizm justified? *IEEE Trans Eng Manage*, 61, 476–87.
- Nujoom, R., Wang, Q., & Bennett, N. (2016 a). An Integrated Method for Sustainable Manufacturing Systems Design, *Proceedings of the 3rd International Conferences in MATEC*, vol. 70, 1-5, Istanbul, Turkey.
- Nujoom, R., Mohammed, A., Wang, Q., & Bennett, N. (2016 b). The multi-objective optimization model for a sustainable manufacturing system design. In *Renewable Energy Research and Applications (ICRERA)*, 2016 IEEE International Conference on 1134-1140.
- Nurjanni, K. P., Carvalho, M. S., & da Costa, L. A. A. F. (2014). Green supply chain design with multi-objective optimization, *Proceedings of the 2014 International Conference on Industrial Engineering and Operations Management Bali, Indonesia*, 7-9.
- Pagell, M., Yang, C.L., Krumwiede, D.W., & Sheu, C. (2004). Does the competitive environment influence the efficacy of investment in environmental management? , *Journal of Supply Chain Management*, 40(3), 30–39.
- Paksoy, T., Pehlivan, N.Y. and Özceylan, E. (2012). Fuzzy multi objective optimization of green supply chain network with risk management of included environmental hazards. *Human and Ecological Risk Assessment (SCI)*, 18 (5), 1121-1152.
- Pinto-Varela, T., Barbosa-Póvoa, A. P. F., & Novais, A. Q. (2011). Bi-objective optimization approach to the design and planning of supply chains: economic versus environmental performances. *Computers & Chemical Engineering*, 35(8), 1454-1468.
- Pishvae, M. S & Razmi, J. (2012). Environmental supply chain network design using multi-objective fuzzy mathematical programming. *Applied Mathematical Modelling* 36 (8), 3433–3446.
- Pusavec, F., Krajnik, P., Kopac, J. (2010). Transitioning to sustainable production—PartI: Application on machining technologies. *J Clean Prod*, 18, 174–84.
- Rodger, J. A., & George, J. A. (2017). Triple bottom line accounting for optimizing natural gas sustainability: A statistical linear programming fuzzy ILOWA optimized sustainment model approach to reducing supply

- chain global cybersecurity vulnerability through information and communications technology. *Journal of Cleaner Production*, 142, 1931-1949.
- Sahar, V., Arijit B. and Byrne, P.J. (2014). A Case Analysis Of A Sustainable Food Supply Chain Distribution System—A Multi-Objective Approach. *International Journal of Production Economics*, 152, 71-87.
- Sharafi, M., & ELMekkawy, T. Y. (2014). Multi-objective optimal design of hybrid renewable energy systems using PSO-simulation based approach. *Renewable Energy*, 68, 67-79.
- Shaw, K., Shankar, R., Yadav, S. S., & Thakur, L. S. (2012). Supplier selection using fuzzy AHP and fuzzy multi-objective linear programming for developing low carbon supply chain, *Expert systems with applications*, 39(9), 8182-8192.
- Taghdisian, H., Pishvaie, M. R., & Farhadi, F. (2015). Multi-objective optimization approach for green design of methanol plant based on CO₂-efficiency indicator. *Journal of Cleaner Production*, 103, 640-650.
- Wang, C., Larsson, M., Ryman, C., Grip, C. E., Wikström, J. O., Johnsson, A., & Engdahl, J. (2008). A model on CO₂ emission reduction in integrated steelmaking by optimization methods, *International journal of energy research*, 32(12), 1092-1106.
- Wang, F., Lai, X., & Shi, N. (2011). A multi-objective optimization for green supply chain network design, *Decision Support Systems*, 51, 262–269.
- Wang, Q., Lassalle, S., Mileham, A. R., & Owen, G. W. (2009). Analysis of a linear walking worker line using a combination of computer simulation and mathematical modeling approaches. *Journal of Manufacturing Systems*, 28(2-3), 64-70.
- Wang, Q., & Chatwin, C.R. (2005). Key issues and developments in modelling and simulation-based methodologies for manufacturing systems analysis, design and performance evaluation. *International Journal of Advanced Manufacturing Technology*, 25 (11-12), 1254-1265.
- Zhou, C. C., Yin, G. F., & Hu, X. B. (2009). Multi-objective optimization of material selection for sustainable products: artificial neural networks and genetic algorithm approach. *Materials & Design*, 30(4), 1209-1215.