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Optimizing Integrated Production-Distribution in a Sustainable Closed-Loop Supply Chain: A Bi-Objective Approach

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ABSTRACT

Efficient integrated production-distribution planning has emerged as a focal point in contemporary forward supply chain management, celebrated for its substantial economic advantages. This research delves into the intricacies of integrated production-distribution planning within the context of a multi-tiered green closed-loop supply chain, encompassing recycling centers, manufacturing/remanufacturing facilities, and decentralized distribution centers. We introduce a comprehensive three-tiered bi-objective model aimed at enhancing profitability while concurrently mitigating adverse environmental impacts. To address the inherent complexity of this problem, we employ a refined multi-choice goal programming methodology and leverage a hierarchical iteration algorithm for resolution. Our research contributes to the evolving field of sustainable supply chain management by offering insights into the optimization of integrated production and distribution within a closed-loop framework, aligning economic interests with environmental stewardship.

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1. Introduction

Production- Supply chain optimization hinges on production-distribution planning, a pivotal activity. Within production planning, decisions encompass workforce allocation, production scheduling in both regular and overtime hours, negotiation of lateral contracts, and scrutiny of machine capacity over a specific planning horizon. Conversely, distribution planning entails identifying the facilities responsible for meeting market demands. In the past, suppliers, manufacturers, distributors, and retailers were seen as distinct entities striving to maximize their individual profits (Barbarosoğlu & Özgür, 1999). Nonetheless, the pursuit of maximum profits by independent companies does not necessarily translate to maximizing the overall profits of the entire supply chain. Hence, integrating production-distribution planning (PDP) decisions is imperative to ensure the holistic performance and significance of the supply chain (Liang & Cheng, 2009).

Green supply chain management (GSCM) seeks to embed environmental considerations and requirements within supply chain management (SCM). This encompasses the sourcing of raw materials, the production and delivery processes, meeting customer demands, and managing product life cycles (Srivastava, 2008). Lin et al. (2014) categorized the diverse strategies employed in designing green closed-loop supply chain networks (CLGSCND) into three main groups: optimizing fuel consumption, reducing greenhouse gas (GHG) emissions, and enhancing waste management (Dekker et al., 2012).

This study aims to optimize integrated production-distribution planning within a green closed-loop supply chain (GCLSC) by introducing a three-tier network design which is formulated and solved by a bi-objective mathematical model and hierarchical iteration algorithm, respectively.

The remainder of this paper is organized as follows: Section 2 presents the literature review, Section 3 delves into assumptions and mathematical models, Section 4 discusses the proposed solutions, and Section 5 provides numerical models. Finally, the paper is concluded in Section 6.

2. Literature Review

The design and analysis of production-distribution systems have been a subject of interest for numerous years. Geoffrion and Graves (1974) introduced an algorithm rooted in Bander's analysis to address the single-cycle multi-product production-distribution problem.

Ma et al. (2016) proposed a production-distribution planning model employing bi-level planning for supply chain management. Rafiei et al. (2018) tackled an integrated production and distribution planning problem within a four-level supply chain, with dual objectives of cost minimization and service level maximization. Jing and Li (2018) conducted an examination of a multi-level decentralized closed-loop supply chain system encompassing a recycling center, various production and reproduction facilities, and decentralized distribution to diverse regions. They recently devised a hierarchical iterative strategy employing the self-adaptive genetic algorithm (SAGA) as a solution approach. Mano et al. (2019) introduced a mathematical model aimed at optimizing the production and distribution of marine equipment in Italy. Their study comprehensively analyzed the impact of each cost factor on production and distribution decisions. Furthermore, Golsefidi and Jokar (2020) utilized robust optimization techniques to concurrently optimize production, distribution, and inventory, using genetic algorithms and simulated annealing for optimization.

This study is a continuation of the research initiated by Jing and Li (2018) and expanded upon by Golsefidi and Jokar (2020). It encompasses the criteria of a bi-objective green closed-loop supply chain, with the goal of enhancing profits, mitigating adverse environmental impacts, and accommodating variable vehicle capacities within the model. Furthemore, a heuristic algorithm is applied in order to deal with the model complexity and find optimal solutions.

3. Mathematical model

This study centers on a multi-level, decentralized, closed-loop supply chain system composed of several recycling centers, numerous production and reproduction factories, and various decentralized distributors operating across distinct regions.

The primary role of recycling centers is to disassemble returned products into their constituent parts. If these parts conform to standardized specifications, they are stored in inventory as high-quality components; otherwise, they are set aside. High-quality parts are then dispatched to production/reproduction factories in accordance with manufacturing demands.

When necessary, these parts undergo processing within the production/reproduction factories. High-quality parts are maintained in the inventory of quality components, while parts generated through the reprocessing of high-quality components are stored in the inventory of reproduced parts. Additionally, factories engage in the production of new parts through the processing of raw materials. The final products are fabricated by assembling reproduced and high-quality parts and are subsequently stockpiled in the inventory of reproduced products. Meanwhile, new products are assembled using new parts and stored in the inventory for new products.

