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RESEARCH

Carbon footprint for designing reverse logistics network with hybrid manufacturing-remanufacturing systems

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Abstract
This article proposes one further step toward the design of Sustainable Manufacturing Enterprise. This article presents an integrated approach for designing a reverse logistics network by minimizing the carbon emissions and the transportation distances between different candidate centers while considering several system design and operational issues of a Hybrid Manufacturing-Remanufacturing System operating within the above-mentioned reverse logistics network. Accordingly, the article attempts to integrate various sustainability aspects indoctrinated in the *Sustainable Manufacturing* philosophy. In view of this, a mixed integer programming model for designing a reverse logistics network is developed. The model considers the carbon foot print, facility location, and the material flow aspects of the reverse logistics network; in which a hybrid manufacturing-remanufacturing system is integrated. A detailed discussion of a numerical example is presented to illustrate the proposed model. The model has potential applications for supply chain managers designing a reverse logistics networks as well as for production managers at the operations level.

Keywords Reverse logistics · Facility location · Sustainable supply chain · Sustainable manufacturing · Carbon footprints · Hybrid manufacturing-remanufacturing systems

Introduction

Design for sustainable manufacturing enterprise (DFSME) is considered to be a new ideologue regarding survival of manufacturing enterprise and it can also be considered as one of the most important solutions to deal with the existing global financial crisis [18]. In order for an

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enterprise to be qualified as a "sustainable manufacturing enterprise" requires simultaneous considerations of a large variety of issues from diverse perspectives; including international/national regulations, business strategies, innovative product designs, manufacturing strategies, manufacturing system designs. The major steps are considerations of the recovery options, Cellular Manufacturing Systems, Reconfigurable Manufacturing Systems, Hybrid Manufacturing-Remanufacturing Systems, Green Closed Loop Supply Chains as well as considerations of sustainability in both the closed loop supply chain and the manufacturing system levels simultaneously (as also depicted in Fig. 1). These issues are reported in different review articles [18; 20; 22; 28].

Aljuneidi and Bulgak [3] introduced a mathematical model for designing reconfigurable cellular hybrid manufacturing-remanufacturing systems. The proposed model considered as an essential step toward the DFSME since it considered many aspects presented in Fig. 1. Then, Aljuneidi and Bulgak [2] extended their previous model by introducing the recycling option to be the source for the raw material, instead of purchasing it. Hence, the material flow of the proposed model formulates a closed loop. Since, *Sustainable Manufacturing* requires simultaneous consideration of economic, environmental, and social implications associated with the production and delivery of goods [22]. Thus, there is a need to go a further step toward the DFSME by designing a green closed supply chain.

As a research area in sustainability, *Reverse Logistics* (RL) is increasingly receiving attention among both academic researchers and practitioners due to sustainability obligations, government legislations, environmental concerns, and economic and social factors [5; 19]. There are many research articles on RL, but little integration with the upstream side of supply chain operations such as product and process design, supply management, and production operations [20]. It is critical that a sustainable supply chain be integrated with sustainable manufacturing processes, design, and systems in order to fulfill the *Sustainable Manufacturing* philosophy [22]. Accordingly, the scope of this article should be considered from the broader context akin to the true meaning of *Sustainable Manufacturing*; in which the article attempts to integrate various sustainability aspects inculcated in the *Sustainable Manufacturing*

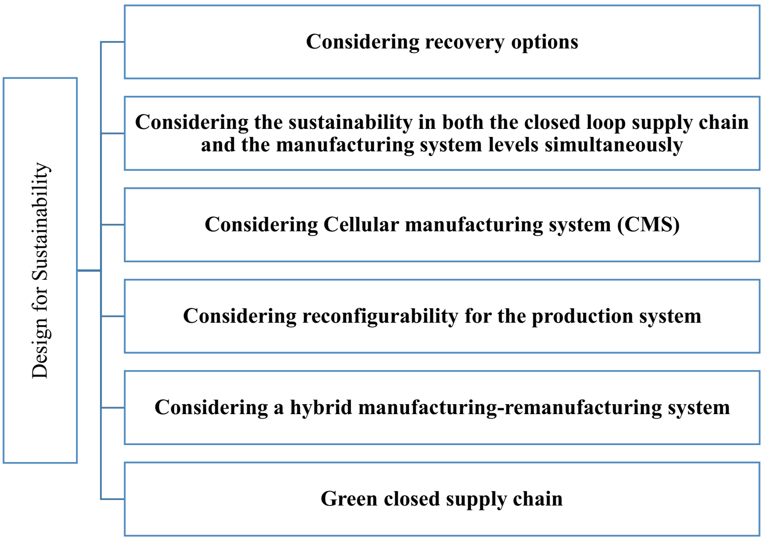

Fig. 1 Framework of the major steps toward the Design for Sustainable Manufacturing Enterprise

philosophy. In view of such an integration effort, this article addresses to simultaneous design and/or consideration of: a) Reverse Logistics networks b) Associated facility location problems in RL networks, c) Hybrid Manufacturing-Remanufacturing Systems, and d) Carbon footprint minimization in the system. As a result, we deduce that such an integrated approach would constitute one major step in attaining *Sustainable Manufacturing* in the true sense.

In this article, we will adopt the following sustainability related definitions, that are also used in several published articles, and we will discuss several relevant issues: *Reverse Logistics* is the process of planning, implementing, and controlling the efficient, cost effective flow of raw materials, in process inventory, finished goods and related information from the point of consumption to the point of origin for the purpose of recapturing value or proper disposal [46]. A well-organized RL network has a large number of advantages such as; cost savings in inventory carrying, transportation, and waste disposal costs, also, RL would allow for the improvement of customer loyalty and future sales [32, 34].

RL starts from the end users (first customers), where used products are collected from customers (return products) and then attempts to manage End-of-Life products through different decisions are undertaken including recycling (to have more raw materials) remanufacturing (to resale them to second markets or if possible to first customers), repairing (to sell in the second markets through repairing), and finally, disposing of some used parts [19]. Reverse logistics or reverse supply chain has been implemented in many industries such as the automobile industry, consumer electronics, book publishers, catalog retail, and so on [55].

