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Benders decomposition algorithm for a green closed-loop supply chain under a build-to-order environment

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Abstract

Nowadays, researches pay more attention to environmental concerns consisted of various communities. This study proposes a multi-echelon, multi-period closed-loop supply chain (CLSC). A comprehensive model considers the selection of selection of technology and environmental effects. The supply chain is under a build-to-order (BTO) environment. So, there is not a final product inventory. Also, the returned products disassembled into reused components. The bi-objective mixed-integer linear problem is solved by a Benders decomposition algorithm by validating some numerical experiments. The convergence is also shown in the property.

Keywords: Green supply chain, closed-loop supply chain, technology, build-to-order, Benders decomposition algorithm

1- Introduction

In recent years, researchers noticed to supply chain models as an essential issue for success in business processes and enhance customer satisfaction (Salehi et al., 2019). On the other hand, pollution reduction and people's livelihood are the other issues paying more attention because of government awareness for environmental aspects. So, green manufacturing, logistic reverse, remanufacturing, and waste management as a subset of green supply chain management (GSCM) are important issues for researchers and manufacturers (Sadegi Rad and Nahavandi, 2018). Environmental effects are the important issue considering in GSCM that way, in which all of the processes (i.e., procurement, production, and distribution) should be done in an environmentally friendly manner (Ma et al., 2016).

A traditional supply chain pays attention to forward logistics from raw materials to final products; however, due to return products and their benefits for the environment, government and manufacturers, firms are focusing not only forward logistics but also reverse logistics (i.e., remanufacturing the return products), which named a closed-loop supply chain (CLSC) (Jabbarzadeh et al., 2018). Collecting, using and recovery returned products make the CLSC valuable (Schankel et al., 2019). According to Zhen et al. (2019), an effective CLSC tries to minimize the supply chain cost by considering environmental protection. Well-designed CLSC provides services leading to customer satisfaction, cost reduction, and protection environment simultaneously. A build-to-order (BTO) strategy is a production system with the aim of satisfying customers.

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In BTO, production activities begin when the orders received from customers, in which before orders reception, none of the production activities is done (Laimazloumian et al. 2013). According to the CLSC literature, issues such as the supply chain network design (Mardan et al. 2019), CO_2 emission control (Yousefi and Ebadi, 2018), capacity constraint (Dominguez et al., 2018), product design (Liu et al. 2019), return quality levels (Yavari and Geraeli, 2019) and social factors (Hassanpour et al., 2019; Wan and Hong, 2019; Wang et al., 2019) were studied; however, a production strategy (e.g., BTO) did not consider. Khalafi et Al. (2019) studied returned perishable food in a CLSC with a case study in a milk and yogurt industry. Shaharudin et al. (2018) examined some hypotheses in Malaysia investigating green capability and product returns in a CLSC. Shimada and Van Wassenhove (2019) considered home appliance recycling law and its impact on a CLSC. They studied the electric home appliance industry of Japan and used the extended procedure responsibility plan. Gaur and Mani (2018) presented a conceptual framework, which studied major menace and chances for an organization engaged in a CLSC operation.

Few studies have considered the BTO in a green supply chain (Ebrahimi and Tavakkoli, 2020). Most of the studies in the BTO are a conceptual framework; few of them are studied quantitatively and mathematically. Mathematical studies (e.g., Ebrahimi et al (2018)) have considered a bi-objective BTO supply chain problem to maximize the total profit and customer's utility, whose demand was dependent on the customer's utility. In the other study, a scenario-based multi-objective BTO problem was presented, in which a return policy and outsourcing were considered (Ebrahimi et al. 2019).

To help the managers, this paper focuses on optimization research to formulate a bi-objective mixed-integer programming (MIP) model to minimize negative environmental impacts (i.e., pollution of the technology and vehicles) and minimizing the supply chain cost under a BTO environment. The novel green CLSC is considered in a BTO environment. Also, the product's shortage is a new issue in the CLSC considered in this paper. Furthermore, choosing the technology and considering the environmental impact of the technology are investigated in our new integrated model. Finally, the benders decomposition algorithm (BDA) is used to efficiently solve the presented model by validating some numerical experiments. The results show the enterprise practice advantages of an integrated model.

