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A location-inventory-routing problem to design a circular closed-loop supply chain network with carbon tax policy for achieving circular economy: An augmented epsilon-constraint approach

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ABSTRACT

The emergence of the circular economy concept has pushed industry owners towards the green supply chain and waste reduction. The closed-loop supply chain originates from the concept of the circular economy and its purpose is to increase efficiency and profitability by reducing waste and energy consumption. Hence, in this research, an integrated bi-objective mixed-integer linear programming model is developed with the aim of optimizing both operational and strategic decisions in a closed-loop supply chain network. The proposed model benefits the location-inventory-routing problem to structure the network, and it applies a carbon tax policy and vehicle scheduling problem to reduce emissions and vehicle waiting time, respectively. Considering problems such as split-delivery, storage possibility, shortage, supplier selection, order allocation, heterogenous vehicles, and uncertain demand has led to the development of a comprehensive model. A stochastic scenario-based approach is used to deal with demand uncertainty, and an augmented epsilon-constraint method is employed to solve the proposed bi-objective model. The applicability of the proposed model and the effectiveness of the bi-objective solution approach for achieving circular economy are examined through its implementation in a cable and wire industry in Iran.

1. . Introduction

As a systematic approach, supply chain network (SCN) design aims to determine an ideal mixture of products, suppliers, and facilities by means of mathematical modeling (Zandkarimkhani et al., 2020). According to (Cammarano et al., 2022; Dwivedi et al., 2021), the current SCN should be reengineered by integrating circular economy concepts in order to achieve sustainable development goals (SDGs). When it comes to the optimization of SCN, one may refer to the design of it with the highest possible efficiency (Jain and Verma, 2021; Moreno-Camacho et al., 2019). In fact, SCN optimization provides companies with the possibility to assess the chain performance via some scenarios such as “what-if” to make practical plans as per robust criteria (Tavana et al., 2021). It should be noted that efficiency for SCNs may be variable based on the decision makers' (DMs) criteria and ideas as well as the modeling preferences they may employ (Chopra et al., 2021). Therefore, this concept has been referred to in the literature differently from varying viewpoints. A number of studies place the main focus on the significance of cost minimization (Salehi-Amiri et al., 2021; Yuchi et al., 2021), whereas some others lay the highest emphasis on the importance of profit maximization (Ghani et al., 2018). But most studies in this domain turn to multiple objectives to measure the efficiency and evaluate the performance of SCNs (Hasani et al., 2021; Nili et al., 2021; Nayeri et al., 2020). The consideration of order allocation and supplier selection is considered as the first step in the design of a SCN with a high efficiency (Bhayana et al., 2021; Kannan et al., 2020). This is so because the supplier is a major element at the top level of a chain and is highly influential in the downstream performance of the SCN (Bartos et

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Table 1
Papers reviewed in the field of reverse supply chain to show research gap.

Authors	Year	Model structure			Network flows		Closed-loop	Facilities location	Routing problem	Storage	Lost sales	Heterogenous vehicles	Vehicle scheduling	Supplier selection	Order allocation	Environmental issues	Carbon tax policy	Uncertainty	Posteriori method	Case study
		Multi-objective	Multi-item	Multi-period	Forward	Reverse														
Tavana et al.	2022	✓	✓	✓	✓	✓	✓	✓	✓	✓	–	✓	–	✓	✓	✓	–	✓	–	–
Salehi-Amiri et al.	2022	✓	✓	✓	✓	✓	✓	✓	–	✓	–	–	–	–	✓	✓	–	–	–	✓
Nasr et al.	2021	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	–	✓	✓	✓	–	✓	–	✓
Emamian et al.	2021	✓	✓	✓	✓	✓	✓	✓	✓	–	–	✓	–	–	–	✓	✓	–	–	–
Sadeghi et al.	2020	–	✓	✓	✓	✓	✓	✓	✓	–	–	✓	–	✓	✓	✓	–	–	–	✓
Govindan et al.	2020	✓	✓	–	✓	✓	✓	✓	✓	✓	✓	✓	–	✓	✓	✓	–	✓	–	✓
Nayeri et al.	2020	✓	✓	–	✓	✓	✓	✓	–	–	–	–	–	✓	✓	✓	–	✓	–	–
Mardan et al.	2019	✓	✓	✓	✓	✓	✓	✓	–	✓	–	–	–	✓	✓	✓	–	–	–	✓
Zhen et al.	2019	✓	✓	–	✓	✓	✓	✓	–	–	–	–	–	–	–	✓	–	✓	–	✓
Yavari and Geraeli, 2019	2019	✓	✓	✓	✓	✓	✓	✓	–	✓	–	–	–	–	–	✓	–	✓	–	–
This paper		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