In order to maximize the benefit from designing a reverse logistics network, the employment of the Hybrid Manufacturing-Remanufacturing Systems (HMRS) is an essential step [9]. HMRS can be defined as a system where common resources are used to perform both manufacturing and remanufacturing processes (i.e. mixed system). Decreasing the variability between orders for both manufactured and remanufactured products, and increasing the flexibility are some advantages from using HMRS [11, 44]. Moreover, HMRS which considered as a mixed system results in decreasing the cost comparing to other systems that are using either manufacturing or remanufacturing (i.e. non-mixed systems) [57].

The most efficient and popular recovery methods used in reverse logistics networks are remanufacturing and recycling. Recycling is the process of recovering material after a product has been discarded. "**Recycling centres are manned facilities for waste collection where visitors can bring, sort and discard worn products as well as large-sized, hazardous, and electrical waste"** [52]. Hence, the centers used in our proposed system is just for material recycling. Remanufacturing is the reprocessing of used products in such a manner that the product quality is as good as or better than new in terms of appearance, reliability and performance [40]. Remanufacturing can take place by either the Original Equipment Manufacturer (OEM); where manufacturing and remanufacturing operations occur simultaneously, Contracted Remanufacture (CR), or Independent Remanufacturer (IR) [4, 36]. After collection, examination, and disassembly of the returned products from the collection zones, there would be three possible outcomes; components no further to be used (to be disposed components), end-of-life components, which can be recycled and used as a raw material used for new components production, and end-of-use components that need some remanufacturing processes to be good for further use (remanufactured components).

Carbon footprint and carbon emissions appear to be key issues to be considered in today's supply chain management, and consequently make a significant impact on the facility location selection decisions. A systematic definition of carbon footprint is offered by Wiedman and Minx [58] as a measure of the total amount of CO_2 emissions that is directly and indirectly caused by an activity or is accumulated over the life stages of a product. Location selection is an important and a systematic problem in logistics operations, and it is also a key component of a corporation's strategic management. Hence, location selection in RL network centers should take the cost of carbon dioxide emission and lowering carbon footprint into account [61].

This article, hence, proposes an integrated design approach for a reverse logistics network by minimizing the carbon emission and transportation distances between different candidate centers while considering the several system design and operational issues of a Hybrid Manufacturing-Remanufacturing System operating within the above mentioned RL network. The reminder of this paper is organized as follows. Section 2 presents a review of the relevant literature. Detailed descriptions of the problem and the proposed model are given in section 3. A numerical example along with in depth discussion of the results as well as a sensitivity analysis of the model with respect to problem parameters are presented in section 4. In section 5, conclusions and future research are presented.

Literature review

Several research articles have been published in the areas of reverse logistics, hybrid manufacturing-remanufacturing systems, facility location, and carbon emissions. This section presents an overview of the relevant research that has been undertaken in four groups; namely, reverse logistics, hybrid manufacturing-remanufacturing systems, carbon emissions, and facility location.

Reverse logistics (RL)

There exists a vast amount of literature on Reverse Logistics (RL) and Closed Loop Supply Chains (CLSCs). An excellent review article of the recent literature focusing on RL and CLSCs can be found in Govindan et al. [19]. Agrawal et al. [1] presented another literature review of selected 242 articles on reverse logistics. They identified the research gaps and discussed future research opportunities. A schematic diagram of interactions among the activities in product life cycle considering product recovery options was presented by Gunger and Gupta [21]. A mixed integer linear programming model for designing a reverse logistics network design was developed by Alshamsi and Diabat [5]. The model was validated by considering a real-life case study on large household appliances in the UAE. Diabat et al. [15] used two methods; namely, genetic algorithms and artificial immune systems for solving their proposed mixed integer nonlinear programming model, which aims to minimize the total cost of a reverse logistics network. Pishvaee et al. [42] presented a mathematical model for designing reverse logistics networks. Product flows between different centres and the opening option for these centres are incorporated in the proposed model. Uncertainty in demand and product returns are considered by Salema et al. [47] through a mixed integer programming model for designing a reverse logistics network.

Hybrid manufacturing-remanufacturing systems

Recently, Original Equipment Manufacturers (OEMs) are forced to rethink about their supply chain network designs due to various environmental and governmental legislations. OEMs are responsible to take back their used, end-of-lease or end-of-life products, or products under warranty to minimize wastes and conserve resources [38]. As a result, OEMs are motivated to combine manufacturing and remanufacturing activities together. Systems which include both manufacturing and remanufacturing activities are called hybrid production systems [26]. A hybrid manufacturing-remanufacturing system with the setup option to switch between manufacturing products using raw materials and remanufacturing products using returned products are studied by Polotski et al. [44]. Returned products are varied in their quality, because of that, there is a need to test these returned products to decide whether to accept or reject them. Acceptance option in a hybrid system have been considered by Vercraene et al. [56]. Su and Xu [50] considered the uncertainty in quality of returned products with the objective of minimizing the remanufacturing cost. Chen and Abrishami [9] developed a mixed integer programming model for designing a hybrid system considering separated demands for both the new and the remanufactured products. The effect of introducing the remanufacturing and disposing options in a hybrid system has been studied by Kim et al. [33]. Various inventory control policies have been studied and compared by Zanoni et al. [59] in a stochastic environment of a hybrid system. Optimal pricing and core acquisition strategy for a hybrid manufacturing/remanufacturing system are studied by Mitra [37]. Inventory and Production planning for a hybrid manufacturing-remanufacturing system are studied by Dev et al. [14]. The setup policies are studied by Polotski et al. [45] in addition to production planning.

Carbon footprint and carbon emissions

An increasing number of articles are being published in the areas of carbon emissions and footprints recently. Carbon footprint measurement provide a good estimate of the total amount of GHGs emitted during the life cycle of goods and services; from the extraction of raw materials, production, transportation, storage and use to waste disposal [43].