In accordance with downstream orders, either new or reproduced products are distributed to various distributors. Each distributor has the flexibility to select one or more factories for service and subsequently delivers both new and reproduced products to retailers or customers for sale. Simultaneously, distributors collect expired products from retailers or customers and return them to recycling centers as returned items. The assumptions of the model include the following:

- Demand for reproduced and new products is definite and the sale price of reproduced products is lower than that of new products.
- The cost of production varies from one factory to another.
- The capacity differs for various vehicles.
- Shipping costs vary between nodes.
- Transportation of vehicles at each level and each period is allowed to emit a limited rate of greenhouse gases.
- The processing of parts will emit greenhouse gases into the environment.

Indices

t: The set of indices of periods $\{1, \dots, T\}$

p: The set of indices of the product type $\{1, \dots P\}$

c: The set of indices of the part type $\{1, \dots C\}$

v: The set of indices of the type of vehicle $\{1, \dots V\}$

i: The set of indices of production/reproductions factories $\{1, \dots I\}$

j: The set of indices of distributors $\{1, \dots J\}$

k: The set of indices of recycling centers $\{1, \dots K\}$

Moreover, the parameters and variables are described in Table 1.

Table 1. Parameters and variables.

Parameters of the first-level model	
PPC_{kict}	The cost of purchasing each part (case) with the quality of c by the production/reproduction factory of i to the recycling center at the period of t
$URCC_{jkpt}$	The cost of purchasing each returned product P of the recycling center of k to the distributor j at the period t
SDT_{kpt}	The cost of implementation if the returned product p is separated and tested in the recycling center k at the period t
$UDTC_{kpt}$	The cost of separating and testing each returned product P in the recycling center k at the period t
UDC_{kct}	The cost of disposing each unit of part c in the recycling center k at the period t
$ICQC^{R}_{kct}$	The cost of each part with the quality of c in the recycling center of k at the period t
$ICRP^{R}_{kpt}$	The cost of each returned part P in the recycling center k at the period t
UTC^{RF}_{kicvt}	The cost of transporting each part with the quality of c from the recycling center k to production/reproduction factories i at the period t
BOC_{pc}	A list of part c in the product p
θ_{ct}	The rate of reproduction of part c at the period t
$\bar{\alpha}^{R}_{kp}$	Maximum inventory of the returned product p in the recycling center k
$\bar{\beta}^{R}_{kc}$	Maximum inventory of the part with the quality of c in the recycling center
MDT^{R}_{kp}	Maximum volume of the returned product p that can be separated and tested in each period in the recycling center k
cap^{RF}_{v}	The capacity of a vehicle v floating between the recycling center and the production/reproduction factory
dis^{RF}_{ki}	The distance between the recycling center k and production/reproduction factories i
$Emis^{RF}_{kicvt}$	The rate of GHGs emission for each part with the quality of c by the vehicle v per each kilometer between the recycling center k and production/reproduction factories i
TE^{maxRF}_{t}	Maximum allowable emission of GHGs by the transportation system floating between the recycling center and factories at the period t
Parameters in the second-level model	
MPN_{ijpt}	Mean price of each unit of product p by the distributor j to the production/reproduction factory i at the period t
MPR_{ijpt}	Mean price of each unit of reproduced product p by the distributor j to the production/reproduction factory i at the period t

SA_{ipt}	The cost of implementation if the new product p is assembled in the factory i at the period t.
SRA_{ipt}	The cost of implementation if the reproduced product p is assembled in the factory i at the period t.
UAC_{ipt}	The cost of assembling each unit of product p in the factory i at the period t
$URAC_{ipt}$	The cost of assembling each unit of reproduced product p in the factory i at the period t
SP_{ict}	The cost of implementation if part c is newly processed in factory i at the period t
RSP_{ict}	The cost of implementation if part c is newly reprocessed in factory i at the period t
UPC_{ict}	The cost of processing each part c in the factory i at the period t
$URPC_{ict}$	The cost of reprocessing each part c in the factory i at the period t
$ICNP_{ipt}^{F}$	The cost of inventory of each unit of new product p in the factory i at the period t
$ICRMP_{ipt}^{F}$	The cost of inventory of each unit of reproduced product p in factory i at the period t
$ICQC_{ict}^{F}$	The cost of inventory of each part with the quality of c in the factory i at the period t
$ICNC_{ict}^{F}$	The cost of inventory of each unit of new part c in the factory i at the period t
$ICRC_{ict}^{F}$	The cost of inventory of each unit of reproduced part c in factory i at the period t
UTC_{ijpvt}^{FD}	The transportation cost of each unit of product p by the vehicle v from the factory i to the distributor j at the period t
$\bar{\beta}_{ic}^{F}$	Maximum inventory of each part with the quality of c in the factory i at the period t
$\bar{\zeta}_{ie}^{F}$	Maximum inventory of new part c in factory i at the period t
$\bar{\xi}_{ic}^{F}$	Maximum inventory of reproduced part c in factory i at the period t
$\bar{\lambda}_{ip}^{F}$	Maximum inventory of new product p in factory i at the period t
$\bar{x}_{ip}^{F}$	Maximum inventory of reproduced product p in factory i at the period t
MA_{ip}	Maximum volume of new product p that can be assembled in factory i
MRA_{ip}	Maximum volume of reproduced product p that can be assembled in the factory i
MP_{ic}	Maximum volume of part c that can be processed in factory i
MRP_{ic}	Maximum volume of part c that can be reprocessed in factory i
cap_{v}^{FD}	The capacity of vehicle v floating between the production/reproduction factory and the distribution center
dis_{ij}^{FD}	The distance between the production/reproduction factory i and the distributor j
$Emis_{ijcvt}^{FD}$	The rate of emitting GHGs by the vehicle v to manufacture each unit of product p per kilometer between the production/reproduction factory i and the distributor j
$Emispnc_{ict}^{F}$	The rate of emitting GHGs during the process of each new part c in the production/reproduction factory i and the distributor j
$Emisprc_{ict}^{F}$	The rate of emitting GHGs during the reprocessing of each new part c in the production/reproduction factory i and the distributor j