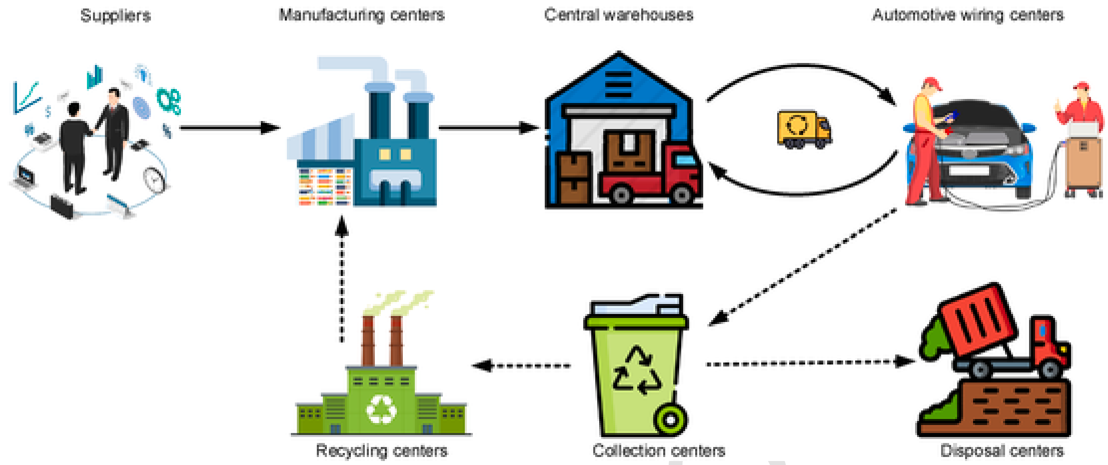

Fig. 1. The structure of network under study.

Table 2
Amount of raw materials used to produce 100 m of AV, AVS, and AVSS wires.

	AV	AVS	AVSS
PVC granule	800 g	700 g	600 g
8 mm copper wire	1800 g	1800 g	1600 g

Table 3
Distance among automotive wiring centers (km).

$\alpha_{a'a}$	$a = 1$	$a = 2$	$a = 3$	$a = 4$	$a = 5$	$a = 6$	$a = 7$
Central warehouse ($a' = 1$)	0	23.6	19	26.4	18.3	28.2	32.9
Karaj Square ($a' = 2$)	23.6	0	19.2	17.3	23.3	20.5	18.1
Jahannama ($a' = 3$)	19	19.2	0	9	8.7	14.2	17.6
Anbar Naft ($a' = 4$)	26.4	17.3	9	0	10.7	3.9	7.3
Atmosfer ($a' = 5$)	18.3	23.3	8.7	10.7	0	13.9	20.6
Sarhadabad ($a' = 6$)	28.2	20.5	14.2	3.9	13.9	0	9.3
Fardis ($a' = 7$)	32.9	18.1	17.6	7.3	20.6	9.3	0

