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Green supply chain design: A mathematical modeling approach based on a multi-objective optimization model

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ABSTRACT

Increasing levels of industrialization of developed nations associated with globalization trends have been creating new challenges to supply chain management (SCM). For decades, the main focus of SCM has been on efficient ways of managing the flows through complex networks of supplier, producers and customers. More recently, and as a result of the exponential increase of energy and materials consumption rates of energy and materials, sustainable development arise as an urgent issue and new approaches to SCM are required to incorporate environmental and economic concerns in the design of supply chains. In this paper, a new green supply chain (GSC) design approach has been proposed to deal with the trade-offs between environmental and financial issues in order to reduce negative impacts on the environment caused by the increasing levels of industrialization. The new approach incorporates a closed loop network to accommodate the reprocessing paradigm of disposal products and a multi-objective optimization mathematical model to minimize overall costs and carbon dioxide emissions when setting the supply chain. Optimization process is performed using three scalarization approaches, namely weighted sum method, weighted Tchebycheff and augmented weighted Tchebycheff. Computational results are analyzed to identify the advantages and drawbacks of each approach. The model was tested in a case study and results allowed to identify the capability of the model to deal with the trade-offs between the costs and environmental issues as well as to identify its main limitation when addressing real size problems.

1. Introduction

The concept of sustainable development has become a key issue in many sectors all over the world, especially for industry which is often seen as one of the main causes of the environmental decay. It aims at "meet the needs of the present without compromising the ability of future generations to meet their own need", according with the report from the World Commission on Environment and Development (WCED, 1987). The industrial sector in developed countries, such as in United States, European Union and Japan, has been enforced to adopt green supply chains (GSC) because of government regulation on environmental subjects (Seman et al., 2012). Consequently, industries are required to redesign their SC in order to incorporate goals from all dimensions of sustainability: social, environmental and financial, the so-called, triple bottom line. The increasing concern on sustainable development triggered by the exponential growth of resource usage needs to be translated into new strategies to manage and operate supply chains. In the context of green supply chain (GSC), new approaches and models struggle to provide support to a more comprehensive decision making process able to incorporate environmental issues further to the traditional merely financial perspective.

In a simplistic way, the supply chain design problem consists of defining where and how to deploy assets (plants, warehouses, distribution centers) and how flows of materials (raw material, parts, final products) should be moved along the network of entities (suppliers, manufactures, distributors, retailers and customers) in order to enhance overall performance. Applied mathematical modeling that has been widely used to assess and optimize supply chain performance, can play an important role in developing sustainable alternatives in the design of complex supply chains. Previous researches on SC design optimization can be grouped into: single objective (SO) and multi-objective (MO).

Additionally, when looking at SC design modeling approaches put forward in the literature, it is still possible to aggregate them into two clusters, namely open loop (OL) optimization and closed loop (CL) networks optimization to incorporate reverse flows. The

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reverse logistics deals mainly with backward flows such as, unused raw materials, packaging, and end-of-life (EOL) and end-of-use (EOU) products among others. In particular, the recovery of EOL products has been ignored by most manufacturers that face now new constraints imposed by an increasing number of legislation (both in European Union and USA) which sets targets in several dimensions: waste prevention, material recycling, disposal options, etc. (Salema et al., 2007). This new legal framework has been forcing a large number of companies to reconfigure their supply chains.

The literature review carried out in the context of this project allowed the identification of a gap in mathematical modeling research regarding GSC design optimization: to the best of our knowledge, there is no research work addressing the CL network design problem using a MO optimization model to address trade-offs between total costs and carbon dioxide (CO_2) emissions in the system. Therefore, in this paper a mathematical model is proposed to design a CL network able to integrate both direct and reverse flows to accommodate the reprocessing paradigm of disposal products such as those associated with EOL products. A mixed integer linear programming in an MO formulation is used to address costs and environmental impacts providing decision makers with a more comprehensive SC evaluation tool to select the most sustainable SC solution.

The rest of the paper is organized as follows. Relevant SC design literature is discussed in Section 2. In Section 3, a MIP model for the GSC design is provided, followed by computational results analysis and discussion in Section 4 and concluding remarks in Section 5.

2. Literature review

SO optimization for OL network in SC research was performed by Abdallah et al. (2010), Che et al. (2010), Ramudhin et al. (2010); Yang et al. (2010) and Zhang and Liu (2013) in which financial indicators are chosen as an optimization target. Even though financial indicators have been selected by these researchers, Abdallah et al. (2010) and Ramudhin et al. (2010) had also included the negative environmental impact in the scheme of carbon trading by converting the amount of excess carbon into a penalty cost. Therefore, the optimization targets were formulated as a SO function in the form of total cost. Combination of financial indicators with other operational performance indicators in a MO formulation have also been widely applied as optimization goals in SC researches in OL network, for example: cost, customer service, and utilization of capacity (Altiparmak et al., 2006); cost, delivery time and quality (Che and Chiang, 2010); profit and supplier defects (Franca et al., 2010); cost and lead time (Cardona-Valdés et al., 2011) and (Moncayo-Martínez and Zhang, 2011); cost, lead time and lost sales (Liu and Papageorgiou, 2013).

Furthermore, there is a few number of approaches combining financial and environmental issues explicitly in OL multi-objective frameworks to address the supply chain design problem: Wang et al. (2011), Jamshidi et al. (2012), Pozo et al. (2012), Sabio et al. (2012), and Giarola et al. (2011). Sabio et al. (2012), Pozo et al. (2012), and Giarola et al. (2011) developed multi-objective approaches incorporating both financial and environmental metrics in the chemical industry area. Sabio et al. (2012) proposed a framework for optimizing hydrogen supply chain including eight environmental indicators combined to produce a damage factor. They used MILP and Principal Component Analysis (PCA) to detect redundant environmental indicators. A similar PCA statistical approach was used by Pozo et al. (2012) to identify the most relevant environmental metrics. In Giarola et al. (2011), a MILP framework was proposed to optimize environmental a financial performance indicators in multi-period and multi-echelon biofuels supply chain. Jamshidi et al. (2012) combined total cost and environmental effect components in a multi-objective approach and used a memetic algorithm to solve it. Wang et al. (2011) developed the concept of environmental protection and defined a total cost function which includes the investment associated with the protection. The total cost is combined with total CO_2 emissions in a MO approach which is solved using the normalized normal constraint method. None of these works addresses the CL supply chains problem.

The SC research to optimize CL supply chains using a SO formulation was proposed by Sheu et al. (2005), Salema et al. (2007), Salema et al. (2009) and Pishvaee et al. (2011) that use also a financial indicator to measure the SC performance. In CL network design approaches, an MO model was proposed to identify several trade-offs such as profit and cost (Shi et al., 2011) and profit, level of satisfaction and fill rates of customer demands (Ozkir and Basligil, 2013). A more detailed review of the state of the art on GSC design optimization models can be found in Nurjanni (2013). A summary of available SC mathematical models is given in Table 1 which classifies different research contributions on SC network design according with the type of network, the type of model and number of dimensions of the objective function and main performance indicators used.

