Green Supply Chain Design with Multi-Objective Optimization

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Abstract

Consideration of environmental and economic aspects in supply chain design is required to reduce negative impacts on the environment caused by the increasing levels of industrialization. In this paper, a new green supply chain design approach has been proposed to deal with the trade-offs between environmental and financial issues. 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 network in which previous models in this type of network have not include environmental impact. A mathematical model is developed by assuming deterministic and satisfied demand. Optimization process of the mathematical model is performed using three scalarization approaches, namely weighted sum method, weighted Tchebycheff and augmented weighted Tchebycheff. Differences in the optimization results are analyzed to identify the advantages and drawbacks of each approach when solving a case study. A detailed discussion of the most appropriate method related to computational outcome is provided hereafter.

Keywords

Green supply chain, closed loop network, multi-objective optimization, weighted sum method, Tchebycheff approach

1. Introduction

A lot of efforts to apply green supply chain (GSC) concept in industrial sector are triggered by environmental degradation which has been growing at an increasing rate around the world. Performing a research in applied mathematical modeling is one of any efforts that can be conducted in GSC area. In supply chain (SC) research, mathematical models have been developed to assess and /or optimize SC performance. Previous researches on SC optimization have been considering two forms: single objective (SO) and multi-objective (MO). Additionally, when looking at SC design modeling approaches put forward in the literatures, it is still possible to aggregate them in two groups, namely optimization for open loop (OL) network and optimization for closed loop (CL) network.

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 Zang and Liu (2013) in which financial indicators are chosen as an optimization target. Even though financial indicator was 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 indicator with other performance indicators in MO format was 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-Valdes et al. (2011) and Moncayo-Marti'nez and Zang (2011)); cost and negative environmental impact of SC activities (Wang et al. (2011) and Jamshidi et al. (2012)); cost, lead time and lost sales (Liu and Papageorgiou (2013)).

The SC research to optimize CL supply chains using a SO formulation was presented 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).

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 an MO optimization model do address trade-offs between total costs and carbon dioxide (CO_2) emissions in the system. Therefore, in this paper a mathematical model is proposed using a mixed integer linear programming in an MO formulation to address cost and environmental impacts providing decision makers with a more comprehensive SC evaluation tool to select the most sustainable SC solution.

2. Research Objectives

GSC concept is required by industries to meet environmental regulation. Reprocessing disposal products for reuse purpose is a key concept in GSC. Therefore, CL network should be implemented in GSC. Even though GSC has been long introduced, research development in this area is still necessary due to its wide scope. Consequently, several gaps are encountered in previous researches which have begun to adopt green concept in SC. 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.

Based on the identified gap in previous SC studies, in this paper a mathematical modeling research is developed to optimize SC performance, including financial and environmental performance indicators, in GSC network design. Economic SC performance indicator is represented by total cost (TC) whereas environment indicator is represented by total emission (TE) of CO_2. Since two SC performance indicators are utilized in mathematical modeling, MO optimization is implemented to construct the mathematical model in GSC. 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 product among different echelons and select the most appropriate transportation mode to move the products 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.

3. Mathematical Model

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 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 Figure 1. A single product is considered. Associated with each connection, there are several transportation alternatives (i.e., road, rail, etc.). Since a specified amount of products is distributed through those connections and different treatment for products is implemented in each echelon, the form of product is not always similar. In this mathematical model, three types of product form (new product, disposal product and dismantle product) flow throughout CL network in which details of product movement based on product form are as follows:

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

Several assumptions are stated to establish the mathematical model:

- demand of all customers is known and deterministic;
- every product produced in a factory and handled in a warehouse is always defect free;
- every customer demand is always satisfied by any factories through any warehouses;
- each customer always returns disposal product and the number of product must comply specified percentage from total demand;
- all disposal products which enter 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 are same no matter the mode network.