al., 2022; Alavi et al., 2021). Another significant component that should be assigned credit in designing a SCN is distribution planning (Guarnaschelli et al., 2020). An area that has garnered much attention in the literature is how to integrate the location-routing problem with inventory control problems (Wu et al., 2021). Some of the areas of inquiry that have received increasing attention are reverse logistics, waste management, and green manufacturing and remanufacturing as a reaction to the enforcement of environmental laws on the reduction of pollution and customer pressure (Chen and Akmalul'Ulya, 2019). The traditional supply chains aim at lowering costs and improving efficiency and profitability. In circular or closed-loop supply chains, the discarded products are circled back into the value chain through recycling, harvesting, and refurbishing. A circular supply chain aims at improving productivity and profitability by decreasing the consumption of resources and energy, reducing the emissions of pollutants, and creating a socially responsible enterprise. Indeed, circular supply chain management refers to the integration of supply chain management and environmental rules which may involve different concepts such as production, customer satisfaction, delivery processes, materials procurement, and the life management of used products (Bhatia and Gangwani, 2021; Tseng et al., 2019). Despite the prevalence of this wrong belief among practitioners that it is highly expensive to implement the circular supply chain processes, a number of reasons can also prove its cost-effectiveness (Waltho et al., 2019). Both theory and practice have proven that implementing circular SCN may be costly in the short term, but most of the costs will be minimized in the long term (Sarkar et al., 2018). One of the criteria that may result in the sound design of a circular SCN is to consider both forward and reverse flows in designing supply chain networks since it will bring about a reduction in disposal products and resources consumption due to the reuse and/or recycling of the returned products (Berlin et al., 2022). This can finally lead to the decrease of negative environmental effects (Fu et al., 2021).

From the above-mentioned points, it can be concluded that considering "both forward and reverse flows", "supplier selection and order allocation", "facilities location", "vehicle routing problem", and "inventory planning" in SCN design can lead the designed network closer to the real world, and may result in higher efficiency and effectiveness. Therefore, in this paper, a bi-objective mixed integer linear programming (MILP) model is developed to design a circular closed-loop supply chain network (CLSCN) by considering supplier selection and order allocation, location-inventory-routing (LIR) problem, and carbon tax policy for achieving circular economy. According to Rafigh et al. (2021) the closed loop supply chain (CLSC) itself compacts with the concepts of circular economy and sustainability. It is noteworthy that uncertain demand, heterogeneous vehicles, and vehicle scheduling are among the key assumptions of the proposed model. A scenario-based approach is used to overcome uncertain demand, and the augmented epsilon-constraint method (AUGMECON) is applied to solve the proposed bi-objective model. Finally, the performance and the efficiency of the proposed model and solution approach are measured by means of the data pertaining to a SCN of wire and cable production and distribution in Iran. In general, the motivation of this paper is to address the following questions.

- What model is proper for reverse supply chain network design to optimize strategic and operational decisions in the wire and cable industry considering LIR and carbon tax policy?
- What approach is appropriate to deal with uncertain demand?
- What method is suitable for solving the proposed bi-objective model?
- How are the performance of the proposed model and the effectiveness of the solution approach evaluated in the wire and cable industry?

The remainder of this research is structured as follows. Section 2 reviews the literatures. In Section 3, we present a problem statement and proposed model. Section 4 proposes the bi-objective solution method. Sections 5 and 6 are assigned to a case study and comparative analysis, respectively. Finally, we state managerial implications and our conclusion in Sections 7 and 8, respectively.