Dekker et al. [12] presented a review of green logistic articles, particularly the transportation CO_2 emissions. Kannan et al. [31] proposed a single product and a single period mixed integer linear programming model for minimizing the carbon foot print in a reverse logistics network. Two types of carbon emission constraints are considered in the multi-period closed loop supply chain developed by Tao et al. [54]. Zhang et al. [60] studied the effect of carbon emissions on a closed loop supply chain taking into consideration the product lifetime. A multi objective linear programming model for minimizing the total cost and the total amount of gas emissions for an international beef supply chain are illustrated by Soysal et al. [49]. Zhao et al. [61] developed a mathematical model for allocating the distribution centres based on minimizing CO_2 emissions. Shaw et al. [48] proposed a mathematical model towards a sustainable supply chain network design considering carbon emissions and carbon trading issues while addressing the capacity uncertainty for suppliers, plants and warehouses as well as the demand uncertainty. Successful implementations and conditions for low-carbon production are exposed by Du et al. [16]. The study also discussed the impact of cap-and-trade on the total carbon emissions and on the low-carbon production. He et al. [25] proposed a low-carbon design approach in order to estimate the carbon footprints during the five stages in a product's lifecycle; namely, raw material acquisition, manufacturing, transportation, usage, recycle, and disposal stages. Production carbon footprints and energy are considered simultaneously with transportation carbon footprints by Bazan et al. [7]. Li [35] proposed a methodical programming model in order to demonstrate strategies on how suppliers can satisfy the retailer's demand while considering the cost of the carbon emissions, time-dependent demands as well as demand-supply interactions. Hao et al. [23] studied the production of electric vehicles and the impact of introducing the recycling option on the energy consumption and greenhouse gas emissions. Chen and Chen [8] studied the carbon footprinting based on activities within a firm.

Facility location

There exists a vast literature on Facility Location problems in general. This review will focus only on facility location problems related to the reverse supply chain environments: John and Sridharam [30] developed a single period and a single product mixed integer programming model for obtaining the facility location and the material flow in a reverse supply chain. A multi-period and a multi-product mathematical model for facility location and production planning within a closed loop supply chain are developed by Özceylan and Paksoy [39]. They also presented a sensitivity analysis to attain the impact of different model parameters. Demirel and Gökçen [13] presented the facility location problem in reverse logistics networks as a mathematical model which aims to minimize the opening costs of the facilities, production costs, transportation costs, as well as the disassembly, disposal, collection, and purchasing costs. Maximization of the profit, allocation of different facilities, delivery activity for various kinds of material, and the classification of returned products based on the quality are incorporated in the mathematical model established by Chen et al. [10]. Uncertainty in various parameters while designing a multi-product, multi-time, multi-echelon closed loop supply chain was studied by Jindal et al. [29]. Amin and Zhang [6] developed a mathematical model for designing a closed loop supply chain. The objective of the proposed model is to maximize the total profit. Different candidate locations for recycling, disassembly, and repair centres are incorporated within the model as well. Recently, Pedram et al. [41] proposed a mixed-integer linear programming model for designing a CLSC under uncertainty. The model has the ability to determine the number and the locations of the candidate facilities as well as the material flow occurring among opened facilities. Facility location decisions were considered by the large neighbourhood search technique framework for CLSC designs by Eskandarpour et al. [17].

From the literature review above, it can be observed that there is no adequate attention given to design integration efforts for sustainable systems (i.e. integrating the Hybrid Manufacturing-Remanufacturing Systems within the Reverse Logistics Networks). As a result, this paper aims to integrate facility location, production planning, material flow, and carbon emission problems for a reverse logistics network within which hybrid manufacturing-remanufacturing systems operate.

Problem description and the proposed model

In this article, we consider a Hybrid Manufacturing-Remanufacturing System (HMRS) operating within the network of forward and reverse supply chains simultaneously (Fig. 2). After collection and examination of the returned products from the collection zone (i.e. the first step in the reverse logistics network), there would be three possible outcomes: a) components with no further use (components to be disposed), b) end-of-life components, which can be recycled and the materials from which they are made are used for new components production, and c) end-of-use components that need some remanufacturing processes (i.e. cleaning, reprocessing, and re-assembly) [51]. to be good for further use (remanufactured components). As long as the

HMRS has the ability of handling both manufacturing and remanufacturing processes simultaneously, both recycled and end-of-use components will be manufactured and remanufactured respectively in the same facility by using shared resources, as can be seen in Fig. 2.

The proposed model is designed to minimize the carbon foot prints and the total cost which contains the opening costs for different centers and the transportation costs between these centers. Returned products are to be collected from the collection zones. Each customer zone has its own demand from both types of new and remanufactured components. Thus, final components are to be transferred from the manufacturing facilities to the customer zones to satisfy each customer zone demand. After collecting returned products from the collection zones by collection centers, where each center needs to send them to the opened disassembly centers to disassemble, test, and sort, the output components are sent in three main groups: a) The first group, the end-of-life components, to be send to the opened recycled centers to recycle them and resend them as raw material to the opened manufacturing facilities, hence to be used to produce the new components, b) The second group, end-of-use components, are to be send to the opened manufacturing facilities for remanufacturing, and c) The third group consists of the components which are not good for any further use, need to be disposed by any opened disposal center. Certain assumptions that have been taken into account while formulating the proposed MILP model are as follows:

- Unlimited source of returned products.
- Single period, multi products, and multi components.
- The demand for each component type and for each customer zone is known and deterministic.
- Since customers perceive recovered items to be of a lower quality, and thus following a different demand rate from the produced (new) ones [24], the demand for each component type from new material and from remanufactured products are separate from each other.
- All distances between the candidate centres, all related costs, carbon emissions, and capacities are predefined.
- Multi existing customer zones.
- One mode of transportation is considered.

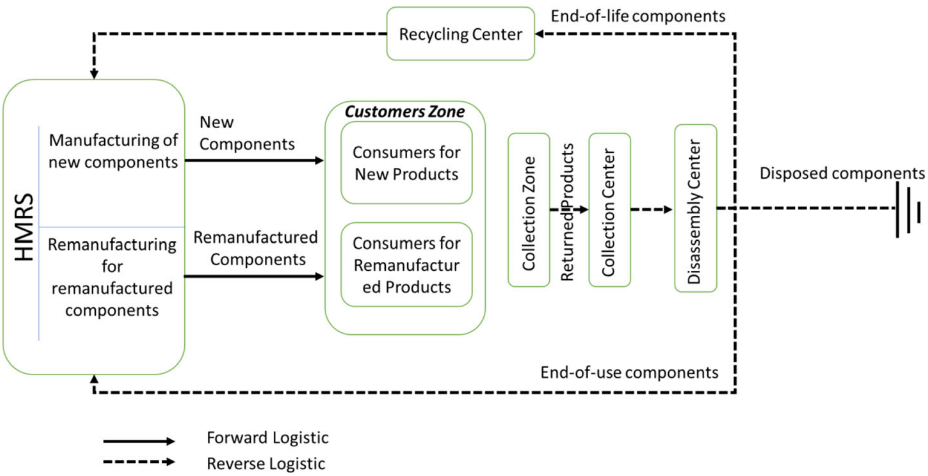

Fig. 2 Forward and reverse logistics processes among the closed loop supply chain network

- Equal processing lead time for different products.