The organization of this study is as follows. The related literature is reviewed in section 2. The developed model (i.e., definition and formulation) is illustrated in section 3. The presented model is solved by the Benders decomposition algorithm in section 4. The results are shown and analyzed in section 5.

2- Problem description and formulation

The structure of the CLSC under this research is shown in figure 1, in which new products are produced in a production center. Since our model is in the BTO environment, all of the final products are sent to their customers. Returned products are gathered in a separation center. All of the returned products are disassembled into components or modals, and then each of the components that has enough quality will be transferred to a production center or plant. The technology impact and transportation effect on the environment are considered. The distance between suppliers and manufacturers (i.e., production center or plant), manufacturers and customers, customers and separation centers, separation centers, and manufacturers is deterministic; however, there are several vehicles, in which each of them has its cost and effect on the environment.

2-1- Notations

The following notations are used to model the given problem.

Indices:

r	Index of the raw materials
n	Index of the component
p	Index of the final product
s	Index of the suppliers

m	Index of the manufacturer
c	Index of the customers
o	Index of the technology
v	Index of the vehicle
d	Index of the separation centre
t	Index of the time

***Parameters*:**

$Dp_{p,c,t}$	Demand of product *p* for customer *c* in period *t*
$Cr_{r,s,t}$	Cost of raw material *r* from supplier *s* in period *t*
$Cp_{m,p,t}$	Cost of producing product *p* in manufacturer *m* in period *t*
$Cn_{n,m,o,t}$	Cost of producing component *n* in manufacturer *m* in period *t*
$Cb_{p,m,t}$	Shortage cost of product *p* for manufacturer *m* in period *t*
$Cvm_{m,c,v,t}$	Transportation cost of vehicle *v* from manufacturer *m* to customer *c* in period *t*
$Cvs_{s,m,v,t}$	Transportation cost of vehicle *v* from supplier s to manufacturer m in period *t*
$Cd_{d,p,t}$	Cost of disassembling or separating of the return product *p* in separation centre *d* in period *t*
$Cvd_{c,d,v,t}$	Transportation cost of vehicle *v* from customer *c* to separation centre *d* in period *t*
$Cvn_{d,m,v,t}$	Transportation cost of vehicle *v* from separation centre *d* to manufacturer m in period *t*
$\gamma_{n,r}$	Amount of raw material *r* required in component *n*
$\mu_{p,n}$	Amount of component *n* required in product *p*
$Ls_{s,m}$	Distance between supplier *s* and manufacturer *m*
$Lm_{m,c}$	Distance between manufacturer *m* and customer *c*
$Ld_{c,d}$	Distance between customer *c* and separation centre *d*
$Ldm_{d,m}$	Distance between separation centre *d* and manufacturer *m*
Puv_v	Environmental damage of vehicle *v* for each kilometre
$Puo_{o,m}$	Environmental damage of technology *o* for manufacturer *m*
$e_{o,m,t}$	Cost of technology o for manufacturer *m* in period *t*
gr_r	Weight of each raw material *r*
gn_n	Weight of each component *n*
gp_p	Weight of each product *p*
$Tn_{n,m,o}$	Required time for producing each component *n* in manufacturer *m*
$Tp_{p,m}$	Required time for producing each product *p* in manufacturer *m*
$Td_{p,d}$	Required time for disassembling or separating of the return product *p* in separation centre *d*
$Hr_{r,m,t}$	Inventory cost of raw material *r* in manufacturer *m* in period *t*
$Hn_{n,m,t}$	Inventory cost of component *n* in manufacturer m in period *t*
$Hd_{p,d,t}$	Inventory cost of product *p* in separation centre *d* in period *t*
Wei_v	Maximum capacity of vehicle *v*
$Mrs_{r,s,t}$	Maximum capacity of supplier *s* for providing raw material *r* in period *t*
$Mri_{r,m,t}$	Maximum inventory capacity of manufacturer *m* for raw material *r* in t period
$Mni_{n,m,t}$	Maximum inventory capacity of manufacturer *m* for component *n* in period *t*
$Mdi_{p,d,t}$	Maximum inventory capacity of separation centre *d* for product *p* in period *t*
$Mnm_{m,t}$	Maximum capacity of manufacturer m for fabricating component in period *t*
$Mpm_{m,t}$	Maximum capacity of manufacturer m for producing products in period *t*
$Mpd_{d,t}$	Maximum capacity of separation centre *d* in period t
$Sat_{p,c}$	Minimal allowable demand fulfilment rate of product *p* for customer c
RR	Average rate of return product