Even though utilization of GSC as research topic has long been performed, a further research in this area is still required to cover special case situations and to address some research gaps such as supply chain design incorporating direct and reverse flows further to incorporate trade-offs between financial and environmental performance indicators providing an effective support to decision makers in a context of sustainable development. More recently, some authors have been extending the sustainability concerns to incorporate lot sizing issues and new haulage-sharing strategies combining costs and environmental issues in integrated approaches. Andriolo et al. (2014) identify the importance of considering the total cost function coupled with emission consequences, and to create new approaches in modeling lot sizing activities in the context of closed-loop supply chains. In Andriolo and Battini (2015), a methodology based on a multi-objective optimization approach is used to evaluated the costs and savings in a new haulage-sharing lot sizing model in which two partners are cooperating in sharing transportation paths and handling units. To the best of our knowledge, there are no equivalent integrated approaches addressing the CL supply chain design problem.

3. Mathematical Model

According with national and international regulatory frameworks, the GSC concept has been translated by industrial companies into a set of strategic decisions and operational practices some of them with impact outside their direct ownership, across the whole supply chain. It is the case of the close loop supply chain, moving units of product from the final consumer back to the recycling and reuse of raw materials. Even though GSC research has long been introduced, more research developments in this area are still necessary due to its wide scope. In fact, although several authors have been dealing with CL supply chains, there are a very limited number of contributions able to assess the negative impact of supply chains options in the environment.

In this paper a mathematical model is developed to optimize SC performance, incorporating both financial and environmental performance indicators, in a GSC network design. In fact, further to a total cost (*TC*) measure to account for all the financial expenses in a particular SC design, environmental performance is evaluated

Table 1
Summary of available mathematical models for supply chain optimization.

Author	Network	Model	Obj.	Indicators	Determine
Tsiakis et al. (2001)	OL	MILP	SO	min total cost	network design; product quantities
Chen and Lee (2004)	OL	MINLP	MO	max {profit; average safe inventory level; average customer service level; robustness objectives to uncertainty}	production plan; transportation plan; sales quantities; product price;inventory level
Sheu et al. (2005)	CL	LP	SO	max profit	product quantities
Altiparmak et al. (2006)	OL	MINLP	MO	min {total cost; equity of capacity utilization}; max customer service	network design; product quantities
Salema et al. (2007)	CL	MILP	SO	min total cost	network design; fractions of product distributions
Al-Othman et al. (2008)	OL	LP	SO	max profit	production plan; product quantities; inventory level
Azaron et al. (2008)	OL	MINLP	MO	min {total investment cost; variance of total cost; financial risk}	network design; production plan; product quantities; shortage
Liang (2008)	OL	LP	MO	min {total cost; total delivery time}	production volume; inventory level; backorder volume; product quantities
Mahnam et al. (2009)	OL	LP	SO	min total cost	fill rate
Salema et al. (2009)	CL	MILP	SO	max profit	network design; production & storage level; product quantities; non-satisfied demand; return volume
Abdallah et al. (2010)	OL	MILP	SO	min total cost	network design; product quantities
Che and Chiang (2010)	OL	MINLP	MO	min {total cost; delivery time}; max part quality	material and product quantities; maximum transport time
Franca et al. (2010)	OL	MINLP	MO	max profit; min supplier defect	production volume; supplier selection; network design
Pishvaee and Torabi (2010)	CL	MILP	MO	min {total cost; total delivery tardiness}	network design; product quantities
Ramudhin et al. (2010)	OL	MILP	SO	min total cost	network design; product quantities
Yang et al. (2010)	CL	NLP	SO	max profit	number of deliveries
Al-e-hashem et al. (2011)	OL	MILP	MO	min {total losses; maximum shortage }	production volume; shortage; number of worker; product quantities
Cardona-Valdés et al. (2011)	OL	MILP	MO	min {total cost; maximum lead time}	network design; product quantities
Giarola et al. (2011)	OL	MILP	MO	max profit; min green house gasses	network design; production rate; inventory level; production plan; transportation plan; financial performance
Kamali et al. (2011)	OL	MINLP	MO	min {defective item; late delivered item}; max total purchasing value	network design; production rate; production plan; transportation plan
Moncayo-Martínez and Zhang (2011)	OL	LP	MO	min {total cost; lead time}	resource plan
Pishvaee et al. (2011)	CL	MILP	SO	min total cost	network design; product quantities
Shi et al. (2011)	CL	NLP	SO	max profit	selling price; production quantity; acquisition price
Wang et al. (2011)	OL	MILP	MO	min {total cost; total CO2}	network design; product quantities; environment protection level
Jamshidi et al. (2012)	OL	MILP	MO	min {total cost; total dangerous gasses}	network design; product quantities
Pozo et al. (2012)	OL	MILP	MO	max NPV; min environmental impact	damage factor; product quantities; purchasing; inventory level
Sabio et al. (2012)	OL	MILP	MO	min {total cost; environmental impact}	network design; production plan; cost structure; transportation plan; product quantities; damage factor
Shaw et al. (2012)	OL	LP	MO	min {total cost; quality rejection; late delivered item; green house gasses}	order quantity
Liu and Papageorgiou (2013)	OL	MILP	MO	min {total cost; total flow time; total lost sales}	network design; production plan; inventory level; product quantities; sales; lost sales
Ozkir and Basligil (2013)	CL	LP	MO	max {profit; customer satisfaction; price expectation}	product quantities; production volume; purchasing
Zhang and Liu (2013)	OL	NL	SO	max profit	green product mark up rate; green product selling price

Note: OL = open loop; CL = closed loop; LP = linear programming; MILP = mixed-integer linear programming; MINLP = mixed-integer non-linear programming; SO = single objective; MO = multi-objective.

based on total emission (*TE*) of CO_2. Since two SC performance indicators are utilized in a mathematical modeling approach, MO optimization is implemented to construct the GSC mathematical model. The model will allow a company to achieve the best SC design, identifying which facilities (factories/warehouses/disassembly centers (DC)) should be included in the network, recognizing the flows of units of product among different echelons and select the most appropriate transportation mode to move the units of product along the SC. An option for the best network scenario will take into account the trade-offs between *TC* (fixed costs of facilities, variable costs and transportation costs) and CO_2 emissions as a result of SC activities (production, handling, collecting, recycling, remanufacturing and transportation) providing useful information to the decision maker, allowing for better analysis, judgments, and finally creating more sustainable decisions.

The description of the proposed mathematical model for GSC design is explained in four sub-sections, namely problem definition, model elements, model formulation and MO formulation, respectively.