One can think that in order to consider the above-mentioned aspects (i.e. to be able to apply this model) the various sites and product flows must be under the control of one organization. it is not mandatory to apply this model, that various sites and product flows to be owned or organized by one organization. The intention to increase the overall profit and to achieve success in the supply chain network will lead all parties in the supply chain to work together and to cooperate to achieve the success in the overall supply chain design. Since the success of a supply chain is not measured in terms of the profits at an individual stage, but in terms of the supply chain surplus, and this pushes all members of the supply chain toward growing the size of the overall pie [53].

The notation used in the proposed MILP mathematical formulation is presented below:

Sets:	
c = {1, 2, 3…C}	Index set of collection centers.
b = {1, 2, 3…B}	Index set of disassembly centers.
r = {1, 2, 3…R}	Index set of recycling centers.
p = {1, 2, 3…P}	Index set of disposal centers.
m = {1, 2, 3…M}	Index set of manufacturing centers.
u = {1, 2, 3…U}	Index set of customer zones.
i = {1, 2, 3…I}	Index set of component types.
j = {1, 2, 3…J}	Index set of product types.
z = {1, 2, 3…Z}	Index set of collection zones.

Parameters	
f_c	Fixed cost to set up collection center ***c***
f_m	Fixed cost to set up manufacturing center ***m***
f_b	Fixed cost to set up disassembly center ***d***
f_r	Fixed cost to set up recycling center ***r***
f_p	Fixed cost to set up disposal center ***p***
c_i	Transportation cost for a unit component per a unit distance
c_j	Transportation cost for a unit product per a unit distance
CAP_{im}	Manufacturing capacity of new component ***i*** in manufacturing center ***m***
$\overline{CAP_{im}}$	Manufacturing capacity of remanufactured component ***i*** in manufacturing center ***m***
CAP_{jc}	Collection capacity of product ***j*** in collection center ***c***
CAP_{jb}	Disassembly capacity of component ***j*** in disassembly center ***b***
CAP_{ir}	Recycling capacity of component ***i*** in recycling center ***r***
CAP_{ip}	Disposal capacity of component ***i*** in disposal center ***p***
D_{iu}	Demand for new component ***i*** from the customer zone ***u***
$\overline{D_{iu}}$	Demand for remanufactured component ***i*** from the customer zone ***u***
$B_{i,j}$	Number of component ***i*** contained in product ***j***
M_1	Max percent of end-of-use returns
M_2	Max percent of end-of-life returns
d_{mu}	Distance between manufacturing center ***m*** and customer zone ***u***
d_{zc}	Distance between collection zone ***z*** and collection center ***c***
d_{cb}	Distance between collection center ***c*** and disassembly center ***b***
d_{bp}	Distance between disassembly center ***b*** and disposal center ***p***
d_{br}	Distance between disassembly center ***b*** and recycling center ***r***
d_{bm}	Distance between disassembly center ***b*** and manufacturing center ***m***
d_{rm}	Distance between recycling center ***r*** and manufacturing center ***m***
φ	Cost of carbon credits in \$ per ton CO_2
CO_2^{cap}	legal limit of the CO_2 quantity can be emitted each year
E_i	CO_2 transportation emissions factor per unit of component ***i*** in g/km

Parameters	
E_j	CO_2 transportation emissions factor per unit of product ***j*** in g/km
LE_m	Amount of CO_2 emitted from the manufacturing center ***m***
LE_c	Amount of CO_2 emitted from the collection center ***c***
LE_b	Amount of CO_2 emitted from the disassembly center ***b***
LE_r	Amount of CO_2 emitted from the recycling center ***r***
LE_p	Amount of CO_2 emitted from the disposal center ***p***

Decision variables	
y_m	$= \begin{cases} 1 \text{ if a manufacturing center is open at location } \boldsymbol{m}; \\ 0 \text{ otherwise} \end{cases}$
y_c	$= \begin{cases} 1 \text{ if a collection center is open at location } \boldsymbol{c}; \\ 0 \text{ otherwise} \end{cases}$
y_b	$= \begin{cases} 1 \text{ if a disassembly center is open at location } \boldsymbol{b}; \\ 0 \text{ otherwise} \end{cases}$
y_r	$= \begin{cases} 1 \text{ if a recycling center is open at location } \boldsymbol{r}; \\ 0 \text{ otherwise} \end{cases}$
y_p	$= \begin{cases} 1 \text{ if a disposal center is open at location } \boldsymbol{p}; \\ 0 \text{ otherwise} \end{cases}$
x_{imu}	Quantity of new components shipped from manufacturing center ***m*** to customer zone ***u***
$\overline{x_{imu}}$	Quantity of remanufactured components shipped from manufacturing center ***m*** to customer zone ***u***
x_{jzc}	Quantity of product ***j*** shipped from collection zone ***u*** to collection center ***c***
x_{jcb}	Quantity of product ***j*** shipped from collection center ***c*** to disassembly center ***b***
x_{ibp}	Quantity of component ***i*** shipped from disassembly center ***b*** to disposal center ***p***
x_{ibr}	Quantity of component ***i*** shipped from disassembly center ***b*** to recycling center ***r***
x_{ibm}	Quantity of component ***i*** shipped from disassembly center ***b*** to manufacturing center ***m***
x_{irm}	Quantity of components shipped from recycling center ***r*** to manufacturing center ***m***
CO_2	Amount of carbon dioxide (CO_2) emitted currently in tons

Minimize.