RS	Average rate of good components after disassembling the product

Variables:

$Qtr_{r,s,m,v,t}$	Quantity of raw material *r* transferred from supplier *s* to manufacturer *m* by vehicle *v* in period *t*
$Qn_{n,m,o,t}$	Quantity of component *n* fabricated by technology *o* in manufacturer *m* in period *t*
$Qtp_{p,m,c,v,t}$	Quantity of product *p* transferred from manufacturer *m* to customer *c* by vehicle *v* in period *t*
$Qrp_{p,m,c,d,v,t}$	Quantity of returned product *p* from customer *c* disassembled in separation centre *d*, transferred to manufacturer m by vehicle *v* in period *t*
$Rp_{c,p,d,v,t}$	Quantity of product *p* returned from customer *c* to separation centre *d* by vehicle *v* in period *t*
$Nir_{r,m,t}$	Inventory of raw material *r* in manufacturer *m* in period *t*
$Nin_{n,m,t}$	Inventory of component *n* in manufacturer *m* in period *t*
$Nid_{p,d,t}$	Inventory of returned product *p* in separation centre d in period *t*
$B_{p,m,t}$	Shortage of product *p* in manufacturer *m* in period *t*
$Xn_{n,m,o,t}$	1 if component *n* produced in manufacturer *m* by technology *o* in period *t*
$Xtr_{r,s,m,v,t}$	1 if raw material *r* transferred from supplier *s* to manufacturer *m* by vehicle *v* in period *t*
$Xtp_{p,m,c,v,t}$	1 if product *p* transferred from manufacturer *m* to customer *c* by vehicle *v* in period *t*
$Xtdp_{p,m,c,d,v,t}$	1 if returned product *p* from customer *c* disassembled in separation centre *d*, transferred to manufacturer *m* by vehicle *v* in period *t*
$Xtd_{p,c,d,v,t}$	1 if product *p* returned from customer *c* to separation centre *d* by vehicle *v* in period *t*

2-2- Mathematical model

$$\begin{aligned}\text{Min } Z_1 = \sum_{t}^{T}\sum_{v}^{V}\sum_{c}^{C}\sum_{p}^{P}\sum_{n}^{N}\sum_{r}^{R}\sum_{m}^{M}\sum_{s}^{S} & Cr_{r,s,t}\,.\,Qtr_{r,s,m,v,t} + Cvs_{s,m,v,t}.Ls_{s,m}.Xtr_{r,s,m,v,t} \\ & + Hr_{r,m,t}.Nir_{r,m,t} + Cn_{n,m,o,t}.Qn_{n,m,o,t} + Hn_{n,m,t}.Nin_{n,m,t} + Cp_{m,p,t}.Qtp_{p,m,c,v,t} \\ & + Cvm_{m,c,v,t}.Lm_{m,c}.Xtp_{p,m,c,v,t} + Cd_{d,p,t}.Qrp_{p,m,c,d,v,t} + Hd_{p,d,t}.Nid_{p,d,t} \\ & + Cvd_{c,d,v,t}.Ld_{c,d}.Xtd_{p,c,d,v,t} + Cvn_{d,m,v,t}.Ldm_{d,m}.Xtdp_{p,m,c,d,v,t} \\ & + e_{o,m,t}.Xn_{n,m,o,t} + Cb_{p,m,t}.B_{p,m,t}\end{aligned} \quad (1)$$

$$\begin{aligned}\text{Min } Z_2 = \sum_{t}^{T}\sum_{v}^{V}\sum_{c}^{C}\sum_{p}^{P}\sum_{n}^{N}\sum_{r}^{R}\sum_{m}^{M}\sum_{s} & Puv_{v}.Ls_{s,m}.Xtr_{r,s,m,v,t} + Puv_{v}.Lm_{m,c}.Xtp_{p,m,c,v,t} \\ & + Puo_{o,m}.Xn_{n,m,o,t}\end{aligned} \quad (2)$$

s.t.