3.1. Problem definition

The mathematical model regarding the above described GSC problem is devoted to accommodate four kinds of echelons, namely factories, warehouses, customers and DCs in which the connection between echelons is depicted in Fig. 1. A single product is considered. It is assumed that this product holds characteristics of EOL product such as an electronic device. Associated with each connection, there are several transportation alternatives (i.e., road, rail, etc.). Since a specified amount of units of product is distributed through those connections and different treatments for units of product is implemented in each echelon, the form of product is not always similar. In this mathematical model, three types of product form (new product, product to be disposed and product to be dismantled) flow throughout the CL network in which details of product movement based on product form are as follows:

- a new product, either brand new or remanufactured, is moved along forward path of network (factory to warehouse and warehouse to customer) to meet the customer demand;
- a product to be disposed is collected from a customer and dispatched to a DC for a recycling process;
- a product to be dismantled is delivered from a DC to a factory for a remanufacturing process.

Several assumptions are stated to establish the mathematical model:

- demand of all customers is known and deterministic;
- every units of product produced in a factory and handled in a warehouse is always defect free;

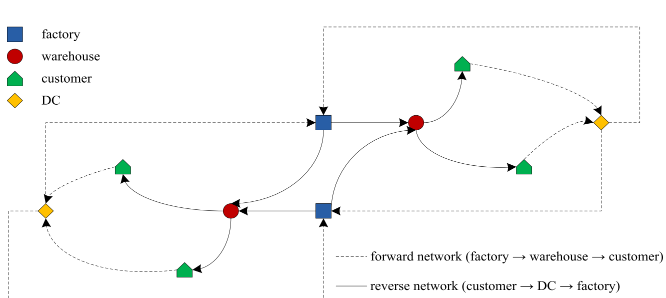


Fig. 1. Configuration of connection between echelons in the supply chain.

- every customer demand is always satisfied by any factories through any warehouses;
- it is assumed that a specified percentage of the total demand is disposed;
- all units of product to be disposed which enter a DC are always successfully disassembled;
- all transportation options have unlimited capacity;
- intermodal transportation options (i.e., road-rail, road-sea, etc.) are not possible to serve customer demand;
- distances between network nodes (used to evaluate CO_2 emissions) are assumed to be given by the straight path between facilities. Transportation rates are used to account for different mode networks characteristics (tortuosity, no feasible link, etc.) (Giarola et al., 2011).

3.2. Model Elements

Considering the problem described in the previous section, GSC model involves the sets, parameters and variables outlined in Tables 2–4. The sets *F*, *W*, *C*, and *I* (Table 2) contain, respectively, the potential factories, the potential warehouses, the customers, and the potential DCs. The sets *TF*, *TW*, *TK*, and *TI*, include the transportation options from factories, warehouses, customers, and DCs, respectively. The parameters of the model are the demand, transportation costs, distances between echelons, fixed costs, variable costs, capacity limits of facilities, limit of units of product being distributed, CO_2 released due to activity of facilities, and CO_2 released by transportation options (Table 3). Binary and continuous decision variables are applied to fulfill the goals of the mathematical model, namely determine GSC network structure and the amount of units of product that flows along the network (Table 4).

3.3. Model formulation

The formulation of the proposed mathematical model in GSC design is divided into two parts, namely objective functions and constraints. The proposed mathematical model has two objectives: to minimize total cost (*TC*) and to minimize total emission of CO_2 throughout supply chain (*TE*). The mathematical formulation of the objective functions is described in Eqs. (1)–(10). The total cost *TC* is the summation of the total fixed cost (*TFC*), the total variable cost (*TVC*), and the total transportation cost (*TTC*). It is assumed that transportation services is carried out by an external logistics provider with predefined unit transportation costs for each mode. The total emission of CO_2 *TE* is computed by adding the total CO_2 due to production (*EP*), the total CO_2 due to handling (*EH*), the total CO_2 due to disassembly (*ED*), the total CO_2 due to remanufacturing (*ER*), and the total CO_2 due to transportation (*ET*). To account for CO_2 emissions of each transportation option a transportation rate is used as described in the previous section:

$$\min f_1 \equiv TC = TFC + TVC + TTC \tag{1}$$

Table 2
Sets of the mathematical model.

Notation	Description
F	Potential factories ($f = 1, 2, \ldots, \lvert F \rvert$)
W	Potential warehouses ($w = 1, 2, \ldots, \lvert W \rvert$)
C	Customers ($c = 1, 2, \ldots, \lvert C \rvert$)
I	Potential DCs ($i = 1, 2, \ldots, \lvert I \rvert$)
TF	Transportation options from factories ($tf = 1, 2, \ldots, \lvert TF \rvert$)
TW	Transportation options from warehouses ($tw = 1, 2, \ldots, \lvert TW \rvert$)
TK	Transportation options from customers ($tk = 1, 2, \ldots, \lvert TK \rvert$)
TI	Transportation options from DCs ($ti = 1, 2, \ldots, \lvert TI \rvert$)

Table 3
Parameters of the mathematical model.

Type	Notation	Description
Demand	d_c	Demand of customer c ($c \in C$)
Transportation costs	ta_{fw}^{tf}	Unit transportation cost from factory f to warehouse w with transportation option tf ($f \in F$, $w \in W$, $tf \in TF$)
	tb_{wc}^{tw}	Unit transportation cost from warehouse w to customer c with transportation option tw ($w \in W$, $c \in C$, $tw \in TW$)
	tc_{ci}^{tk}	Unit transportation cost for collecting units of product to be disposed from customer c to DC i ($c \in C$, $i \in I$, $tk \in TK$)
	td_{if}^{ti}	Unit transportation cost from DC i to factory f with transportation option ti ($i \in I$, $f \in F$, $ti \in TI$)
Transportation rates	τ_{fw}^{tf}	Transportation rate from factory f to warehouse w with transportation option tf ($f \in F$, $w \in W$, $tf \in TF$)
	τ_{wc}^{tw}	Transportation rate from warehouse w to customer c with transportation option tw ($w \in W$, $c \in C$, $tw \in TW$)
	τ_{ci}^{tk}	Transportation rate for collecting units of product to be disposed from customer c to DC i ($c \in C$, $i \in I$, $tk \in TK$)
	τ_{if}^{ti}	Transportation rate from DC i to factory f with transportation option ti ($i \in I$, $f \in F$, $ti \in TI$)
Distances between echelons	ma_{fw}	Distance between factory f and warehouse w ($f \in F$, $w \in W$)
	mb_{wc}	Distance between warehouse w and customer c ($w \in W$, $c \in C$)
	mc_{ci}	Distance between customer c and DC i ($c \in C$, $i \in I$)
	md_{if}	Distance between DC i and factory f ($i \in I$, $f \in F$)
Fixed costs	fa_f	Fixed cost for opening factory f ($f \in F$)
	fb_w	Fixed cost for opening warehouse w ($w \in W$)
	fd_i	Fixed cost for opening DC i ($i \in I$)
Variable costs	va_f	Unit variable cost for producing a unit of product in the factory f ($f \in F$)
	vb_w	Unit variable cost for handling a unit of product in the warehouse w ($w \in W$)
	vc_c	Unit variable cost for collecting a unit of product to be disposed from customer c ($c \in C$)
	vd_i	Unit variable cost for disassembling a unit of product to be disposed in DC i ($i \in I$)
	vr_f	Unit variable cost for remanufacturing a unit of product to be dismantled in the factory f ($f \in F$)
Capacity limits of facilities	ha_f	Maximum production capacity of factory f ($f \in F$)
	hb_w	Maximum processing capacity of warehouse w($w \in W$)
	hd_i	Maximum disassembly capacity of DC i ($i \in I$)
	hr_f	Maximum remanufacturing capacity of factory f ($f \in F$)
Limit of units of product being distributed	qd	Minimum percentage of units of product to be disposed to be collected from a customer
	qr	Minimum percentage of units of product to be dismantled to be sent from a DC
CO_2 released due to the activity of facilities	ea_f	Rate of released CO_2 to produce one unit of product in factory f ($f \in F$)
	eb_w	Rate of released CO_2 to handle one unit of product in warehouse w ($w \in W$)
	ed_i	Rate of released CO_2 to disassemble one unit of product to be disposed in DC i ($i \in I$)
	er_f	Rate of released CO_2 to remanufacture one unit of product to be dismantled in the factory f ($f \in F$)
CO_2 released by a transportation option	eta^{tf}	CO_2 released by transportation option tf to dispatch a unit of product from factory to warehouse for a unit distance ($tf \in TF$)
	etb^{tw}	CO_2 released by transportation option tw to ship a unit of product from warehouse to customer for a unit distance ($tw \in TW$)
	etc^{tk}	CO_2 released by transportation option tk to collect a unit disposal from customer to DC for a unit distance ($tk \in TK$)
	etd^{ti}	CO_2 released by transportation option ti to dispatch a unit product to be dismantled from DC to factory for a unit distance ($ti \in TI$)