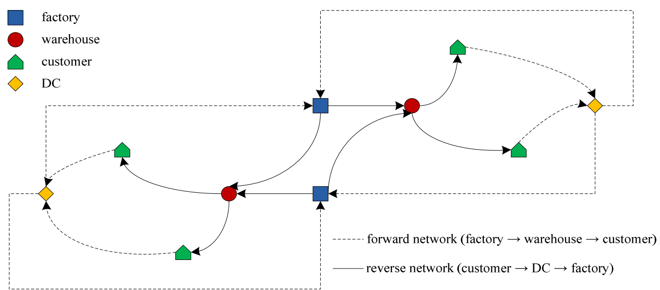

Figure 1: Configuration of connection between echelons in the supply chain

3.2 Model Elements

Considering the problem described in the previous section, GSC model involves the following sets, parameters and variables. Two types of decision variables are applied to fulfill the goals of the mathematical model, namely determine GSC network structure and the amount of product that flows along the network. A summary of model sets, parameters and variables is outlined in Table 1, Table 2 and Table 3.

Table 1: Sets of the mathematical model

No.	Notation	Description	No.	Notation	Description
1.	F	potential factories ($f = 1,2,\dots,F$)	5.	TF	transportation options from factories ($tf = 1,2,\dots,TF$)
2.	W	potential warehouses ($w = 1,2,\dots,W$)	6.	TW	transportation options from warehouses ($tw = 1,2,\dots,TW$)
3.	C	customers ($c = 1,2,\dots,C$)	7.	TK	transportation options from customers ($tk = 1,2,\dots,TK$)
4.	I	potential DCs ($i = 1,2,\dots,I$)	8.	TI	transportation options from DCs ($ti = 1,2,\dots,TI$)

Table 2: Parameters of the mathematical model

No.	Not.	Description
1.	d_c	demand of customer c ($c \in C$)
2.	ta_{fw}^{tf}	unit transportation cost from factory f to warehouse w with transportation option tf ($f \in F, w \in W, tf \in TF$)
3.	tb_{wc}^{tw}	unit transportation cost from warehouse w to customer c with transportation option tw ($w \in W, c \in C, tw \in TW$)
4.	tc_{ci}^{tk}	unit transportation cost for collecting disposal products from customer c to DC i ($c \in C, i \in I, tk \in TK$)
5.	td_{if}^{ti}	unit transportation cost from DC i to factory f with transportation option ti ($i \in I, f \in F, ti \in TI$)
6.	ma_{fw}	distance between factory f and warehouse w ($f \in F, w \in W$)
7.	mb_{wc}	distance between warehouse w and customer c ($w \in W, c \in C$)
8.	mc_{ci}	distance between customer c and DC i ($c \in C, i \in I$)
9.	md_{if}	distance between DC i and factory f ($i \in I, f \in F$)
10.	fa_f	fixed cost for opening factory f ($f \in F$)
11.	fb_w	fixed cost for opening warehouse w ($w \in W$)

Table 2: Parameters of the mathematical model (continuation)

No.	Not.	Description

12.	fd_i	fixed cost for opening DC i ($i \in I$)
13.	va_f	unit variable cost for producing a product in the factory f ($f \in F$)
14.	vb_w	unit variable cost for handling a product in the warehouse w ($w \in W$)
15.	vc_c	unit variable cost for collecting a disposal product from customer c ($c \in C$)
16.	vd_i	unit variable cost for disassembling a disposal product in DC i ($i \in I$)
17.	vr_f	unit variable cost for remanufacturing a dismantle product in the factory f ($f \in F$)
18.	ha_f	maximum production capacity of factory f ($f \in F$)
19.	hb_w	maximum processing capacity of warehouse w ($w \in W$)
20.	hd_i	maximum disassembly capacity of DC i ($i \in I$)
21.	hr_f	maximum remanufacturing capacity of factory f ($f \in F$)
22.	qd	minimum percentage of disposal products to be collected from a customer
23.	qr	minimum percentage of dismantle products to be sent from a DC
24.	ea_f	rate of released CO_2 to produce one unit product in factory f ($f \in F$)
25.	eb_w	rate of released CO_2 to handle one unit product in warehouse w ($w \in W$)
26.	ed_i	rate of released carbon dioxide to disassembly one unit disposal product in DC i ($i \in I$)
27.	er_f	rate of released carbon dioxide to remanufacture one unit dismantle product in the factory f ($f \in F$)
28.	eta^{tf}	CO_2 released by transportation option tf to dispatch a unit product from factory to warehouse for a unit distance ($tf \in TF$)
29.	etb^{tw}	CO_2 released by transportation option tw to ship a unit product from warehouse to customer for a unit distance ($tw \in TW$)
30.	etc^{tk}	CO_2 released by transportation option tk to collect a unit disposal from customer to DC for a unit distance ($tk \in TK$)
31.	etd^{ti}	CO_2 released by transportation option ti to dispatch a unit dismantle product from DC to factory for a unit distance ($ti \in TI$)