$$Dp_{p,c,t} \le \sum_{m}\sum_{v} Qtp_{p,m,c,v,t} \quad (3)$$

$$B_{p,m,t} \le \left(1 - Sat_{p,c}\right).Dp_{p,c,t} \quad (4)$$

$$\sum_{m}\sum_{v} Qtp_{p,m,c,v,t} + B_{p,m,t} = Dp_{p,c,t} + B_{p,m,t-1} \quad (5)$$

$$\sum_{d}\sum_{v} Rp_{c,p,d,v,t} > RR.Dp_{p,c,t} \quad (6)$$

$$\sum_{d}\sum_{v} Rp_{c,p,d,v,t} \le Dp_{p,c,t} \quad (7)$$

$$Nir_{r,m,t} = Nir_{r,m,t-1} + \sum_{s}\sum_{v} Qtr_{r,s,m,v,t} - \sum_{n}\sum_{o} \gamma_{n,r}.Qn_{n,m,o,t} \quad (8)$$

$$Nin_{n,m,t} = Nin_{n,m,t} + \sum_{o} Qn_{n,m,o,t} - \sum_{p} \mu_{p,n} . \sum_{c} \sum_{v} Qtp_{p,m,c,v,t} \tag{9}$$

$$Nid_{p,d,t+1} = Nid_{p,d,t} + \sum_{c} \sum_{v} Rp_{c,p,d,v,t} - \sum_{c} \sum_{m} \sum_{v} Qrp_{p,m,c,d,v,t} \tag{10}$$

$$\sum_{m} \sum_{v} Qtr_{r,s,m,v,t} \leq Mrs_{r,s,t} \tag{11}$$

$$\sum_{n} \sum_{o} Qn_{n,m,o,t}.Tn_{n,m,o} \leq Mnm_{m,t} \tag{12}$$

$$\sum_{p} \sum_{c} \sum_{v} Qtp_{p,m,c,v,t}.Tp_{p,m} \leq Mpm_{m,t} \tag{13}$$

$$\sum_{c} \sum_{m} \sum_{v} \sum_{d} Qrp_{p,m,c,d,v,t} .Td_{p,d} < Mpd_{d,t} \tag{14}$$

$$\sum_{r} Qtr_{r,s,m,v,t}.gr_{r} \leq Wei_{v} \tag{15}$$

$$\sum_{p} Qtp_{p,m,c,v,t}.gp_{p} \leq Wei_{v} \tag{16}$$

$$\sum_{p} Rp_{c,p,d,v,t}.gp_{p} \leq Wei_{v} \tag{17}$$

$$\sum_{c} \sum_{p} \sum_{n} Qrp_{p,m,c,d,v,t} .(1 - RS).\mu_{p,n}.gn_{n} < Wei_{v} \tag{18}$$

$$Qtr_{r,s,m,v,t} \leq Mbig\ .Xtr_{r,s,m,v,t} \tag{19}$$

$$Qtp_{p,m,c,v,t} \leq Mbig.Xtp_{p,m,c,v,t} \tag{20}$$

$$Qn_{n,m,o,t} \leq Mbig.Xn_{n,m,o,t} \tag{21}$$

$$Rp_{c,p,d,v,t} < M.Xtd_{p,c,d,v,t} \tag{22}$$

$$Qrp_{p,m,c,d,v,t} < M.Xtdp_{p,m,c,d,v,t} \tag{23}$$

$$Nin_{n,m,t} \leq Mni_{n,m,t} \tag{24}$$

$$Nir_{r,m,t} \leq Mri_{r,m,t} \tag{25}$$

$$Nid_{p,d,t} < Mdi_{p,d,t} \tag{26}$$

$$\sum_{o} Xn_{n,m,o,t} \leq 1 \tag{27}$$

$$\begin{aligned} &Qtr_{r,s,m,v,t}, Qn_{n,m,o,t}, Qtp_{p,m,c,v,t}, Nir_{r,m,t}, Nin_{n,m,t}, Nid_{p,d,t}, Rp_{c,p,d,v,t} \\ &Qrp_{p,m,c,d,v,t}, B_{p,m,t} \geq 0 \\ &Xn_{n,m,o,t}, Xtr_{r,s,m,v,t}, Xtp_{p,m,c,v,t}, Xtdp_{p,m,c,d,v,t}, Xtd_{p,c,d,v,t} = 0,1 \end{aligned} \tag{28}$$