$$TFC = \sum_{f\in F} fa_f Xa_f + \sum_{w\in W} fb_w Xb_w + \sum_{i\in i} fd_i Xd_i \tag{2}$$

$$TVC = \sum_{f\in F} va_f \sum_{w\in W}\sum_{tf\in TF} Ya_{fw}^{tf} + \sum_{w\in W} vb_w \sum_{c\in C}\sum_{tw\in TW} Yb_{wc}^{tw} + \sum_{c\in C} vc_c \sum_{i\in I}\sum_{tk\in TK} Yc_{ci}^{tk} + \sum_{i\in I} vd_i \sum_{c\in C}\sum_{tk\in TK} Yc_{ci}^{tk} + \sum_{f\in F} vr_f \sum_{i\in I}\sum_{ti\in TI} Yd_{if}^{ti} \tag{3}$$

$$TTC = \sum_{f\in F}\sum_{w\in W}\sum_{tf\in TF} ta_{fw}^{tf} Ya_{fw}^{tf} + \sum_{w\in W}\sum_{c\in C}\sum_{tw\in TW} tb_{wc}^{tw} Yb_{wc}^{tw} + \sum_{c\in C}\sum_{i\in I}\sum_{tk\in TK} tc_{ci}^{tk} Yc_{ci}^{tk} + \sum_{i\in I}\sum_{f\in F}\sum_{ti\in TI} td_{if}^{ti} Yd_{if}^{ti} \tag{4}$$

$$\min f_2 \equiv TE = EP + EH + ED + ER + ET \tag{5}$$

$$EP = \sum_{f\in F} ea_f \sum_{w\in W}\sum_{tf\in TF} Ya_{fw}^{tf} \tag{6}$$

$$EH = \sum_{w\in W} eb_w \sum_{c\in C}\sum_{tw\in TW} Yb_{wc}^{tw} \tag{7}$$

$$ED = \sum_{i\in I} ed_i \sum_{c\in C}\sum_{tk\in TK} Yc_{ci}^{tk} \tag{8}$$

$$ER = \sum_{f\in F} er_f \sum_{i\in I}\sum_{ti\in TI} Yd_{if}^{ti} \tag{9}$$

Table 4
Variables of the mathematical model.

Type	Notation	Description
Binary (network nodes)	Xa_f	$\begin{cases} 1 & \text{if factory} f \text{ is opened} \\ 0 & \text{otherwise} \end{cases}$ $(f \in F)$
	Xb_w	$\begin{cases} 1 & \text{if warehouse } w \text{ is opened} \\ 0 & \text{otherwise} \end{cases}$ $(w \in W)$
	Xd_i	$\begin{cases} 1 & \text{if disassembly center } i \text{ is opened} \\ 0 & \text{otherwise} \end{cases}$ $(i \in I)$
Continuous (amount of product shipped by transportation mode)	Ya_{fw}^{tf}	Quantity of units of product dispatched from factory f to warehouse w using transportation option tf $(f \in F,\ w \in W,\ tf \in TF)$
	Yb_{wc}^{tw}	Quantity of units of product dispatched from warehouse w to customer c using transportation option tw $(w \in W,\ c \in C,\ tw \in TW)$
	Yc_{ci}^{tk}	Quantity of units of product to be disposed collected from customer c to DC i using transportation option tk $(c \in C,\ i \in I,\ tk \in TK)$
	Yd_{if}^{ti}	Quantity of units of product to be dismantled dispatched from DC i to factory f using transportation option ti $(i \in I,\ f \in F,\ ti \in TI)$

$$ET = \sum_{tf \in TF} eta^{tf} \sum_{f \in F} \sum_{w \in W} Ya_{fw}^{tf} ma_{fw} \tau_{fw}^{tf} + \sum_{tw \in TW} etb^{tw} \sum_{w \in W} \sum_{c \in C} Yb_{wc}^{tw} mb_{wc} \tau_{wc}^{tw} + \sum_{tk \in TK} etc^{tk} \sum_{c \in C} \sum_{i \in I} Yc_{ci}^{tk} mc_{ci} \tau_{ci}^{tk} + \sum_{ti \in TI} etd^{ti} \sum_{i \in I} \sum_{f \in F} Yd_{if}^{ti} md_{if} \tau_{if}^{ti} \tag{10}$$

The constraints of the mathematical model are given next, Eqs. (11)–(21):

- Total quantity of units of product shipped from a factory to any warehouses through any transportation options should be lower or equal to the maximum capacity of respective factory

$$\sum_{w \in W} \sum_{tf \in TF} Ya_{fw}^{tf} \le ha_f Xa_f \quad \forall f \in F \tag{11}$$

- Total quantity of units of product which enter a warehouse from any factories through any transportation options should be lower or equal to the maximum capacity of respective warehouse

$$\sum_{f \in F} \sum_{tf \in TF} Ya_{fw}^{tf} \le hb_w Xb_w \quad \forall w \in W \tag{12}$$

- Total quantity of units of product dispatched from a warehouse to any customers through any transportation options should be lower or equal to total quantity of units of product which enter respective warehouse from any factories through any transportation options

$$\sum_{c \in C} \sum_{tw \in TW} Yb_{wc}^{tw} \le \sum_{f \in F} \sum_{tf \in TF} Ya_{fw}^{tf} \quad \forall w \in W \tag{13}$$

- Total quantity of units of product distributed from any warehouses through any transportation options to fulfill demand of a customer should be higher or equal to respective customer demand

$$\sum_{w \in W} \sum_{tw \in TW} Yb_{wc}^{tw} \ge d_c \quad \forall c \in C \tag{14}$$