$$\sum_{c=1}^{C} f_c \cdot y_c + \sum_{b=1}^{B} f_b \cdot y_b + \sum_{r=1}^{R} f_r \cdot y_r + \sum_{p=1}^{P} f_p \cdot y_p + \sum_{m=1}^{M} f_m \cdot y_m + \tag{1}$$

$$\begin{aligned} &\sum_{i=1}^{I}\sum_{m=1}^{M}\sum_{u=1}^{U} c_i.d_{mu}.\left(x_{imu}+\overline{x_{imu}}\right) + \sum_{j=1}^{J}\sum_{z=1}^{Z}\sum_{c=1}^{C} c_j.d_{zc}.x_{juc} \\ &+ \sum_{j=1}^{J}\sum_{c=1}^{C}\sum_{b=1}^{B} c_j.d_{cb}.x_{jcb} + \sum_{i=1}^{I}\sum_{b=1}^{B}\sum_{p=1}^{P} c_i.d_{bp}.x_{ibp} + \sum_{i=1}^{I}\sum_{b=1}^{B}\sum_{r=1}^{R} c_i.d_{br}.x_{ibr} \\ &+ \sum_{i=1}^{I}\sum_{b=1}^{B}\sum_{m=1}^{M} c_i.d_{bm}.x_{ibm} + \sum_{i=1}^{I}\sum_{r=1}^{R}\sum_{m=1}^{M} c_i.d_{rm}.x_{irm} \end{aligned} \tag{2}$$

$$+\varphi\left(CO_2 - CO_2^{cap}\right) \tag{3}$$

Subject to

$$\sum_{m=1}^{M} x_{imu} = D_{iu} \quad \forall i, u \tag{4}$$

$$\sum_{m=1}^{M}\overline{x_{imu}} = \overline{D_{iu}} \quad \forall i, u \tag{5}$$

$$\sum_{b=1}^{B}x_{jcb} = \sum_{z=1}^{Z}x_{jzc} \quad \forall j, c \tag{6}$$

$$\sum_{m=1}^{M}x_{irm} = \sum_{b=1}^{B}x_{ibr} \quad \forall i, r \tag{7}$$

$$\sum_{u=1}^{U}\overline{x_{imu}} = \sum_{b=1}^{B}x_{ibm} \quad \forall i, m \tag{8}$$

$$\sum_{u=1}^{U}x_{imu} = \sum_{r=1}^{R}x_{irm} \quad \forall i, m \tag{9}$$

$$\sum_{m=1}^{M}x_{ibm} \leq M_1.\left(\sum_{j=1}^{J}\sum_{c=1}^{C}B_{ij}.x_{jcb}\right) \quad \forall i, b \tag{10}$$

$$\sum_{r=1}^{R}x_{ibr} \leq M_2.\left(\sum_{j=1}^{J}\sum_{c=1}^{C}B_{ij}.x_{jcb}\right) \quad \forall i, b \tag{11}$$

$$\sum_{p=1}^{P}x_{ibp} = (1-M_1-M_2).\left(\sum_{j=1}^{J}\sum_{c=1}^{C}B_{ij}.x_{jcb}\right) \quad \forall i, b \tag{12}$$

$$\sum_{m=1}^{M}x_{irm} \leq CAP_{im}*y_m \tag{13}$$

$$\sum_{b=1}^{B}x_{ibm} \leq \overline{CAP_{im}}*y_m \tag{14}$$

$$\sum_{z=1}^{Z}x_{jzc} \leq CAP_{jc}*y_c \tag{15}$$

$$\sum_{c=1}^{C}x_{jcb} \leq CAP_{jb}*y_b \tag{16}$$

$$\sum_{b=1}^{B}x_{ibr} \leq CAP_{ir}*y_r \tag{17}$$

$$\sum_{b=1}^{B}x_{ibp} \leq CAP_{ip}*y_p \tag{18}$$

$$\sum_{i=1}^{I}\sum_{m=1}^{M}\sum_{u=1}^{U}E_i.d_{mu}.x_{imu}+\sum_{i=1}^{I}\sum_{m=1}^{M}\sum_{u=1}^{U}E_i.d_{mu}.\overline{x_{imu}}+\sum_{j=1}^{J}\sum_{z=1}^{Z}\sum_{c=1}^{C}E_j.d_{zc}.x_{jzc}$$
$$+\sum_{j=1}^{J}\sum_{c=1}^{C}\sum_{b=1}^{B}E_j.d_{cb}.x_{jcb}+\sum_{i=1}^{I}\sum_{b=1}^{B}\sum_{p=1}^{P}E_i.d_{bp}.x_{ibp}+\sum_{i=1}^{I}\sum_{b=1}^{B}\sum_{r=1}^{R}E_i.d_{br}.x_{ibr}$$
$$+\sum_{i=1}^{I}\sum_{b=1}^{B}\sum_{m=1}^{M}E_i.d_{bm}.x_{ibm}+\sum_{i=1}^{I}\sum_{r=1}^{R}\sum_{m=1}^{M}E_{\mathrm{i}}.d_{rm}.x_{irm}+\sum_{m=1}^{M}LE_m.\ y_m$$
$$+\sum_{c=1}^{C}LE_c.y_c+\sum_{b=1}^{B}LE_b.y_b+\sum_{r=1}^{R}LE_r.y_r+\sum_{p=1}^{P}LE_p.y_p$$
$$=CO_2 \tag{19}$$

$$y_m, y_c, y_b, y_r, y_p \epsilon[0,1] \tag{20}$$

$$x_{imu}, \overline{x_{imu}}, x_{jzc}, x_{jcb}, x_{ibp}, x_{ibr}, x_{ibm}, x_{irm}, x_{imu}, \overline{x_{imu}}, CO_2 \geq 0 \tag{21}$$

The objective function minimizes overall costs, divided into three main categories; are as follows: The first term represents the fixed opening cost of collection, disassembly, recycling, disposal, and manufacturing centers respectively. Transportation cost of the components and products between all centers are shown in the second term. The third term is the cost of the carbon emissions, which is the cost of carbon credits in \$ per ton CO_2 multiplied by the difference between the amount of carbon dioxide (CO_2) emitted currently in tons and CO_2 cap; the legal limit of the CO_2 quantity can be emitted each year.