The first objective function minimizes the total cost consisting of raw materials cost, component cost, product cost, shortage cost, and technology cost. The second objective function minimizes the environmental damage involving the transportation and technology environmental effects. The required quantity transferred to customers is stated in equation (3). The amount of permissible backordered products is shown in equation (4). Equation (5) shows the relationship between the volume of products delivered to each customer and the demand of each customer and the amount of backordered products. The restriction of the quantity of returned products is illustrated in equations (6) and (7). Inventory balance restriction of raw materials and components and returned product is stated in equations (8) – (10), respectively. The maximum capacity for supplying raw materials, fabricating components, producing final products, and separating of returned products are mentioned in equations (11) – (14), respectively. Equations (15) – (17) state the maximum capacity of vehicles to transfer raw materials, final products, and returned products, respectively. Transferring of component *n*, which achieved after disassembling, is shown in equation (18).

There is raw material *r* supplied from supplier *s* if and only if the raw material *r* transferred from supplier *s* (i.e., equation (19)). Also, there is final product *p* in customer *c* if and only if the product *p* transferred to customer *c* (equation 20). Equation (21) stated there is a quantity of component *n* (expect of inventory) if and only if the component n fabricated in manufacturer m by technology *o*. There is a quantity of returned product *p* if and only if product *p* returned from customer *c* to separation center *d* by vehicle *v* in period *t* (i.e., equation (22)). Returned product *p* from customer *c* disassembled in separation center *d*, if and only if transferred to manufacturer *m* by vehicle *v* in period *t* (i.e., equation (23)). Equations (24) – (26) are determined the maximum inventory capacity of raw materials and components and returned product. The component n should be fabricated only one technology which stated in equation (27).

3- Solution algorithm

The utility function method (Howang et al. 1980 and Pishvaee et al. 2014) is applied to convert the proposed bi-objective CLSC problem to a single objective model. The developed CLSC problem in a BTO environment organizes a large-sized problem. If the problem size increases, the computational time will be enhanced exponentially. The mixed-integer linear problem will be separated into a small-sized mode; so the Benders decomposition algorithm (BDA) is suitable for this model. In the BDA, the hard variables should be determined. The binary variables are considered the hared variables and fixed in this model. By fixing the hard variables, the sub-problem (SP) will be determined and following that the dual sub-problem (DSP) and master problem (MP) must be formulated. In this model, the DSP is the upper bound for the original problem as stated bellow:

$$\begin{aligned}\max DSP =& \textstyle\sum_p \sum_c \sum_t \sum_c \sum_r \sum_n \sum_s \sum_m \sum_v \sum_t Dp_{p,c,t}.Z2_{p,c,t} - Wei_v.Z3_{s,m,v,t} - Wei_v.Z4_{m,c,v,t} - \\ & Mnm_{m,t}.Z7_{m,t} - Mpm_{m,t}.Z8_{m,t} - Mni_{n,m,t}.Z9_{n,m,t} - Mri_{r,m,t}.Z10_{r,m,t} - \big(1 - \\ & Sat_{p,c}\big).Dp_{p,c,t}.Z13_{p,c,t} - M.\overline{Xtr_{r,s,m,v,t}}.z14_{r,s,m,v,t} - \\ & M.\overline{Xn_{n,m,o,t}}.Z15_{n,m,o,t} - \mathrm{M}.\overline{Xtp_{p,m,c,v,t}}.\ Z16_{p,m,c,v,t} + RR.Dp_{p,c,t}.Z17_{p,c,t} \\ & -Dp_{p,c,t}.Z18_{p,c,t} - Mdi_{p,d,t}.Z20_{p,d,t} - M.\overline{Xtdp_{p,m,c,d,v,t}}.Z21_{p,m,c,d,v,t} - M.\overline{Xtd_{p,c,d,v,t}}.Z22_{p,c,d,v,t} - \\ & Mpd_{d,t}.Z23_{d,t} - Wei_v.Z24_{d,m,v,t} - Wei_v.Z25_{c,d,v,t} + w1.(Cvs_{s,m,v,t}.\overline{Xtr_{r,s,m,v,t}}.Ls_{s,m} + \\ & Cvm_{m,c,v,t}.\overline{Xtp_{p,m,c,v,t}}.Lm_{m,c} + e_{o,m,t}.\overline{Xn_{n,m,o,t}} + \\ & Cvd_{c,d,v,t}.Ld_{c,d}.\overline{Xtd_{p,c,d,v,t}}Cvm_{m,c,v,t}.Ldm_{d,m}.\overline{Xtdp_{p,m,c,d,v,t}}) + w2.(Puv_v.\big(Ls_{s,m}.\overline{Xtr_{r,s,m,v,t}} + \\ & Lm_{m,c}.\overline{Xtp_{p,m,c,v,t}} + Ld_{c,d}.\overline{Xtd_{p,c,d,v,t}} + Ldm_{d,m}.\overline{Xtdp_{p,m,c,d,v,t}}\big) + Puo_{o,m}.\overline{Xn_{n,m,o,t}})\end{aligned} \tag{29}$$