- Total quantity of units of product to be disposed collected from a customer to any DCs through any transportation options should be lower than the respective customer demand

$$\sum_{i \in I} \sum_{tk \in TK} Yc_{ci}^{tk} \le d_c \quad \forall c \in C \tag{15}$$

- Total quantity of units of product to be disposed collected to a DC through any transportation options from any customers should be lower or equal to the maximum capacity of respective DC

$$\sum_{c \in C} \sum_{tk \in TK} Yc_{ci}^{tk} \le hd_i Xd_i \quad \forall i \in I \tag{16}$$

- Total quantity of units of product to be disposed sent to any DCs through any transportation options from a customer should be higher or equal to the minimum percentage of restitution from total number of demand of respective customer

$$\sum_{i \in I} \sum_{tk \in TK} Yc_{ci}^{tk} \ge qd \cdot d_c \quad \forall c \in C \tag{17}$$

- Total quantity of units of product to be dismantled delivered to any factories from a DC through any transportation options should be greater or equal to minimum percentage of units of product to be dismantled from total amount of units of product to be disposed entered the respective DC

$$\sum_{f \in F} \sum_{ti \in TI} Yd_{if}^{ti} \ge qr \sum_{c \in C} Yc_{ci} \quad \forall i \in I \tag{18}$$

- Total quantity of units of product to be dismantled dispatched from any DCs to a factory through any transportation options should be lower or equal to the maximum remanufacturing capacity of respective factory

$$\sum_{i \in I} \sum_{ti \in TI} Yd_{if}^{ti} \le hr_f Xa_f \quad \forall f \in F \tag{19}$$

- Total amount of units of product flowed from a factory to a warehouse through a transportation mode, a warehouse to a customer through a transportation mode, a customer to a DC and a DC to a factory through a transportation mode should be higher or equal to zero

$$Ya_{fw}^{tf},\ Yb_{wc}^{tw},\ Yc_{ci}^{tk},\ Yd_{if}^{ti} \ge 0 \tag{20}$$

- Binary number which used to describe existence of facilities (factories, warehouses and DCs)

$$Xa_f,\ Xb_w,\ Xd_i \in \{0, 1\} \tag{21}$$

3.4. Multi-objective formulation

The mathematical model includes two conflicting objectives which give rise to the existence of a set of efficient solutions known as Pareto-optimal set. A solution is Pareto-optimal if there is no other solution that dominates it, i.e., none of the objectives can be improved without deteriorating at least one of the other objectives. Pareto-optimal solutions define a Pareto-optimal frontier in objective space representing trade-offs between objectives.

Multi-objective optimization of the mathematical model is performed through three scalarization approaches, namely weighted sum method, weighted Tchebycheff and augmented weighted Tchebycheff. Thus, the multi-objective problem is converted into a single objective optimization problem with some parameters. Different combinations allow computing approximations to the Pareto-optimal set using a single objective optimization method. The mathematical formulations of these approaches for solving a MO problem with two objectives are as follows:

- Weighted sum method

$$\min w_1 f_1 + w_2 f_2 \text{ s. t. Eqs. (11)–(21)} \quad (22)$$

where $w_1 \ge 0$ and $w_2 \ge 0$ are weights such that $w_1 + w_2 = 1$, and f_1 and f_2 the objective functions;

- Weighted Tchebycheff method

$$\min \gamma \text{ s. t. } w_1(f_1 - z_1^{**}) \le \gamma w_2(f_2 - z_2^{**}) \le \gamma \text{Eqs. (11)–(21)} \quad (23)$$

where $w_1 \ge 0$ and $w_2 \ge 0$ are weights such that $w_1 + w_2 = 1$, f_1 and f_2 the objective functions, and $z^{**} = (z_1^{**}, z_2^{**})^T = (\min f_1, \min f_2)^T$ is a reference point (approximation to the ideal vector);

- Augmented weighted Tchebycheff method

$$\min \gamma + \rho \sum_{k=1}^{2} (f_k - z_k^{**}) \text{ s. t. } w_1(f_1 - z_1^{**}) \le \gamma w_2(f_2 - z_2^{**}) \le \gamma \text{Eq. (11)–(21)} \quad (24)$$

where $\rho > 0$ is a small quantity, $w_1 \ge 0$ and $w_2 \ge 0$ are weights such that $w_1 + w_2 = 1$, f_1 and f_2 the objective functions, and $z^{**} = (z_1^{**}, z_2^{**})^T = (\min f_1, \min f_2)^T$ is a reference point (approximation to the ideal vector).

4. Results and discussion

A numerical example is established to illustrate and analyze the mathematical model performance. The closed-loop network in the proposed numerical example is composed of four kinds of facilities, namely factory, warehouse, customer, and disassembly center. Every facility in the closed-loop network has a specified function which details are described as follow:

- *factory*: producing a brand new unit of product and remanufacturing a unit of product to be dismantled;
- *warehouse*: storing a new unit of product, either brand new or remanufacture, before deliver the unit of product to customers;
- *DC*: disassembling a unit of product to be disposed into a unit of product to be dismantled.

Three types of products are distributed along a closed-loop network, namely new units of product (either brand new or remanufactured), units of product to be disposed and units of product to be dismantled. New units of product are distributed within the forward network (factories–warehouses–customers). Units of product to be disposed are collected from all customers and subsequently delivered to DCs. Units of product to be dismantled are dispatched from DCs to factories. Potential location of SC facilities (factories, warehouses and DCs) and existing customers are given in Fig. 2. More than one transportation mode is available to dispatch the units of product between echelons. Three transportation options are available for the three types of connections, namely factory to warehouse, warehouse to customer and DC to factory (road/rail/air) whereas units of product to be disposed from customer to DC are sent through road and rail. Several data sources are used to develop the case study. An unitary transportation rate for all modes was assumed for simplicity. A summary of data sources is given in Table 5.

Computational process is conducted through *CPLEX v12.4 Solver* for *Microsoft Excel*. The ideal solution for each objective function was calculated before performing the computational processes using the scalarization approaches. The ideal value (minimum) of total cost is 133,581.095 € while the ideal value (minimum) of total CO_2 emission is 840,614.486 kg. This ideal point is used as reference point for both Tchebycheff approaches. Different combinations of weights were obtained by uniformly varying the weights by 0.025. The solutions of the numerical example, for different combinations of weights, using weighted sum method and Tchebycheff approaches (both Tchebycheff approaches give identical results) are depicted in Fig. 3 which shows four distinct optimal network designs for different trade-offs between *TC* and *TE*.