Table 3: Variables of the mathematical model

No.	Notation	Description	
1.	Xa_f	$\begin{cases} 1 & if\ factory\ f\ is\ opened \\ 0 & otherwise \end{cases}$	($f \in F$)
2.	Xb_w	$\begin{cases} 1 & if\ warehouse\ w\ is\ opened \\ 0 & otherwise \end{cases}$	($w \in W$)
3.	Xd_i	$\begin{cases} 1 & if\ disassembly\ center\ i\ is\ opened \\ 0 & otherwise \end{cases}$	($i \in I$)
4.	Ya_{fw}^{tf}	quantity of products dispatched from factory f to warehouse w using transportation option tf ($f \in F$, $w \in W$, $tf \in TF$)	
5.	Yb_{wc}^{tw}	quantity of products dispatched from warehouse w to customer c using transportation option tw ($w \in W$, $c \in C$, $tw \in TW$)	
6.	Yc_{ci}^{tk}	quantity of disposal products collected from customer c to DC i using transportation option tk ($c \in C$, $i \in I$, $tk \in TK$)	
7.	Yd_{if}^{ti}	quantity of dismantle products dispatched from DC i to factory f using transportation option ti ($i \in I$, $f \in F$, $ti \in TI$)	

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 and to minimize total emission of CO_2 throughout supply chain. The mathematical formulation of the objective functions is described in Equation (1) to Equation (10) whereas detailed explanation of notation is given in Table 4.

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

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

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

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

$$min\ f_2 \quad TE = EP + EH + ET \tag{5}$$

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

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

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

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

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

Table 4: Explanation of notation in the objective functions

No.	Notation	Description	No.	Notation	Description
1.	TC	Total cost	6.	EP	Total CO_2 due to production
2.	TFC	Total fixed cost	7.	EH	Total CO_2 due to handling
3.	TVC	Total variable cost	8.	ED	Total CO_2 due to disassembly
4.	TTC	Total transportation cost	9.	ER	Total CO_2 due to remanufacturing
5.	TE	Total emission of CO_2	10.	ET	Total CO_2 due to transportation

The constraints of the mathematical model are given next, from Equation (11) to Equation (21):

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

$$\sum_{w\in W}\sum_{tf\in TF} Ya_{fw}^{tf} \leq ha_f Xa_f \qquad \forall f \qquad (11)$$

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

$$\sum_{f\in F}\sum_{tf\in TF} Ya_{fw}^{tf} \leq hb_w Xb_w \qquad \forall w \qquad (12)$$

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

$$\sum_{c\in C}\sum_{tw\in TW} Yb_{wc}^{tw} \leq \sum_{f\in F}\sum_{tf\in TF} Ya_{fw}^{tf} \qquad \forall w \qquad (13)$$

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

$$\sum_{w\in W}\sum_{tw\in TW} Yb_{wc}^{tw} \geq d_c \qquad \forall c \qquad (14)$$

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

$$\sum_{i\in I}\sum_{tk\in TK} Yc_{ci}^{tk} \leq d_c \qquad \forall c \qquad (15)$$

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

$$\sum_{c\in C}\sum_{tk\in TK} Yc_{ci}^{tk} \leq hd_i Xd_i \qquad \forall i \qquad (16)$$

- Total quantity of disposal products 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

$$\sum_{i\in I}\sum_{tk\in TK} Yc_{ci}^{tk} \geq qd \cdot d_c \qquad \forall c \qquad (17)$$

- Total quantity of dismantle products delivered to any factories from a DC through any transportation options should be greater or equal to minimum percentage of dismantle products from total amount of disposal products entered the respective DC

$$\sum_{f\in F}\sum_{ti\in TI} Yd_{if}^{ti} \geq qr\sum_{c\in C} Yc_{ci} \qquad \forall i \qquad (18)$$

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

$$\sum_{i\in I}\sum_{ti\in TI} Yd_{if}^{ti} \leq hr_f Xa_f \qquad \forall f \qquad (19)$$