s.t.

$$\begin{aligned}Z2_{p,c,t} - Z4_{m,c,v,t}.gp_p + \sum_n Z6_{n,m,t}.\mu_{p,n} - \sum_n ZZ6_{n,m,t}.\mu_{p,n} - Z8_{m,t}.Tp_{p,m} + Z12_{p,c,t} - ZZ12_{p,c,t} \\ - Z16_{p,m,c,v,t} \le w1.Cp_{m,p,t}\end{aligned} \tag{30}$$

$$-Z3_{s,m,v,t}.gr_r - Z5_{r,m,t} + ZZ5_{r,m,t} - Z14_{r,s,m,v,t} \le w1.Cr_{r,s,t} \tag{31}$$

$$Z5_{r,m,t} - Z5_{r,m,t+1} - ZZ5_{r,m,t} + ZZ5_{r,m,t+1} - Z10_{r,m,t} \le w1.Hr_{r,m,t} \tag{32}$$

$$\sum_r Z5_{r,m,t}.\gamma_{n,r} - Z6_{n,m,t} - \sum_r ZZ5_{r,m,t}.\gamma_{n,r} + ZZ6_{n,m,t} - Tn_{n,m,o}.Z7_{m,t} - Z15_{n,m,o,t} \le w1.Cn_{n,m,o,t} \tag{33}$$

$$Z6_{n,m,t} - Z6_{n,m,t+1} - ZZ6_{n,m,t} + ZZ6_{n,m,t+1} - Z9_{n,m,t} \le W1.Hn_{n,m,t} \tag{34}$$

$$\begin{aligned}-\sum_n Z6_{n,m,t}.(1-RS).\mu_{p,n} + Z19_{p,d,t} + \sum_n ZZ6_{n,m,t}.(1-RS).\mu_{p,n} - ZZ19_{p,d,t} \\ -Z21_{c,p,d,m,v,t} - Z23_{d,t}.Td_{p,d} - \sum_n Z24_{d,,m,v,t}.(1-RS).\mu_{p,n}.gn_n \le w1.Cd_{d,p,t}\end{aligned} \tag{35}$$

$$Z12_{p,c,t} - ZZ12_{p,c,t} - Z13_{p,c,t} \le W1.Cb_{p,m,t} \tag{36}$$

$$Z17_{p,c,t} - Z18_{p,c,t} - Z19_{p,d,t} + ZZ19_{p,d,t} - Z22_{c,p,d,v,t} - Z25_{c,d,v,t}.gp_p \le 0 \tag{37}$$

$$Z19_{p,d,t} - Z19_{p,d,t+1} - ZZ19_{p,d,t} + ZZ19_{p,d,t+1} - Z20_{p,d,t} \le W1.Hd_{p,d,t} \tag{38}$$

The master problem defined below is the lower bound of the objective function.

$$\mathrm{Min}\ MP = \textstyle\sum_t \sum_r \sum_n \sum_p \sum_s \sum_m \sum_c \sum_v \sum_d \sum_o w1.(Cvs_{s,m,v,t}.Xtr_{r,s,m,v,t}.Ls_{s,m} + \tag{39}$$