$OPE_t^{\max F}$	Maximum allowable emission of GHGs at the period t during production/reproduction operations in factories
$TE_t^{\max FD}$	Maximum allowable emission of GHGs by the transportation system floating between the factory and the distributor j
PPC_{kicvt}	These parameters have occurred at the first level of the model.
BOC_{pc}	These parameters have occurred at the first level of the model.
The third-level model	
SPN_{jpt}	The sale price of each unit of new product p in the distributor j at the period t
SPR_{jpt}	The sale price of each unit of reproduced product p in the distributor j at the period t
DNM_{jpt}	Demand for a new product p in the market of distributor j at the period t
DRM_{jpt}	Demand for a reproduced product p in the market of distributor j at the period t
$URCD_{jpt}$	The cost of purchasing each returned product p paid to retailers or customers by the distributor j at the period t
$USNP_{jpt}$	The cost of the lake of each new product p by the distributor at the period t
$USRP_{jpt}$	The cost of the lake of each reproduced product p by the distributor at the period t
$ICNP_{jpt}^D$	The inventory cost of each new product p in the distributor j at the period t
$ICRM_{jpt}^D$	The inventory cost of reproduced product p in the distributor j at the period t
$ICRP_{jpt}^D$	The inventory cost of each returned product p in the distributor j at the period t
UTC_{jkpt}^{DR}	The cost of transporting each unit of returned product p by the distributor j to the recycling center k at the period t
EPA_{jpt}	Maximum volume of the returned product p available in the market of distributor j at the period t
$\bar{\lambda}_{ip}^D$	Maximum inventory of new products p in the market of distributor j
$\bar{x}_{ip}^d$	Maximum inventory of reproduced products p in the market of distributor j
$\bar{\alpha}_{ip}^d$	Maximum inventory of returned products p in the market of distributor j
cap_v^{DR}	The capacity of vehicle v floating between the distributor and the recycling center
dis_{jk}^{DR}	The distance between the distributor j and the recycling center k
$Emis_{jkpvt}^{DR}$	The rate of emitting GHGs by the vehicle v for each unit of returned product p per kilometer between the distributor j and the recycling center k
$TE_t^{\max DR}$	Maximum allowable emission of GHGs by the transportation system between the distributor and recycling centers at the period t
Decision variables at the first level of the model	
af_{kicvt}	The volume of a part with the quality of c that is transported by the vehicle v from the recycling center k to the factory i at the period t
da_{jkpvt}	The volume of the returned product p that is transported by the vehicle v from the distributor j to the recycling center k at the period t

dt_{kpt}	The volume of returned product p that is separated and tested in the recycling center k at the period t
d_{kct}	The volume of product c that is disposed in the recycling center k at the period t
α^{R}_{kpt}	The inventory of returned product p in the recycling center k at the end of the period t
β^{R}_{kpt}	The inventory of product with the quality of c in the recycling center k at the end of the period t
σ_{kpt}	Zero and one. If the returned product p is separated and tested in the recycling center k at the period t, it will gain the value of one, otherwise zero.
Decision variables at the second level of the model	
fdn_{ijpvt}	The volume of new product p that is transported by the vehicle v from the factory i to the distributor at the period t
fdr_{ijpvt}	The volume of reproduced product p that is transported by the vehicle v from the factory i to the distributor at the period t
x_{ipt}	The volume of new product p that is assembled in the factory i at the period t
y_{ipt}	The volume of reproduced product p that is assembled in the factory i at the period t
w_{ict}	The volume of new part c that is processed in the factory i at the period t
z_{ict}	The volume of part c that is reprocessed in the factory i at the period t
λ^{F}_{ipt}	The inventory of new product p in the factory i at the end of the period t
x^{F}_{ipt}	The inventory of reproduced product p in the factory i at the end of the period t
β^{F}_{ict}	The inventory of part with the quality of c in the factory i at the end of the period t
ζ^{F}_{ict}	The inventory of reproduced part c in the factory i at the end of the period t
ξ^{F}_{ict}	Binary variable; if the new product p is assembled in the factory i at the period t, it will gain the value of one, otherwise zero.
η_{ipt}	Binary variable; if the reproduced product p is assembled in the factory i at the period t, it will assigned the value of one, otherwise zero.
δ_{ipt}	Binary variable; if the new part c is assembled in factory i at the period t, it will gain the value of one, otherwise zero.
π_{ict}	Binary variable; if the new part c is processed in factory i at the period t, it will gain the value of one, otherwise zero.
τ_{ict}	Binary variable; if the new part c is reprocessed in factory i at the period t, it will gain the value of one, otherwise zero.
$subc_{ict}$	The value for alternating part c in the factory i at the period t
af_{kicvt}	This variable has occurred at the first level of the model
Decision variables at the third level of the model	
nss_{jpt}	The volume of the lake of new product p in the distributor j at the period t
rss_{jpt}	The volume of the lake of reproduced product p in the distributor j at the period t