Different approximations to the Pareto-optimal frontier are determined by weighted sum method and Tchebycheff

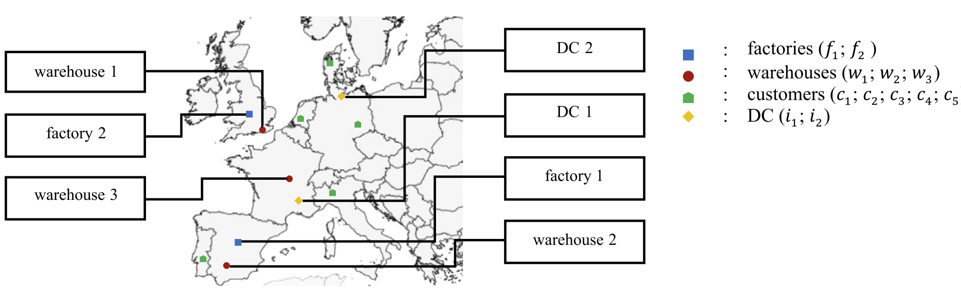


Fig. 2. Potential location of facilities and existing customers of numerical example.

Table 5
Summary of data sources to establish the numerical example.

Data	Data Sources
Potential location of facilities and customers location, demand of customers, fixed costs, and factory capacity data	Tsiakis et al. (2001)
Variable cost	Tsiakis et al. (2001) and King County (2013)
Transportation cost	Wilson (1996) and Tsiakis et al. (2001)
Distance between echelons	Google Maps (2013)
Rate of CO_2 released	Heidelberg Cement Group (2013), UKWA (2013), and ECTA (2011)

approaches. This occurs due to the limitation of weighted sum method which cannot obtain solutions in non-convex regions of the Pareto-optimal frontier. Conversely, solutions in non-convex regions are achieved by Tchebycheff approaches (either weighted Tchebycheff or augmented weighted Tchebycheff). Weighted Tchebycheff does not guarantee that all solutions found are Pareto-optimal. Both weighted sum method and weighted Tchebycheff method have shown limitations in finding Pareto-optimal solutions and therefore, the third approach, the weighted Tchebycheff method was adopted. This approach allows to handle non-convexity of the Pareto-optimal frontier and to avoid the computation of weakly Pareto-optimal solutions.

Conceptually, the trade-offs between *TC* and *TE* of CO_2 are conceived as conflicting relationship of the objectives. This situation is suitable with the frontier obtained for the numerical example in which decreasing *TC* gives rise to worsening *TE* of CO_2. However, in Fig. 3, it can be observed that a large deviation, either *TC* or *TE* of CO_2, occurs when the design of SC network is changed. Therefore, the Pareto frontier reflects a discontinuous pattern. Solutions for combinations of weights with an interval of 0.025 are presented in Table 6 to make a further analysis of the numerical example.

As it can be seen in Fig. 3, four clusters of optimal network designs are produced by three scalarization approaches. Details are given in Table 7. In general, lower *TC* can be obtained with a lower level of facilities but increasing levels of *TE*. On the other hand, to decrease *TE*, a larger network with more facilities will be required.

The information on *TC* and *TE* of CO_2 elements is illustrated in Fig. 4. Total variable cost (*TVC*) becomes the most stable component of *TC* compared with total fixed cost (*TFC*) and total transportation cost (*TTC*). This condition denotes that the *TVC* is not influenced by the change of weight and network design. Therefore, the transformation of *TC* is not affected by the amount of *TVC* since

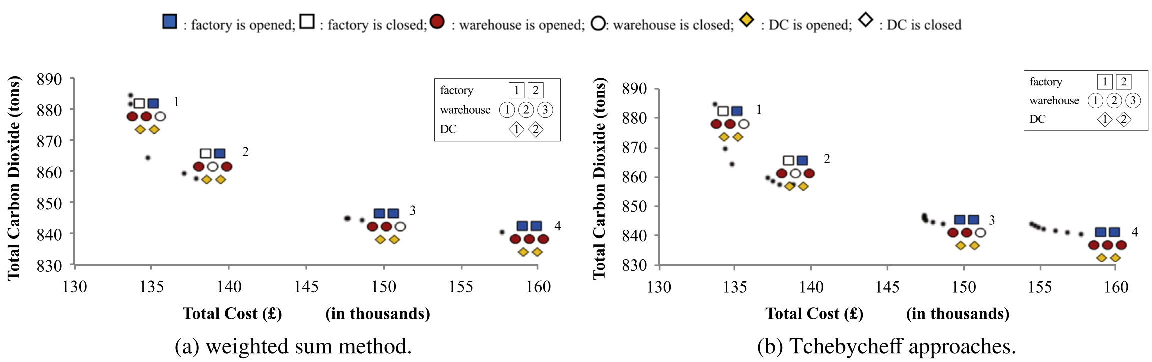


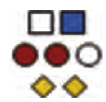
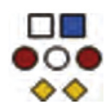
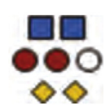
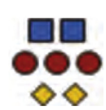
Fig. 3. Optimization result of numerical example using scalarization approaches.

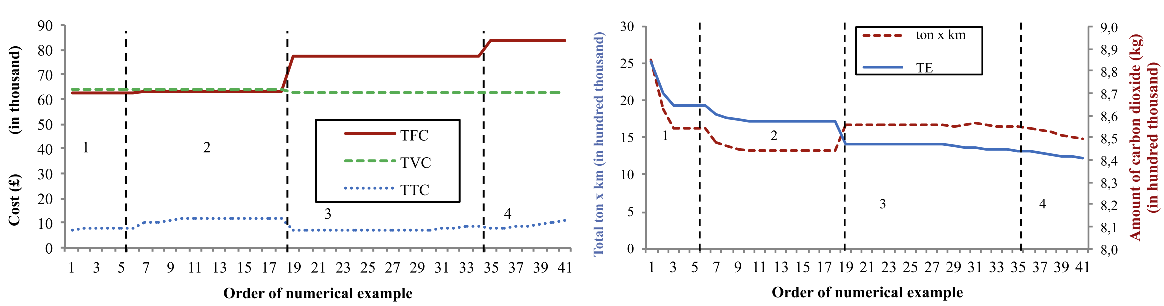
Table 6
Objective functions value that of numerical example through augmented weighted Tchebycheff approach.