$Cvm_{m,c,v,t}.Xtp_{p,m,c,v,t}.Lm_{m,c} + e_{o,m,t}.Xn_{n,m,o,t} + Cvd_{c,d,v,t}.Ld_{c,d}.Xtd_{p,c,d,v,t} +$
$Cvm_{m,c,v,t}.Ldm_{d,m}.Xtdp_{p,m,c,d,v,t}) + w2.(Puv_v.\begin{pmatrix} Ls_{s,m}.Xtr_{r,s,m,v,t} + Lm_{m,c}.Xtp_{p,m,c,v,t} \\ +Ld_{c,d}.Xtd_{p,c,d,v,t} + Ldm_{d,m}.Xtdp_{p,m,c,d,v,t} \end{pmatrix} +$
$Puo_{o,m}.Xn_{n,m,o,t}) + \Gamma$

s.t.

$$\Gamma \geq \sum_p \sum_c \sum_t \sum_c \sum_r \sum_n \sum_s \sum_m \sum_v \sum_t Dp_{p,c,t}.Z2_{p,c,t} - Wei_v.Z3_{s,m,v,t} \tag{40}$$
$$-Wei_v.Z4_{m,c,v,t} - Mpm_{m,t}.Z8_{m,t} - Mni_{n,m,t}.Z9_{n,m,t} - Mri_{r,m,t}.Z10_{r,m,t} -$$
$$(1 - Sat_{p,c}).Dp_{p,c,t}.Z13_{p,c,t} - M.Xtr_{r,s,m,v,t}.z14_{r,s,m,v,t} - M.Xn_{n,m,o,t}.Z15_{n,m,o,t}$$
$$-\mathrm{M}.Xtp_{p,m,c,v,t}.\ Z16_{p,m,c,v,t} + RR.Dp_{p,c,t}.Z17_{p,c,t} - Dp_{p,c,t}.Z18_{p,c,t}$$
$$-M.Xtdp_{p,m,c,d,v,t}.Z21_{p,m,c,d,v,t} - M.Xtd_{p,c,d,v,t}.Z22_{p,c,d,v,t} - Mpd_{d,t}.Z23_{d,t}$$
$$-Wei_v.Z24_{d,m,v,t} - Wei_v.Z25_{c,d,v,t}$$

$$\sum_p \sum_c \sum_t \sum_c \sum_r \sum_n \sum_s \sum_m \sum_v \sum_t Dp_{p,c,t}.Z2_{p,c,t} - Wei_v.Z3_{s,m,v,t} - Wei_v.Z4_{m,c,v,t} - Mnm_{m,t}.Z7_{m,t} - \tag{41}$$
$$Mpm_{m,t}.Z8_{m,t} - Mni_{n,m,t}.Z9_{n,m,t} - Mri_{r,m,t}.Z10_{r,m,t} - (1 - Sat_{p,c}).Dp_{p,c,t}.Z13_{p,c,t} -$$
$$M.Xtr_{r,s,m,v,t}.z14_{r,s,m,v,t} - M.Xn_{n,m,o,t}.Z15_{n,m,o,t} - \mathrm{M}.Xtp_{p,m,c,v,t}.\ Z16_{p,m,c,v,t} + RR.Dp_{p,c,t}.Z17_{p,c,t}$$
$$-Dp_{p,c,t}.Z18_{p,c,t} - Mdi_{p,d,t}.Z20_{p,d,t} - M.Xtdp_{p,m,c,d,v,t}.Z21_{p,m,c,d,v,t}$$
$$-M.Xtd_{p,c,d,v,t}.Z22_{p,c,d,v,t} - Mpd_{d,t}.Z23_{d,t} - Wei_v.Z24_{d,m,v,t} - Wei_v.Z25_{c,d,v,t} \leq 0$$

$$\sum_o Xn_{n,m,o,t} \leq 1 \tag{42}$$

4- Computational results

Although there are several approaches to solve mixed-integer bi-objective models, exact methods are suitable. Our problem is presented by a mixed-integer linear model and can be divided into sub-problems. Then, we use the Benders decomposition algorithm (BDA). The GAMS software using by CPLEX solver is applied to solve the model performed with a Pentium CPU 2117U @ 1.80 GHz computer.