γ_{jpt}	The volume of returned product p that is collected by the distributor j from downstream markets at the period t
λ^{D}_{jpt}	The inventory of new product p in the distributor j at the end of the period t
x^{D}_{jpt}	The inventory of reproduced product p in the distributor j at the end of the period t
α^{D}_{jpt}	The inventory of returned product p in the distributor j at the end of the period t

3.1. First level: Recycling Centers

In recycling centers, it is attempted to increase total profit and diminish harmful environmental impacts, as follows:

$$\max F_1^R = \sum_{k=1}^{K}\sum_{i=1}^{I}\sum_{c=1}^{C}\sum_{v=1}^{V}\sum_{t=1}^{T} PPC_{kict} - \left(\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{p=1}^{P}\sum_{v=1}^{V}\sum_{t=1}^{T} URCC_{jkpt}\, da_{ijpvt} + \sum_{k=1}^{K}\sum_{p=1}^{P}\sum_{t=1}^{T} SDT_{kpt}\sigma_{kpt} + \sum_{k=1}^{K}\sum_{p=1}^{P}\sum_{t=1}^{T} UDTCT_{kpt}\, dt_{kpt} + \sum_{k=1}^{K}\sum_{c=1}^{C}\sum_{t=1}^{T} UDC_{kct}\, d_{kct} + \sum_{k=1}^{K}\sum_{p=1}^{P}\sum_{t=1}^{T} ICRP^R_{kpt}\alpha^R_{kpt} + \sum_{k=1}^{K}\sum_{c=1}^{C}\sum_{t=1}^{T} ICRP^R_{kct}\beta^R_{kct} + \sum_{k=1}^{K}\sum_{i=1}^{I}\sum_{c=1}^{C}\sum_{v=1}^{V}\sum_{t=1}^{T} PPUTC^{RF}_{kicvt}\, af_{kicvt}\right) \quad (1)$$

Objective function (1): It includes the total profit of recycling centers, revenue minus total expenses of recycling, total costs of separation and testing, total costs of disposal, total inventory costs, and total transportation costs.

Objective function (2): It minimizes the rate of emitting GHGs by each transportation vehicle for each high-quality part per kilometer between recycling centers and production/reproduction factories.

3.1.1. Constraints of the first level

Equations to retain inventory of returned products and high-quality parts are as follows:

$$\alpha^R_{kpt} = \alpha^R_{kp,t-1} + \sum_{j=1}^{J}\sum_{v=1}^{V} da_{jkpvt} - dt_{kpt} \quad \forall k,p,t, \quad (3)$$

$$\beta^R_{kpt} = \beta^R_{kp,t-1} + \sum_{p=1}^{P} BOC_{pc}.dt_{kpt} - d_{kpt} \quad \forall k,c,t, \quad (4)$$

The value assigned for low-quality parts that must be disposed as follows (the capacity of disposing parts):

$$\sum_{p=1}^{P} BOC_{pc}.dt_{kpt}(1-\theta_{kct}) \le d_{kpt} \quad \forall k,c,t, \quad (5)$$

Constraints for inventory of returned products and high-quality parts are as follows:

$$\alpha^R_{kpt} \le \bar{\alpha}^R_{kp} \quad \forall k,p,t, \quad (6)$$

$$\beta_{kct}^{R} \le \bar{\beta}_{kc}^{R} \qquad \forall k,c,t, \tag{7}$$

Constraint for the capacity of separating and testing is as follows:

$$dt_{kpt} \le MDT_{kp}^{R}\ \sigma_{kpt} \qquad \forall k,c,t, \tag{8}$$

The limitation for capacity of transportation from the recycling center to production/reproduction factories is as the following equation:

$$\sum_{k=1}^{K}\sum_{i=1}^{I}\sum_{c=1}^{C}\sum_{t=1}^{T} af_{kicvt} \le cap_{v}^{RF} \qquad \forall v, \tag{9}$$

Constraint on the maximum allowable emission of GHGs by transportation vehicles is as follows:

$$\sum_{k=1}^{K}\sum_{i=1}^{I}\sum_{v=1}^{V}\sum_{t=1}^{T} dis_{ki}^{RF}.Emis_{kicvt}^{RF} \le TE_{t}^{\max RF} \qquad \forall t, \tag{10}$$

Constraint of a negative integer for variables is as follows (the set of integers Z):

$$af_{kicvt}, da_{jkpt}, dt_{kpt}, d_{kct}, \alpha_{kpt}^{R}, \beta_{kct}^{R} \ge 0 \in Z, \qquad \forall k,i,p,c,v,t, \tag{11}$$

Constraint of binary numbers for variables is according to Equation (12), as follows:

$$\sigma_{kpt} \in (0,1) \qquad \forall k,p,t. \tag{12}$$

3.2. Second Level: Production/Reproduction Factories

The first objective function of the second level seeks to maximize the total profit of all factories, including sale revenue minus total expenses of production, total costs of reproduction, total inventory costs, and total transportation costs.