- Total amount of products 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

$$Ya_{fw}^{tf}, Yb_{wc}^{tw}, Yc_{ci}^{tk}, Yd_{if}^{ti} \geq 0 \qquad (20)$$

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

$$Xa_f, Xb_w, Xd_i \in \{0,1\} \qquad (21)$$

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 to 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 for these approaches are as follows:

- Weighted sum method

$$\begin{array}{ll} minimize & w_1 f_1 + w_2 f_2 \\ subject\ to & \text{Equation (11) to Equation (21)} \\ \text{in which,} & w_1, w_2 \geq 0 \ \text{ and } \ w_1 + w_2 = 1 \end{array} \qquad (22)$$

*Note: w = weight; f = objective function value

- Weighted Tchebycheff

$$\begin{aligned} &minimize && \gamma && (23)\\ &subject\ to && w_1(f_1 - z_1^{**}) \leq \gamma && (24)\\ & && w_2(f_2 - z_2^{**}) \leq \gamma && (25)\\ & && \text{Equation (11) to Equation (21)} && \\ &\text{in which,} && w_1, w_2 \geq 0 \text{ and } w_1 + w_2 = 1 && \end{aligned}$$

*Note: z^{**} = reference point (approximation to the ideal vector); γ = zero or positive

- Augmented weighted Tchebycheff

$$\begin{aligned} &minimize && \gamma + \rho \textstyle\sum_{k=1}^{2}(f_k - z_k^{**}) && (26)\\ &subject\ to && w_1(f_1 - z_1^{**}) \leq \gamma && \\ & && w_2(f_2 - z_2^{**}) \leq \gamma && \\ & && \text{Equation (11) to Equation (21)} && \\ &\text{in which,} && w_1, w_2 \geq 0 \text{ and } w_1 + w_2 = 1 && \end{aligned}$$

*Note: ρ = very small and positive

4. Results and Discussion

A numerical example is established to illustrate and analyze the mathematical model performance. Potential location of SC facilities (factories, warehouses and DCs) and existing customers are given in Figure 2. More than one transportation mode is available to dispatch the products between echelons. Three choices of transportation option are available for the three types of connections, namely factory to warehouse, warehouse to customer and DC to factory whereas disposal products from customer to DC are sent through road and rail. Several data sources are used to develop the case study. A summary of data sources is given in Table 5.

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

No.	Data	Data Sources
1.	Potential location of facilities and customers location, demand of customers, fixed costs, and factory capacity data	Tsiakis et al. (2001)
2.	Variable cost	Tsiakis et al. (2001) and King County (2013),
3.	Transportation cost	Wilson (1996) and Tsiakis et al. (2001)
4.	Distance between echelons	Google Maps (2013)
5.	Rate of CO_2 released	Heidelberg Cement Group (2007), UKWA (2010), and ECTA and Cefic (2011)

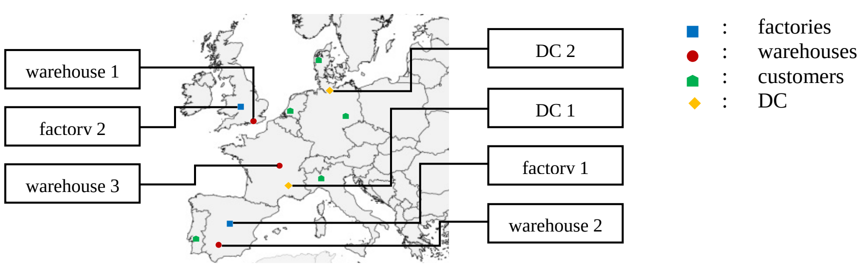

Figure 2: Potential location of facilities and existing customers of numerical example

Computational process for optimization purpose is conducted through *CPLEX v12.4 Solver* for *Microsoft Excel*. The solutions of the numerical example, for different combinations of weights, using weighted sum method, weighted Tchebycheff and augmented Tchebycheff approaches are depicted in Figure 3. In this figure, several distinct optimal network designs are obtained for different trade-offs between TC and TE of CO_2. Different approximations to the Pareto-optimal frontier are determined by weighted sum method and Tchebycheff 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). Even though similarity of the graph pattern is illustrated by both of Tchebycheff approaches, weighted Tchebycheff does not guarantee that all solutions found are Pareto-optimal. In fact, some of them can be only weekly Pareto-optimal as can be observed by the solutions listed in Table 6. These solutions were obtained using weighted Tchebycheff for the given weights and it can be seen that one of the solutions is not Pareto-optimal since it is dominated by the other (the solution with better value of TE of CO_2 and the same value of TC). Therefore, either weighted sum method or weighted Tchebycheff approach have limitations on finding Pareto-optimal solutions. Since these two methods do not ensure to calculate trade-off solutions TC and TE of CO_2 that constitute a good approximation to the Pareto-optimal frontier, the third approach, namely augmented weighted Tchebycheff was adopted. This approach allows to handle non-convexities and to avoid the computation of weakly Pareto-optimal solutions.