No.	Weights		Objective functions		Properties value			
	TC	*TE*	*TC* (€)	*TE* (kg)	*TC* (€) (in thousands) *TFC*	*TVC*	*TTC*	ton × km (in millions)
1	1.000	0.000	133,581.095	884,554.772	62.500	63.785	6.995	2.553
2	0.975	0.025	134,329.483	869,801.624	62.500	63.797	7.729	1.882
3	0.950	0.050	134,789.360	864,309.635	62.500	63.799	8.181	1.632
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
6	0.875	0.125	134,789.360	864,309.635	62.500	63.799	8.181	1.632
7	0.850	0.150	137,030.452	860,160.840	63.000	63.783	9.944	1.444
8	0.825	0.175	137,427.245	858,746.334	63.000	63.783	10.341	1.379
9	0.800	0.200	137,895.305	857,871.323	63.000	63.783	10.805	1.340
10	0.775	0.225	138,524.758	857,642.659	63.000	63.783	11.432	1.329
11	0.750	0.250	138,744.460	857,580.428	63.000	63.782	11.652	1.326
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
18	0.575	0.425	138,744.460	857,580.428	63.000	63.782	11.652	1.326[a]
19	0.550	0.450	147,388.645	847,164.390	77.000	62.735	7.352	1.673[a]
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
28	0.325	0.675	147,388.645	847,164.390	77.000	62.735	7.352	1.673
29	0.300	0.700	147,389.409	846,532.335	77.000	62.735	7.352	1.645
30	0.275	0.725	147,399.922	845,856.110	77.000	62.657	7.439	1.681
31	0.250	0.750	147,510.301	845,257.555	77.000	62.688	7.519	1.699
32	0.225	0.775	147,907.977	844,773.903	77.000	62.713	7.884	1.677
33	0.200	0.800	148,587.780	844,408.989	77.000	62.719	8.559	1.661
34	0.175	0.825	148,587.780	844,408.989	77.000	62.719	8.559	1.661
35	0.150	0.850	154,351.219	844,279.802	83.500	62.707	7.840	1.655
36	0.125	0.875	154,602.702	843,617.573	83.500	62.703	8.096	1.625
37	0.100	0.900	154,857.041	842,978.480	83.500	62.698	8.355	1.596
38	0.075	0.925	155,146.165	842,363.005	83.500	62.689	8.673	1.566
39	0.050	0.950	155,920.460	841,790.242	83.500	62.684	9.426	1.541
40	0.025	0.975	156,767.124	841,209.000	83.500	62.678	10.279	1.515
41	0.000	1.000	157,633.120	840,614.486	83.500	62.672	11.151	1.488

[a] A significant increase when opening new facility (a factory).

Table 7
Optimal structure of supply chain facilities.

No.	Structure of SC Facilities		SC Facilities	Index	Description
1.	Factory = 1 Warehouse = 2 DC = 2		Factory 1	f_1	Close
			Factory 2	f_2	Open
			Warehouse 1	w_1	Open
			Warehouse 2	w_2	Open
			Warehouse 3	w_3	Close
			DC 1	i_1	Open
			DC 2	i_2	Open
2.	Factory = 1 Warehouse = 2 DC = 2		Factory 1	f_1	Close
			Factory 2	f_2	Open
			Warehouse 1	w_1	Open
			Warehouse 2	w_2	Close
			Warehouse 3	w_3	Open
			DC 1	i_1	Open
			DC 2	i_2	Open
3.	Factory = 2 Warehouse = 2 DC = 2		Factory 1	f_1	Open
			Factory 2	f_2	Open
			Warehouse 1	w_1	Open
			Warehouse 2	w_2	Open
			Warehouse 3	w_3	Close
			DC 1	i_1	Open
			DC 2	i_2	Open
4.	Factory = 2 Warehouse = 3 DC = 2		Factory 1	f_1	Open
			Factory 2	f_2	Open
			Warehouse 1	w_1	Open
			Warehouse 2	w_2	Open
			Warehouse 3	w_3	Open
			DC 1	i_1	Open
			DC 2	i_2	Open



(a) cost structure. (b) total ton × km between echelons and CO_2 emission.

Fig. 4. Elements of objective function.

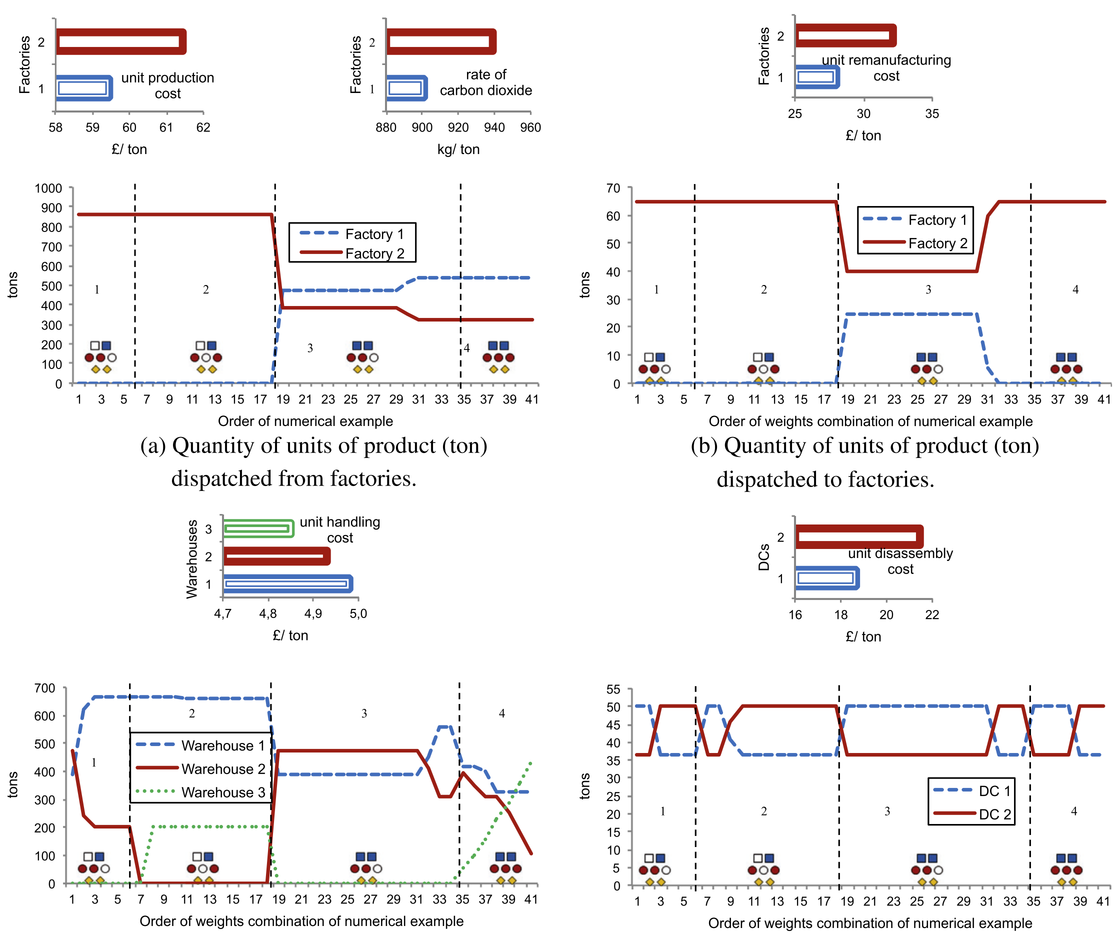
it does not show a fluctuated trend. Another behavior is demonstrated by other *TC* components. *TFC* increases significantly when a new facility is open (22.2% for a new factory (network change in sections 2–3 in Fig. 3) and 8.4% for a new warehouse (network change in sections 3–4)) while the change of *TTC* depends on the unit transportation cost and total amount of units of product flowed.