$$\begin{aligned}
\max F_{1}^{R} = {} & \sum_{i=1}^{i}\sum_{j=1}^{J}\sum_{p=1}^{P}\sum_{v=1}^{V}\sum_{t=1}^{T} MPN_{ijpt}.fdn_{ijpvt} + \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{p=1}^{P}\sum_{v=1}^{V}\sum_{t=1}^{T} MPR_{ijpt}.fdr_{ijpvt} \\
& - \left(\sum_{i=1}^{I}\sum_{p=1}^{P}\sum_{t=1}^{T} \left(SA_{ipt}.\eta_{ipt} + UAC_{ipt}x_{ipt}\right) + \sum_{i=1}^{I}\sum_{c=1}^{C}\sum_{t=1}^{T} \left(Sp_{cit}.\pi_{cit} + UpC_{cit}.w_{cit}\right) \right. \\
& + \sum_{i=1}^{I}\sum_{p=1}^{P}\sum_{t=1}^{T} \left(SRA_{ipt}.\delta_{ipt} + URAC_{ipt}y_{ipt}\right) + \sum_{c=1}^{C} \left(SRP_{cit}.\tau_{cit} + URPC_{cit}.z_{cit}\right) \\
& + \sum_{i=1}^{I}\sum_{p=1}^{P}\sum_{t=1}^{T} \left(ICNP_{ipt}^{F}.\lambda_{pit}^{F} + ICRMP_{pit}^{F}.x_{ipt}^{F}\right) \\
& + \sum_{i=1}^{I}\sum_{c=1}^{C}\sum_{t=1}^{T} \left(ICQC_{ict}^{F}\beta_{ict}^{F} + ICNC_{ict}^{F}\zeta_{ict}^{F} + ICRC_{ict}^{F}\xi_{ict}^{F}\right) \\
& + \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{p=1}^{P}\sum_{v=1}^{V}\sum_{t=1}^{T} \left(UTC_{ijpvt}^{FD} fdn_{ijpvt} + UTC_{ijpvt}^{FD}.fdr_{ijpvt}\right) \\
& \left. + \sum_{k=1}^{K}\sum_{i=1}^{I}\sum_{c=1}^{C}\sum_{v=1}^{V}\sum_{t=1}^{T} PPC_{kict}.af_{kicvt} \right)
\end{aligned} \tag{13}$$

The second objective function minimizes the emission of GHGs by each transportation vehicle for each new and reproduced product per kilometer between recycling centers and production/reproduction factories, and the rate of emitting GHGs during the processing of new products and reprocessing of parts.

$$\min F_2^R = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{p=1}^{P}\sum_{v=1}^{V}\sum_{t=1}^{T} dis_{ij}^{FD}\, Emmis_{ijpvt}^{FD}.(fdn_{ijpvt} + fdr_{ijpvt}) + \sum_{i=1}^{I}\sum_{c=1}^{C}\sum_{t=1}^{T} Emispnv_{ict}^{F}.w_{ict} + \sum_{i=1}^{I}\sum_{c=1}^{C}\sum_{t=1}^{T} Emispnv_{ict}^{F}.z_{ict} \quad (14)$$

3.2.1. Constraints of the second level

Equations for retaining the inventory of high-quality parts, reproduced parts, new products, and reproduced produces are as follows:

$$\beta_{ict}^{F} = \beta_{ic,t-1}^{F} + \sum_{k=1}^{K}\sum_{v=1}^{V} af_{kicvt} - z_{ict} \qquad \forall i,c,t, \quad (15)$$

$$\zeta_{ict}^{F} = \zeta_{ic,t-1}^{F} + w_{ict} - \sum_{p=1}^{P} BOC_{pc}.x_{ipt} - subc_{ict} \qquad \forall i,c,t, \quad (16)$$

$$\xi_{ict}^{F} = \xi_{ic,t-1}^{F} + z_{ict} - \sum_{p=1}^{P} BOC_{pc}.y_{ipt} - subc_{ict} \qquad \forall i,c,t, \quad (17)$$

$$\lambda_{ipt}^{F} = \lambda_{ip,t-1}^{F} + x_{ipt} - \sum_{j=1}^{J}\sum_{v=1}^{V} fdn_{ijpvt} \qquad \forall i,p,t, \quad (18)$$

$$x_{ipt}^{F} = x_{ip,t-1}^{F} + y_{ipt} - \sum_{j=1}^{J}\sum_{v=1}^{V} fdr_{ijpvt} \qquad \forall i,p,t. \quad (19)$$