As one example to this legal limit, the Cap and Trade system of the Province of Québec in Canada can be discussed. The Québec Cap and Trade (C&T) system is intended for companies in industrial and electricity sectors that emit 25,000 metric tons or more of CO_2 equivalent annually (ex: aluminum smelters, cement factories, electricity producers, etc.), as well as fossil fuel distributors that must cover GHG (Greenhouse Gas) emissions associated with all products they distribute in Québec (gasoline, diesel fuels, propane, natural gas and heating oil) (Gouvernement du Québec, 2016). "Under the cap-and-trade or emissions program, a company that is emitting less than its capped limit may sell its unused credits to another company that is exceeding its limit. For example, say Company A has a cap of 10 tons but produces 12 tons of emissions. Company B also has an emission cap of 10 tons but emits only eight, resulting in a surplus of two credits. Company A may purchase the additional credits from Company B to remain in compliance. Without buying those carbon credits, Company A would face penalties." [27].

Constraints (4) and (5) ensure that the quantity of new and remanufactured components transferred from the manufacturing centers to customer zones would equal to the demand of each type respectively. Constraints 6–9 are the balance equations for the collection, recycling, disposal, and manufacturing centers. The quantities that enter to these centers are equal to the number of products/components that leave the centers. Constraints (10), (11), and (12) restrict the number of components transferred from the disassembly center to the manufacturing, recycling, and disposal centers respectively based on the recovery rates (i.e. balance equations for the disassembly centers to the manufacturing, recycling, and disposal centers). Quantities transferred from one center to another one should not exceed the recipient center's capacity, and this is satisfied through constraints 13–18. CO_2 emissions from transportation and facilities are calculated by the constraint 19. Constraints (20) and (21) are the logical binary and non-negativity integer requirements on the decision variable.

Illustrative example

Several example problems were solved in order to validate the applicability of the model developed with full details. In this section, the model will be illustrated through a detailed example, the data set used is within the same range of the data used in the literature, where applicable, with additions of certain realistic cost parameters based on our experience of such systems. The network under consideration includes one collection center (z_1), two customer zones (u_1, u_2), two potential collection centers (c_1, c_2), three potential disassembly centers (b_1, b_2, and b_3), two potential recycling centers (r_1, r_2), two potential disposal centers (p_1, p_2), three potential manufacturing centers (m_1, m_2, and m_3), three components types, and two types of returned products. The objective of this network design is to specify which candidate centers to be opened and to determine the quantity of components and products flow between the network facilities. The amount of carbon dioxide (CO_2) emitted currently is in tons. The proposed model is solved using IBM ILOG CPLEX Optimization Studio 12.2/OPL. Number of constraints and variables for the illustrative example are 1108 and 151 respectively. The optimal total cost (objective function value) is obtained as $3,540,872 and the amount of carbon dioxide (CO_2) emitted currently in tons is equal to 10,868. The second candidate of the collection centers, the first candidate of the disassembly centers, both candidates of the recycling centers, the second candidate of the disposal centers, and two of the potential manufacturing centers are opened. Accordingly, optimal results; the opened centers and the quantities of products and components flow between the centers are shown in Fig. 3.

Returned products; 63 units of product 1 and 26 units of product 2 are to be collected from the collection zone 2 by collection center 2 and then these quantities are transferred to the disassembly center 1, which disassemble these products into components. The three types of output components that are to be transferred to disposal, recycling, and manufacturing centers are as follows: 282 units of component 1, 293 units of component 2, and 241 units of component 3 are to be transferred to disposal center 2. The quantities transferred to the recycling centers are as follows: 700 units of component 1 (300 to recycling center 1 and 400 to recycling center 2), 200 units of component 2 to recycling center 2, and 600 units of component 3 (100 to recycling center 1 and 500 to recycling center 2). The quantities received by the hybrid manufacturing-remanufacturing centers from the disassembly center in order to produce the remanufactured components are as follows: 300 units of component 1 to center 2, 350 units of component 2 (300 to center 2 and 50 units to center 3), and 300 units of components 3 (200 to center 2 and 100 units to center 3). The remanufactured components produced by the hybrid manufacturing-remanufacturing centers and transferred to the customer zones are as follows: 300 units of component 1 (100 from center 2 to customer zone 1, and 200 from center 2 to customer zone 2), 350 units of component 2 (150 from center 2 to customer zone 1, 50 from center 3 to