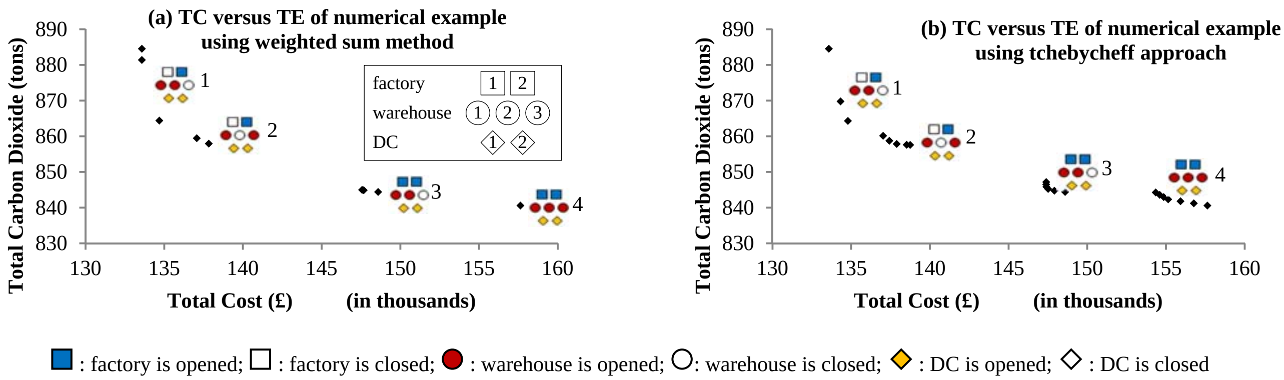

Figure 3: Optimization result of numerical example using scalarization approaches:
(a) weighted sum method; (b) Tchebycheff

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 increasing TC gives rise to worsening TE of CO_2. However, in Figure 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. Several computational experiments by modifying the interval between weight combination values (0.050, 0.025 and 0.001) were conducted to confirm the discontinuity of Pareto frontier. Similar patterns of trade-offs were obtained by combinations with different interval values. Thus, solutions for combinations of weights with an interval of 0.025 are presented to make a further analysis of numerical example.

Table 6: Objective functions values of weekly Pareto solutions of numerical example
(weighted Tchebycheff approach)

Order of Numerical Example	Weight		Objective functions	
	TC	TE	TC (£)	TE (kg)
4.	0.925	0.075	134789.360350000	864309.634908000
5.	0.900	0.100	134789.360350000	864309.634907998

The information on TC and TE of CO_2 elements is illustrated in Figure 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 it does not show a fluctuated trend. Another behavior is demonstrated by other TC components. TFC increases significantly when the new facility is opened (22.2% for a new factory (network change 2 to 3 in Figure 3) and 8.4% for a new warehouse (network change 3 to 4)) while the change of TTC depends on the unit transportation cost and total amount of the products flowed. Based on the computational process, 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 combination of weights between two objectives are tested in optimization process. Thus, the type of transportation option does not give an impact to TC. 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.

Based on the mathematical formulation, the amount of TE of CO_2 is proportional to the products quantity and the distance between echelons. Therefore an increasing amount of TE of CO_2 can be caused by the increasing multiplication value of both elements. A significant increase can be observed on total products multiplied by distances in a solid line of Figure 4b which details are given in Table 7. This situation is caused by opening a new facility and the resulting changes on connection routes. When both of factories are opened, the amount of emission due to production activities is lower than only with one factory since more products are produced in a factory with the lowest rate of CO_2 released (1: 812235 kg CO_2; 2: 812235 kg CO_2; 3:794185-791715 kg CO_2; 4: 791715 kg CO_2). As a result, total products multiplied by distance increase significantly when a new factory is open.