Constraints for the inventory of high-quality parts, new parts, reproduced parts, new products, and reproduced parts are as follows:

$$\beta_{ict}^{F} \le \bar{\beta}_{ic}^{F} \qquad \forall i,c,t, \quad (20)$$

$$\zeta_{ict}^{F} \le \bar{\zeta}_{ic}^{F} \qquad \forall i,c,t, \quad (21)$$

$$\xi_{ict}^{F} \le \bar{\xi}_{ic}^{F} \qquad \forall i,c,t, \quad (22)$$

$$\lambda_{ipt}^{F} \le \bar{\lambda}_{ip}^{F} \qquad \forall i,p,t, \quad (23)$$

$$x_{ipt}^{F} \le \bar{x}_{ip}^{F} \qquad \forall i,p,t. \quad (24)$$

Constraints for the capacity of processing, reprocessing, and assembling new and reproduced products are applied as follows:

$$w_{ict} \le MP_{ic}.\pi_{ict} \qquad \forall i,c,t, \quad (25)$$

$$z_{ict} \le MRP_{ic}.\tau_{ict} \qquad \forall i,c,t, \quad (26)$$

$$x_{ipt} \le MA_{ip}\eta_{ipt} \qquad \forall i,p,t, \quad (27)$$

$$y_{ipt} \le MRA_{ip}\delta_{ipt} \qquad \forall i,p,t. \quad (28)$$

Constraint for the capacity of transportation from production/reproduction factories to distribution centers are as follows:

$$\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{p=1}^{P}\sum_{t=1}^{T}(fdn_{ijpvt} + fdr_{ijpvt}) \le cap_{v}^{FD} \qquad \forall v, \quad (29)$$

Constraint for maximum allowable emission of GHGs by transportation vehicles are as follows:

$$\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{p=1}^{P}\sum_{t=1}^{T} dis_{ij}^{FD}.Emis_{ijpvt}^{FD}.(fdn_{ijpvt}+fdr_{ijpvt}) \le TE_t^{\max FD} \qquad \forall t, \qquad (30)$$

Constraint for maximum allowable emission of GHGs for the processing and reprocessing operations in factories is applied as follows:

$$\sum_{i=1}^{I}\sum_{c=1}^{C} Emispnc_{ict}^{F}.w_{ict}+\sum_{i=1}^{I}\sum_{c=1}^{C} Emispnc_{ict}^{F}.z_{ict} \le OPE_t^{\max F} \qquad \forall t, \qquad (31)$$

Constraint of negative integer for variables is applied as follows:

$$fdn_{ijpvt}, fdr_{ijpvt}, af_{kicvt}, x_{ipt}, y_{ipt}, w_{ict}, z_{ict}, \beta_{ict}^{F}, \zeta_{ict}^{F}, \xi_{ict}^{F}, \lambda_{ipt}^{f}, x_{ipt}^{F} \ge 0, \qquad (32)$$

Constraint for binary variables is applied as follows:

$$\pi, \tau, \eta, \delta \in (0,1). \qquad (33)$$

3.3. Third Level: Distributors

The first objective function of the third level tries to maximize the total profit of all distributors, including sale revenue minus total expenses of purchases, total costs of recycling, total costs of deficiencies, total inventory costs, and total transportation costs.

$$\begin{aligned}
\max F_1^D = & \sum_{j=1}^{J}\sum_{p=1}^{P}\sum_{t=1}^{T} SPN_{ijpt}.(DNM_{ipt}-nss_{jpt}) \\
& + \sum_{j=1}^{J}\sum_{p=1}^{P}\sum_{t=1}^{T} SPR_{ijpt}.(DRM_{ipt}-rss_{jpt}) + \sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{p=1}^{P}\sum_{v=1}^{V}\sum_{t=1}^{T} URCC_{jkpt}da_{ijpvt} \\
& - \Bigg(\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{p=1}^{P}\sum_{v=1}^{V}\sum_{t=1}^{T} (MPN_{ijpt}.fdn_{ijpvt}+MRN_{ijpt}.fdr_{ijpvt}) \\
& + \sum_{j=1}^{J}\sum_{p=1}^{P}\sum_{t=1}^{T} URCD_{jpt}.\gamma_{jpt} + \sum_{j=1}^{J}\sum_{p=1}^{P}\sum_{t=1}^{T} S(USNP_{jpt}.nss_{jpt}+USRP_{jpt}.rss_{jpt}) \\
& + \sum_{j=1}^{J}\sum_{p=1}^{P}\sum_{t=1}^{T} (ICNP_{jpt}^{D}.\lambda_{jjpt}^{D}+ICRMP_{jpt}^{D}.x_{jpt}^{D}+ICRP_{jpt}^{d}.\alpha_{jpt}^{D}) \\
& + \sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{p=1}^{P}\sum_{v=1}^{V}\sum_{t=1}^{T} UTC_{jkpvt}^{DR}.da_{jkpvt} \Bigg)
\end{aligned} \qquad (34)$$

The second objective function of the third level minimizes the emission of GHGs by each transportation vehicle for each returned product per kilometer between distributors and recycling centers.

$$min\ F_2^R = \sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{p=1}^{P}\sum_{v=1}^{V}\sum_{t=1}^{T} dis_{ik}^{DR}\, Emis_{jkpvt}^{DR}.\, da_{jkpvt} \tag{35}$$

3.3.1. Constraints of the third level of the model

Equations of retaining the inventory of new products, reproduced products, and returned products are as follows:

$$\lambda_{jpt}^{D} = \lambda_{jp,t-1}^{D} + \sum_{i=1}^{I}\sum_{v=1}^{V} fdn_{ijpvt} - \left(DNM_{jpt} - nss_{jpt}\right) \quad \forall\, j,p,t, \tag{36}$$

$$x_{jpt}^{D} = x_{jp,t-1}^{D} + \sum_{i=1}^{I}\sum_{v=1}^{V} fdr_{ijpvt} - \left(DRM_{jpt} - rss_{jpt}\right) \quad \forall\, j,p,t, \tag{37}$$

$$\alpha_{jpt}^{D} = \alpha_{jp,t-1}^{D} + \gamma_{jpt} + \sum_{k=1}^{K}\sum_{v=1}^{V} da_{kjpvt} \quad \forall\, j,p,t, \tag{38}$$