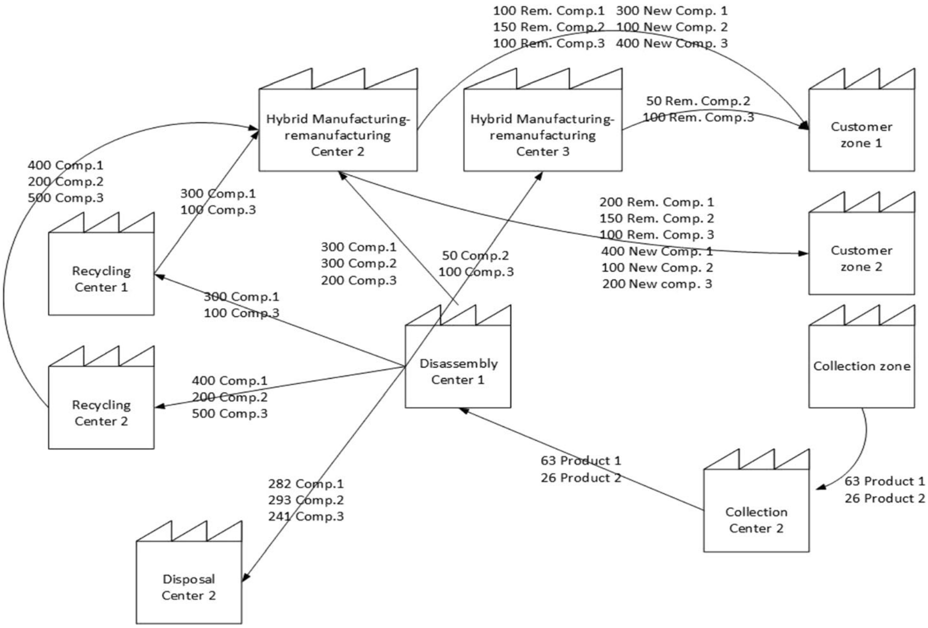

Fig. 3 Optimal results for illustrative example

customer zone 1, 150 from center 2 to customer zone 2) and 300 units of component 3 (100 from center 2 to customer zone 1, 100 from center 3 to customer zone 1, and 100 from center 2 to customer zone 2). In order for the hybrid manufacturing-remanufacturing centers to satisfy the demand for the new components, they should receive (from the solution of this example, only center 2 will be responsible for manufacturing the new components) the following units from the recycling centers: 700 units of component 1 (400 from recycling center 2 and 300 from recycling center 1), 200 units of component 2 from recycling center 2, and 600 units of component 3 (500 from recycling center 2 and 100 from recycling center 1). Quantities of new components transferred from the hybrid manufacturing-remanufacturing center 2 to the customer zones are as follows: 700 units of component 1 (300 to customer zone 1 and 400 to customer zone 2), 200 units of component 2 (100 to customer zone 1 and 100 to customer zone2), and 600 units of component 3 (400 to customer zone 1 and 200 to customer zone 2).

Computational results and discussions

In this section, nine different test problems of various sizes are solved in order to validate the proposed model. The proposed model is solved using IBM ILOG CPLEX Optimization Studio 12.2/OPL on Intel® Core i5, 3.3 GHz processor with 16 GB RAM. The results of nine diverse scenario problems are presented in Table 1. CPU times and optimality gaps are also shown in Table 1. As the problem size increases, one can clearly observe that the CPU time also increases. One can possibly classify the problems displayed in Table 1 as the small-size (problems 1–7) and the medium-

Table 1 Summary of computational results

`	Producct	Comp.	Collec center	Disass center	recycling center	Manufact center	Disposal center	Custom. zone	CPU time	Gap %	Variable	Const.
1	2	3	2	3	2	3	2	2	0.52	0	151	108
2	2	3	4	3	4	3	4	4	1.26	0	283	146
3	4	6	4	3	4	3	4	4	0.89	0	288	215
4	2	3	4	6	4	6	4	4	1.78	0	574	215
5	2	3	8	6	8	6	8	8	1.4	0.05	1090	291
6	2	3	8	12	8	12	8	8	6.07	0	2242	429
7	2	3	8	24	8	24	8	8	1.19	0	5149	705
8	2	3	16	24	16	24	16	16	4597	0.10	8866	857
9	4	6	16	24	16	24	16	16	7986	0.05	17,634	1713

size (problems 8 and 9) problems. The CPLEX software is terminated to provide solutions solving larger than the problem 9 as a result of insufficient memory. On the other hand, small-size problems were solved within 7 s. The medium-size problem (i.e. Problem 8) was solved within 2.5 h. One can, accordingly, observe that the branch and cut algorithm of CPLEX has difficulty to generate an acceptable quality solution within equitable computational times for medium-size problems of the model presented.

Sensitivity analysis

Both M1 (maximum percent of end-of-use returns) and M2 (maximum percent of end-of-life returns) are crucial parameters in the reverse logistics network, since both reflect the quality of returned products. In order to observe the effect of these two parameters on the objective function value, a sensitivity analysis is implemented. Change in the objective function value is observed while changing the values of both parameters. In the first scenario, the value of M2 was set to a fix value 0.3 and M1 has been varied from 0.3–0.7. In the second scenario, the value of M1 was set to a fix value 0.3 and M2 has been varied from 0.3–0.7. For both scenarios Fig. 4 shows the results. It is obvious from the figure that both M1 and M2 have a strong impact on the objective function value; that is when we decrease the values of M1 and/or M2, the objective function value increases. However, M2 has somewhat higher impact than that of M1 on the objective function value. Now, the question is what the optimal value is for both parameters that gives the minimum objective function value. To answer to this question, both parameter values have been varied simultaneously. The results are plotted in Fig. 5. One can see that the recommended value of M1 and M2 to get a minimum objective function value is achieved when the value of M1 = 0.3 and M2 = 0.7, and this optimal value is the minimum even if we compared it with the values obtained from the first and the second scenarios. On the other hand, the maximum value of the objective function is achieved when M1 = 0.9 and M2 = 0.1.