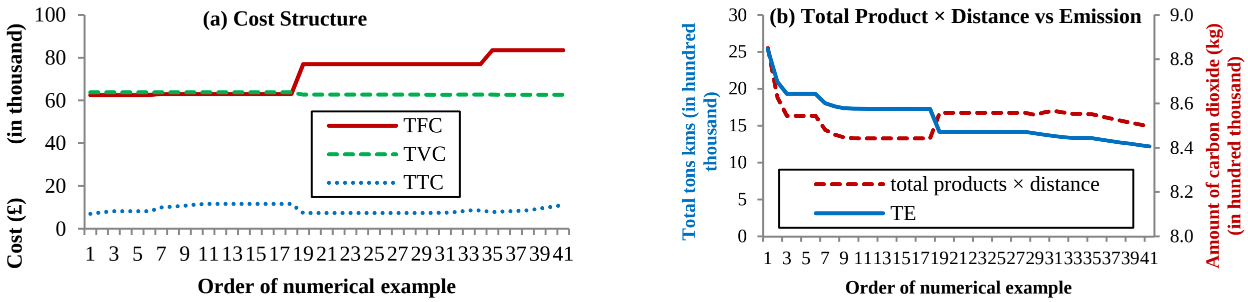

Figure 4: Elements of objective function: (a) cost structure; (b) total products × distances between echelons and CO_2 emission

Table 7: Objective functions value that of numerical example through augmented weighted Tchebycheff approach

No.	Weights combination		Objective functions		Properties value			
	TC	TE	TC (£)	TE (kg)	TC (£) (in thousands)			Total Product × Distance (tons kms) (in millions)
					TFC	TVC	TTC	
1.	1.000	0.000	133581.095	884554.772	62.500	63.785	6.995	2.553
2.	0.975	0.025	134329.483	869801.624	62.500	63.797	7.729	1.882
3.	0.950	0.050	134789.360	864309.635	62.500	63.799	8.181	1.632
:	:	:	:	:	:	:	:	:
6.	0.875	0.125	134789.360	864309.635	62.500	63.799	8.181	1.632
7.	0.850	0.150	137030.452	860160.840	63.000	63.783	9.944	1.444
8.	0.825	0.175	137427.245	858746.334	63.000	63.783	10.341	1.379
9.	0.800	0.200	137895.305	857871.323	63.000	63.783	10.805	1.340
10.	0.775	0.225	138524.758	857642.659	63.000	63.783	11.432	1.329
11.	0.750	0.250	138744.460	857580.428	63.000	63.782	11.652	1.326
:	:	:	:	:	:	:	:	:
18.	0.575	0.425	138744.460	857580.428	63.000	63.782	11.652	1.326 *
19.	0.550	0.450	147388.645	847164.390	77.000	62.735	7.352	1.673 *
:	:	:	:	:	:	:	:	:
28.	0.325	0.675	147388.645	847164.390	77.000	62.735	7.352	1.673
29.	0.300	0.700	147389.409	846532.335	77.000	62.735	7.352	1.645
30.	0.275	0.725	147399.922	845856.110	77.000	62.657	7.439	1.681
31.	0.250	0.750	147510.301	845257.555	77.000	62.688	7.519	1.699
32.	0.225	0.775	147907.977	844773.903	77.000	62.713	7.884	1.677
33.	0.200	0.800	148587.780	844408.989	77.000	62.719	8.559	1.661
34.	0.175	0.825	148587.780	844408.989	77.000	62.719	8.559	1.661
35.	0.150	0.850	154351.219	844279.802	83.500	62.707	7.840	1.655
36.	0.125	0.875	154602.702	843617.573	83.500	62.703	8.096	1.625
37.	0.100	0.900	154857.041	842978.480	83.500	62.698	8.355	1.596
38.	0.075	0.925	155146.165	842363.005	83.500	62.689	8.673	1.566
39.	0.050	0.950	155920.460	841790.242	83.500	62.684	9.426	1.541
40.	0.025	0.975	156767.124	841209.000	83.500	62.678	10.279	1.515
41.	0.000	1.000	157633.120	840614.486	83.500	62.672	11.151	1.488

* a significant increase when opening new facility (a factory)

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. Even though the proposed mathematical model is capable to illustrate the trade-offs between TC and TE of CO_2, the model assumes different transportation mode network but equal distance/costs which become a big limitation of this approach.

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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