Constraint for the volume of collected returned products that cannot be greater than the volume of returned products available at the market is applied as follows:

$$\gamma_{jpt} \le EPA_{jpt} \quad \forall\, j,p,t, \tag{39}$$

Constraints for the lack of new and reproduced products are as follows:

$$nss_{jpt} \le DNM_{jpt} \quad \forall\, j,p,t, \tag{40}$$

$$rss_{jpt} \le DRM_{jpt} \quad \forall\, j,p,t, \tag{41}$$

Constraints of the level of inventory of new and reproduced products are applied as follows:

$$nss_{jpt} \le DNM_{jpt} \quad \forall\, j,p,t, \tag{40}$$

$$rss_{jpt} \le DRM_{jpt} \quad \forall\, j,p,t, \tag{41}$$

Constraints of the level of inventory of new, reproduced, and returned products are as follows:

$$\lambda_{ipt}^{D} \le \bar{\lambda}_{ip}^{D} \quad \forall i,p,t, \tag{42}$$

$$x_{ipt}^{D} \le x_{ip}^{D} \quad \forall i,p,t, \tag{43}$$

$$\alpha_{ipt}^{D} \le \bar{\alpha}_{ip}^{D} \quad \forall i,p,t, \tag{44}$$

Constraint for the capacity of transportation vehicles is applied as follows:

$$\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{p=1}^{P}\sum_{t=1}^{T} dda_{jkpvt} \le cap_v^{DR} \quad \forall v, \tag{45}$$

Constraint for maximum allowable emission of GHGs by transportation vehicles used by distributors is as the following equation:

$$\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{p=1}^{P}\sum_{v=1}^{V} dis_{jk}^{DR}.\, Emis_{jkpvt}^{DR}.\left(da_{jkpvt}\right) \le TE_t^{\max DR} \quad \forall t, \tag{46}$$

Constraint of negative integer for variables is applied as follows:

$$nss_{jpt}, rss_{jpt}, da_{jkpvt}, fdn_{ijpvt}, fdr_{ijpvt}, \gamma_{ipt}, \lambda^{D}_{jpt}, x^{D}_{jpt}, \alpha^{D}_{jpt} \geq 0. \quad (47)$$

4. Solution Method

4.1. Modified multi-objective goal programming

Numerous solutions have been recently proposed, which offer a scientific framework for problems of deciding on the modeling of opposite objectives, including meta-goal programming (Tirkolaee et al., 2020), fuzzy meta-programming (Selim et al., 2008), multi-choice goal programming (Chang, 2007), and revised multi-choice goal programming (Chang, 2008). This study was carried out based on the revised multi-choice goal programming.

$$\min \sum_{i=1}^{2} [w_i(d_i^+ - d_i^-) + \alpha_i(e_i^+ - e_i^-)] \quad (48)$$

$$F_1(x) - d_1^+ + d_1^- = y_1, \quad (49)$$

$$g_{1.\min} \leq y_1 \leq g_{1.\max}, \quad (50)$$

$$y_1 - e_1^+ + e_1^- = g_{1.\min}, \quad (51)$$

$$F_2(x) - d_2^+ + d_2^- = y_2, \quad (52)$$

$$g_{2.\min} \leq y_2 \leq g_{2.\max}, \quad (53)$$

$$y_2 - e_2^+ + e_2^- = g_{2.\min}, \quad (54)$$

$$e_1^+, e_1^-, e_2^+, e_2^-, d_1^+, d_1^-, d_2^+, d_2^- \geq .0 \quad (55)$$

4.2. Hierarchical iteration algorithm

According to a 3-D structure of the model, the hierarchical iteration strategy was employed to solve problems as follows:

Step 1: Initialization: The variable $\mathrm{da_{jkpvt}}$ that is at the third level of the model is generated randomly according to its range of values.

Step 2: Solving the first level of the model: The bi-objective model is solved in the first level using the goal programming approach. The value of a goal objective function $\left(F_1^k\right)$ and decision variables are obtained, where $\mathrm{af_{kicvt}}$ is considered for the second level.

Step 3: Solving the second level of the model considering values of $\mathrm{af_{kicvt}}$ from the first level. The bi-objective model of the second level is solved by the goal programming approach and the values of the goal objective function $\left(F_2^k\right)$ and decision variables of the second level are obtained, where values of fdr_{ijpvt} between fdn_{ijpvt} are considered for the third level.

Step 4: Solving the third level of the model: By including decision variables of $\mathrm{fdr_{ijpvt}}$ and fdn_{ijpvt} from solving of the model in the second level, values of the goal objective function $(\mathrm{F_3^k})$ and decision variables are obtained for the third level, where values of da_{jkpvt} are considered for the first level with a renewable iteration.