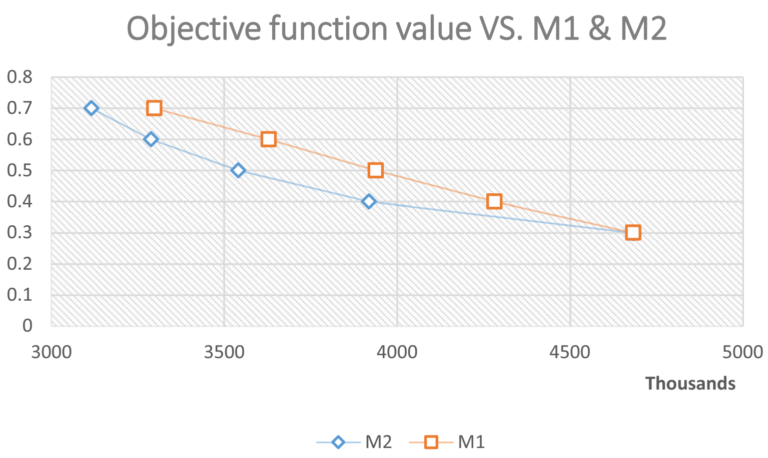

Fig. 4 The effect of M1 and M2 separately on the objective function

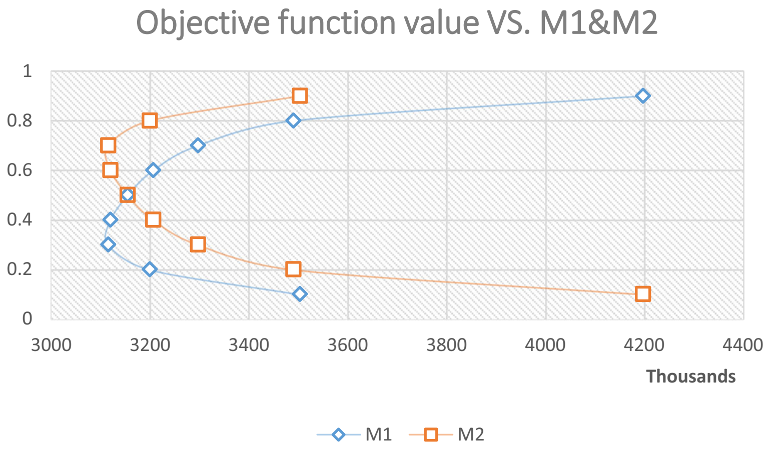

Fig. 5 The combined effect of M1 and M2 on the objective function

Another critical factor in designing a reverse logistics network is *E;* the CO_2 transportation emissions factor per unit of returned product/component in g/km, which has a main impact on the total cost and the carbon foot-print. In order to demonstrate this impact, Fig. 6 represents how the value of the objective function varies over changing the value of *E* between 0.01–0.1. It can be observed that there is a linear relationship between the objective value and *E*. The increment of the total cost while increasing the *E* value is due to the considerable increment in the value of carbon dioxide (CO_2) emitted, as shown in Fig. 6.

Conclusions

In this paper, a carbon footprint-based reverse logistics network design that consists of customer, collection, disassembly, recycling, disposal, and manufacturer (operating a hybrid manufacturing-remanufacturing system) sites are introduced. The proposed mixed integer linear programming model aims to minimize the total cost involved in the reverse logistics network consisting of fixed opening costs of collection, disassembly, recycling, disposal, and

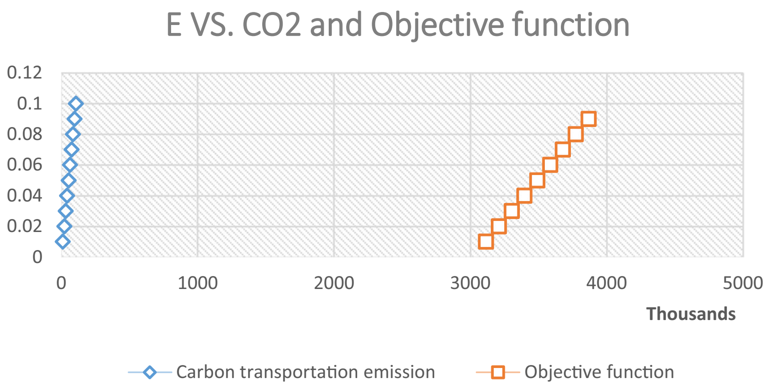

Fig. 6 The effect of E on the CO_2 and the objective function values

manufacturing centers, transportation costs of the components and products between all centers, and the cost of carbon emissions resulting from the transportation and the facilities. The model proposed has potential applications for supply chain managers designing a reverse logistics networks while simultaneously considering hybrid manufacturing-remanufacturing systems. The model will help them to answer many relevant design questions for such a network (such as which candidate sites are to be opened). The proposed approach has also potential applications at the operations level for production managers; offering solutions to operational problems; such as production planning problems (e.g. the number of new and remanufactured components to be produced in each period). Furthermore, the model integrates a large number of important sustainability issues dictated by the *Sustainable Manufacturing* philosophy. The future work in this research is to apply the model to a real case study as well as to apply meta-heuristics approaches to solve the proposed model for larger size, real-life problems. In addition, the model could be extended by the consideration of different transportation modes, bi-objective modeling, and a pareto analysis of costs vs. CO_2 emission.

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Appendix 1

Tables 2, 3, 4 and 5 present the example input data. Table 2 shows the setup cost for each potential center and the equivalent CO_2 to be emitted by each potential center. Table 3 gives the capacity for each manufacturing and the demand for each component type. Table 4 presents the capacity of the disposal and recycling centers and the number of components contained in a product. Distances between each and every pair of centers are shown in Table 5. Percentage rates of returned products are as follows: M1 = 0.3 and M2 = 0.5. CO_2. Transportation emissions factor per unit of returned product/component in g/km is 0.01, and the cost of carbon credits in \$ per ton CO_2 is 10, and the legal limit of the CO_2 quantity can be emitted each year is 5000. Transportation cost for components 1, 2, and 3 are 2, 3, and 4 dollars per component respectively, while transportation cost for products 1 and 2 are 8 and 9 dollars per product respectively.

Table 2 Setup cost and CO_2 equivalent for each center

Center		Setup cost	CO_2 equivalent
Collection centers	c1	8000	20
	c2	10,000	20
Disassembly centers	b1	30,000	10
	b2	20,000	10
	b3	25,000	10
Recycling centers	r1	20,000	40
	r2	25,000	40
Disposal centers	p1	10,000	50
	p2	12,000	50
Manufacturing centers	m1	60,000	20
	m2	50,000	20
	m3	55,000	20

Table 3 Demand and Manufacturing facility capacity in terms of components

	Manufacturing facility capacity			Demand	
	m1	m2	m3	Customer zone 1	Customer zone 2
New Comp. 1	1000	800	900	300	400
New Comp. 2	500	300	400	100	100
New Comp. 3	700	900	800	400	200
Rem. Comp.1	400	300	350	100	200
Rem. Comp.2	250	300	400	200	150
Rem. Comp.3	300	200	350	200	100

Table 4 Disposal and recycling centers capacity and number of components contained in product

	Capacity									Number of component i contained in product j	
	p1	p2	r1	r2	b 1	b 2	b3	c1	c2	Product 1	Product 2
Comp. 1	600	550	500	400	–	–	–	–	–	10	30
Comp. 2	600	700	250	200	–	–	–	–	–	15	20
Comp. 3	500	650	600	500	–	–	–	–	–	15	10
Product 1	–	–	–	–	700	600	650	100	100	–	–
Product 2	–	–	–	–	800	600	700	600	400	–	–

Table 5 Distances between disassembly, manufacturing, disposal, recycling, and collection centers

	m1	m2	m3	p1	p2	r1	r2	c1	c2
b1	200	180	190	200	150	150	150	200	200
b2	180	200	180	200	190	200	190	250	120
b3	200	150	170	250	180	200	250	150	200
Customer zone 1	320	130	200	–	–	–	–	200	200
Customer zone 2	300	150	300	–	–	–	–	160	160
m1	–	–	–	–	–	100	150	–	–
m2	–	–	–	–	–	150	100	–	–
m3	–	–	–	–	–	120	140	–	–

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