Table 1. Implementing the BDA

Size of the problem	BDA	
r × n × p × s × m × s × d × o × v × t	Lower bound	Upper bound
3 × 2 × 1 × 1 × 1 × 1 × 1 × 1 × 1 × 1	353137.643	353137.643
3 × 2 × 1 × 1 × 1 × 1 × 1 × 1 × 2 × 1	556284.318	556284.318
2 × 2 × 1 × 1 × 1 × 1 × 2 × 1 × 2 × 1	630134.808	630134.808
3 × 2 × 1 × 1 × 1 × 1 × 2 × 1 × 2 × 1	1010515.261	1010515.261
2 × 2 × 1 × 1 × 2 × 1 × 2 × 1 × 2 × 1	1266103.126	1266103.126
2 × 2 × 1 × 1 × 2 × 2 × 2 × 1 × 2 × 1	2538973.701	2538973.701
4 × 3 × 1 × 1 × 2 × 2 × 2 × 1 × 2 × 1	8023462.901	8023462.901
5 × 3 × 1 × 1 × 2 × 2 × 2 × 1 × 2 × 1	13053250	13053250
5 × 4 × 2 × 1 × 2 × 2 × 2 × 1 × 2 × 1	1828356.923	1828356.923
5 × 4 × 3 × 2 × 2 × 2 × 2 × 1 × 2 × 1	236985300	236985300
6 × 4 × 3 × 1 × 2 × 2 × 2 × 1 × 2 × 1	400422700	400422700

Different size problems are randomly generated to implement the BDA. Table 1 shows the upper and lower bounds for different size problems by setting $w_1 = 0.3$, $w_2 = 0.7$. As demonstrated in the sample instants, the BDA can be useful for different size problems. The convergence of the upper and lower bounds is shown in figure 1. It is reasonable, in which the trend of the lower bound is ascending and the upper bond has irregular changes. The values of upper and lower bounds in each iteration are detailed in table 2.

Table 2. Upper and lower bounds in the BDA

Iteration	Lower bound	Upper bound
1	-34267.8151919989	42427.8222627205
2	-31190.2657730436	978111.942775472
3	-30778.9832491514	467636.460381835
4	-30778.9832491514	595379.686329431
5	-28112.7163540883	454170.638077462
6	-25731.8751807304	333606.428215466
7	-25731.8751807304	459217.746145883
8	-23065.6082856673	389653.417106419
9	-22654.3257617752	1003494.26225401
10	-17398.1063383262	326041.872343223
11	325013.020962277	325013.020962277

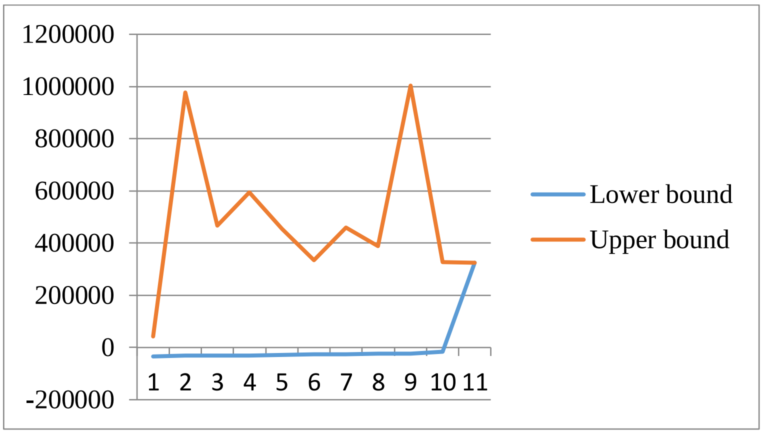

Fig. 1. Convergence of upper and lower bounds

5- Conclusions

This study considered a new bi-objective CLSC problem in a BTO environment, which presented in a mixed-integer linear programming (MILP) model. The chosen technology and its effect on the environment were considered. This bi-objective model aimed at minimizing the cost and environmental effect simultaneously. Since it was a BTO problem, there was no inventory of the final product. Also, since the model is in a BTO environment, the returned products from customers disassembled in the separation centre, and the components are transferred to the plants to remanufacture. The presented model has decomposed a structure; thus, the BDA was used to solve the problem. The extension of our study can be found in using the queue theory or game theory in the model. Also, double Benders decomposition is another suggestion for future study.

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