Step 5: Stop criteria: The solving process is stopped if $\max(\bar{w}_1, \bar{w}_2, \bar{w}_3) \leq w^*$, where $\bar{w}_1 = \left|\frac{F_1^{K+1} - F_1^K}{F_1^{K+1}}\right|, \bar{w}_2 = \left|\frac{F_2^{K+1} - F_2^K}{F_2^{K+1}}\right|, \bar{w}_3 = \left|\frac{F_3^{K+1} - F_3^K}{F_3^{K+1}}\right|$ and w^* is tolerance with a value of to stop the algorithm. If it is true, stop the algorithm, otherwise, go back to the second level.

5. Numerical results

By taking into account random values of parameters based on ranges defined in [9], the proposed model was solved at a small size $(i = j = k = p = t = c = v = 2)$ with a weight of both objective functions of 0.5 in GAMS. The values of objective functions for each level are presented in Table 2.

Table 2. Values of the objective function at different levels.

	The first objective function	**The second objective function**
The first level	42462	13217
The second level	126216	16933
The third level	293753	36283

The results from this section reveal that the lowest value for the first objective function is achieved at the first level. Transitioning from the first to the second level results in an increase of 54,000 units. Furthermore, progressing from the second to the third level brings about a more significant increase of 167,000 units. The same trend holds true for the second objective function. The increment in the value of the second objective function when moving from the second to the third level surpasses the corresponding increase when moving from the first to the second level. Consequently, it can be deduced that advancing from the first to the second level amplifies the problem's complexity. Similarly, the problem becomes more intricate when progressing from the second to the third level, with a greater degree of complexity compared to the transition from the first to the second level.

5.1. Analysis of the Results

In the following, we will compare the proposed model in two deterministic and stable states for (nominal data) and then analyze the sensitivity analysis of the model (see Table 3).

As seen in Table 3, the most significant impact pertains to environmental costs, with factors such as supply chain risk having a relatively limited influence. This observation highlights the paramount importance of environmental considerations within the context of this analysis. Environmental costs, which encompass various aspects such as emissions, waste management, and sustainable practices, play a pivotal role in shaping the overall performance of the supply chain. The prominence of these environmental costs underscores the necessity for businesses and organizations to prioritize eco-friendly practices and sustainable strategies in their supply chain operations. This not only aligns with global efforts to reduce carbon footprints and minimize ecological harm but also reflects a growing

trend among consumers who are increasingly conscious of the environmental footprint of the products they purchase.

Table 3. Different solution models and their comparison

Weight of objective functions				3.5	2	4	0.5
Run	**Model**	**Number of Scenarios**	**Probability of each scenario**	**Total fixed cost**	**Total CO2 cost**	**Total shortage cost**	**Total risk cost**
1	2-stage deterministic planning	1	1	9389	867053	0	1220
2	2-stage non-deterministic planning	2	0.5	10481	1221826	0	1400
3	Deterministic planning	1	1	8669	867195	0	1310
4	Deterministic planning	2	0.5	10481	1221826	0	1400

Furthermore, it is essential to recognize that while supply chain risk is a factor of concern, its impact appears to be less pronounced in comparison to environmental costs. This suggests that companies should allocate resources and efforts strategically, focusing on mitigating and managing environmental expenses to achieve a more sustainable and cost-efficient supply chain.

In conclusion, the findings emphasize the critical role of environmental costs in supply chain management, urging businesses to adopt eco-conscious practices as a means of not only reducing environmental impact but also optimizing their overall operational efficiency and profitability. While supply chain risk remains a relevant concern, it should be managed in conjunction with a strong commitment to environmental responsibility to strike the right balance in achieving supply chain excellence.

6. Conclusion

This study embarked on an exploration of a three-tier supply chain configuration, comprising recycling centers at the first level, production/reproduction factories at the second level, and decentralized distributors at the third level. To address the dual objectives of profit maximization and the reduction of adverse environmental impacts, a comprehensive bi-objective three-level model was developed. This model not only ascertains the quantities of products with parts processed at recycling centers and production/reproduction factories but also delineates the allocation of products or components at each level. Solving this intricate model was achieved through the application of revised multi-objective goal programming, facilitated by a sophisticated hierarchical iterative algorithm.

While this research tackled a noteworthy segment of the supply chain optimization challenge, it's worth noting that the complexity of real-world supply chain scenarios often encompasses greater intricacies. One such aspect is the presence of uncertainties, particularly in parameters like demand,

which can significantly influence the decision-making process. To account for these uncertainties and tackle larger-scale supply chain optimization challenges, advanced techniques and methodologies come into play.

One promising avenue for addressing larger and more complex models involves embracing meta-heuristic algorithms like NSGA-II (Non-dominated Sorting Genetic Algorithm II). These powerful algorithms excel at handling intricate optimization problems with uncertain parameters. They possess the capability to explore a broader solution space and uncover more robust and efficient supply chain configurations, thereby enhancing the resilience and adaptability of supply chains in the face of real-world variability.

In conclusion, this study represents a crucial step in the direction of optimizing supply chains with an emphasis on profit maximization and environmental sustainability. As supply chain complexities continue to evolve, future research endeavors may delve deeper into handling uncertainties and employing advanced meta-heuristic algorithms to achieve even more robust and adaptive supply chain solutions.

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