In general, *TTC* accounts for the smallest share in *TC* (between 5% and 8.4%). Based on the computational results, the same transportation option (rail) is chosen as single transportation mode for all connections between echelons (factory to warehouse, warehouse to customer, customer to DC and DC to factory) although different combinations of weights between two objectives are tested in the optimization process. As it could be expected, rail is selected as the most appropriate transportation option because it has the lowest unit transportation cost and rate of CO_2 released compared to other choices. In this case, the type of transportation option does not give a significant impact on *TC*.

Based on the mathematical formulation, the amount of *TE* of CO_2 is proportional to the total ton × km generated. A significant increase can be observed on total ton × km in a dashed line of Fig. 4b. This situation is caused by opening a new facility and the resulting changes on connection routes. When both factories are opened, the amount of emission due to production activities is lower than only with one factory since more units of product are produced in a factory with the lowest rate of CO_2 released (1: 812,235 kg CO_2; 2: 812,235 kg CO_2; 3: 794,185–791,715 kg CO_2 2; 4: 791,715 kg CO_2). As a result, total ton × km increase significantly when a new factory is opened.

A detailed analysis of *TC* and *TE* for each optimal supply chain network (Table 7) scenario is presented next:

- Supply chain network no. 1 is characterized by one factory, two warehouses and two DCs. The lowest *TC* is observed in this type of network, namely €62,500 (factory=€35,000; warehouses=€10,000; DCs=€17,500). The factory used in this type of supply chain network, Factory 2, has the highest unit cost for production (61.440€/ton), the highest cost for remanufacturing (32.184 €/ton) and the highest CO_2 emission as shown in section 1 of Fig. 5a and b. Therefore, the highest production and remanufacturing cost and the highest CO_2 emission of production is owned by type 1 of supply chain network. The options for handling also include two highest cost of facilities, namely Warehouse 1 (4.980€/ton) and Warehouse 2 (4.930€/ton) as depicted in section 1 of Fig. 5c. The *TE* is highly influenced by emission of production since the rate of CO_2 released for handling, disassembly and remanufacture is equal for all facilities. The decreasing trend of *TE* in a solid line of Fig. 4b is caused by the reduction amount of total ton × km.
- Supply chain network no. 2 is characterized by one factory, two warehouses and two DCs. An equal number of facilities (when compared with supply chain network no. 1) are open. However, total fixed cost raises by €500 (factory=€35,000; warehouses=€10,500; DCs=€17,500) due to a substitution of a warehouse in which Warehouse 2 is replaced by Warehouse 3 that has a lower unit cost for handling a unit of product (4.85 €/ton). This replacement does not result in total variable cost reduction because the difference value of unit handling cost is quite small (0.080 €/ton). In addition, a larger amount of units of product to be disposed is processed in DC 2 which has a higher unit disassembly cost (i_2=18.664 €/ton; i_2=21.456 €/ton) as given by a solid line of section 2 of Fig. 5d. The amount of total CO_2 emission is getting lower in this type of network. This result is not influenced by the change of warehouse since all warehouses have an equal value of CO_2 emission (9224.400 g CO_2/ton). However, the situation occurs due to a rearrangement of echelons connections. Thus, the value of total ton × km is reduced as can be observed in a dash line of Fig. 4b.
- Supply chain network no. 3 is characterized by two factories, two warehouses and two DCs. A new factory (Factory 1) is opened and it significantly increases total fixed cost to €77,000 (factory = €49,500; warehouses=€10,000; DCs=€17,500). A larger amount of units of product is produced in the new factory which has the lowest unit production cost (59.450 €/ton), as illustrated in a dash line of section 3 of Fig. 5. Even though, Factory 1 also offers the lowest unit of remanufacturing cost (27.996 €/ton), the remanufacturing capacity of this factory is lower than Factory 2. Therefore, more units of product to be dismantled are processed in Factory 2. A large increase on total ton × km is shown in a dash line of Fig. 4b with lower total CO_2



(a) Quantity of units of product (ton) dispatched from factories.

(b) Quantity of units of product (ton) dispatched to factories.

(c) Quantity of units of product (ton) dispatched from ware- houses.

(d) Quantity of units of product (ton) dispatched to DCs. dispatched to DCs.

Fig. 5. Quantity of units of product (ton) dispatched.

emission in a solid line of section 3 of Fig. 4b is observed. This situation is caused by opening a new facility (Factory 1) which has a lower rate of CO_2 released (Factory 1=939 kg CO_2/ton; Factory 2=901 kg CO_2/ton) and resulting changes on connection routes. When both factories are opened, the amount of emission due to production activities is lower than only with one factory since more units of product are produced in a factory with the lowest rate of CO_2 released (Section 1: 812,235 kg CO_2; Section 2: 812,235 kg CO_2; Section 3: 794,185–791,715 kg CO_2; Section 4: 791,715 kg CO_2) as portrayed in the solid line of Fig. 4b. As a result, total ton × km increases significantly when a new factory is opened (the dash line of section 3 of Fig. 4b).

- Supply chain network no. 4 is characterized by two factories, three warehouses and two DCs. All facilities are operated in this chain network. Consequently, total fixed cost becomes the highest compare with any other regions (€83,500). A higher level of units of product is produced in the Factory 1 as seen in the section 4 of Fig. 5a. This option is chosen due to the lowest unit production cost and the lowest rate of CO_2 emission. All units of product to be dismantled are remanufactured in the Factory 2 as observed in section 4 of Fig. 5b. Thus, total the remanufacturing cost is getting higher after decreasing in section 3. The higher total cost in section 4 of Fig. 4a is affected by processing all units of product to be dismantled in a factory with the most expensive unit remanufacturing cost and opening a new warehouse. A descending trend is performed by the value of total ton × km. This result is caused by the change of routes and finally resulting on a lower *TE*.

5. Conclusion and future work

A mathematical modeling research in GSC area arises easily when environmental issue becomes a company concern besides financial considerations. This paper reports a research work developed to accommodate a gap in previous researches in mathematical modeling concerning GSC area. It proposes a new mathematical model to assess and optimize GSC performance in a CL network type incorporating a multi-objective approach. Two evaluation indicators, namely *TC* and *TE* of CO_2, are chosen to create an MO mixed integer linear model. A numerical example is utilized to verify and validate the mathematical model. A discontinuous frontier representing trade-offs between *TC* and *TE* of CO_2 is generated from the numerical example where four different CL network designs are obtained. The model is sensitive to the cost structure. Therefore, it is very important to get reliable data of costs elements and to carry out sensitivity tests to analyze the model behavior. The proposed mathematical model is capable to illustrate the trade-offs between *TC* and *TE* of CO_2, the model assumes a different transportation mode network. However, to fully explore the sensitivity of the model, a more comprehensive set of tests should be performed including using different transportation rates to take into account different modal choices. This constitutes a big limitation of this study.

Even though the mathematical model developed in this paper addresses new issues on GSC design modeling and provides new insights on the impact of both *TC* and *TE* of CO_2 in alternative GSC design scenarios, the application of the mathematical model is still limited by model boundaries. Consequently, this model is not appropriate to solve GSC problem in real complex situations. Therefore, further work will be addressed to improve the mathematical model by modifying the model scenario and utilization of other solving methods for MO optimization.

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