2. Literature review

CLSCN is a circular SCN that regards environmental issues while considering the economic aspect (Govindan and Soleimani, 2017). A review of literature shows that CLSCN design has been applied in various fields such as food industry (Salehi-Amiri et al., 2021; Jabarzadeh et al., 2020), healthcare (Tirkolaee et al., 2022; Rafigh et al., 2021), waste management (Govindan et al., 2021; Sadeghi Ahangar et al., 2021), tire industry (Fazli-Khalaf et al., 2021; Abdolazimi et al., 2020), and several review articles have been presented to introduce its applications and methods used in this field (MahmoumGonbadi et al., 2021; Peng et al., 2020; Kazemi et al., 2019). Some researchers have taken a step further and examined CLSCN by focusing on the circular economy. Govindan et al. (2020) and Nasr et al. (2021) have applied the concept of circular economy to design a CLSCN for automotive and clothing industries, respectively. In this regard, MahmoumGonbadi et al. (2021) presented a systematic review on the methods and applications of CLSCN articles with the aim of transition towards circular economy. In the following, some articles that have used mathematical programming approach to design CLSCN are reviewed. Jindal and Sangwan (2014) formulated their MILP model for designing a multi-facility CLSCN under uncertainty. Their model maximizes network profits and uses a fuzzy approach to deal with uncertain parameters. Garg et al. (2015) examined a CLSCN with regard to environmental issues. For this purpose, they proposed a bi-objective mixed-integer nonlinear programming (MINLP) model with the aim of maximizing network profits and minimizing the number of vehicles used to transport products. They proposed the second objective function to reduce carbon emissions. An MILP model was developed by Chen et al. (2015) to structure a comprehensive CLSCN considering location allocation problem and quality level. They suggested a modified genetic algorithm for solving their problem. Zhalechian et al. (2016) presented a sustainable CLSCN considering the queuing theory and LIR problem under uncertainty. They employed a possibilistic-stochastic approach to overcome uncertainty and proposed a meta-heuristic algorithm for solving their proposed problem in large sizes. A multi-objective optimization model aimed at reducing total costs, improving supplier performance, and reducing carbon emissions to design an efficient CLSCN was proposed by Govindan et al. (2017). They used a weighted fuzzy programming method to solve their multi-objective model, and finally assessed their model performance using data from an inkjet printers' production and distribution industry in India. In this vein, Soleimani et al. (2017) presented a multi-objective mathematical programming model for structuring a green and sustainable CLSCN under uncertainty. They used fuzzy theory to consider uncertainty, and designed a GA-based meta-heuristic to solve their proposed problem in large sizes. A LIR problem was suggested for designing a multi-period CLSCN considering forward and reverse flows by Forouzanfar et al. (2018). For this purpose, they formulated a bi-objective MINLP model with the aim of minimizing service time and total costs, and implemented their proposed model in a car industry in Iran. In order to trade-off among network costs and carbon emissions, a sustainable CLSCN was designed by Zhen et al. (2019). They applied a scenario-based approach to cope demand uncertainty and proposed a Lagrangian relaxation approach to solve their proposed model. Mardan et al. (2019) formed a multi-product, multi-period green CLSCN by a bi-objective MILP model. They engaged the LP-metric method to convert the bi-objective model to the single-objective one, and developed a Benders decomposition algorithm for solving the model in large sizes. Finally, the performance of their proposed model and algorithm was evaluated by data from a wire and cable industry in Iran. Govindan et al. (2020) presented a fuzzy multi-criteria decision-making-based approach and MILP model to structure a green CLSCN by considering supplier selection and LIR problem. Their model minimizes lost demands and total costs, simultaneously. They employed a fuzzy solution method for solving their bi-objective model and implemented their proposed approach in an automotive parts production industry in Iran. Similarly, Sadeghi Ahangar et al. (2021) proposed an MILP model for designing a green CLSCN using the facility location and heterogeneous vehicle routing problem. They evaluated the performance of their proposed model using data from an automotive parts company. A multi-objective optimization model was suggested to design a sustainable CLSCN taking into account production and routing decisions by Emamian et al. (2021). Their model minimizes network costs, maximizes social responsibility, and minimizes emissions, simultaneously. In this vein, Nasr et al. (2021) formulated a multi-objective MILP model to structure a sustainable CLSCN. For this purpose, they applied a LIR problem with the possibility of scheduling vehicles. Finally, the proposed multi-objective model was solved by a fuzzy goal programming approach and implemented in a garment industry in Iran. Salehi-Amiri et al. (2022) proposed a CLSCN to optimize avocado industry operations with social considerations. Their goal was to minimize total costs and maximize job creation, and for this purpose, they developed an MILP model. They used the LP-metric method to solve their multi-objective model. Tavana et al. (2022) suggested a comprehensive sustainable CLSCN considering LIR problem with simultaneous pickup and delivery, supplier selection, and transportation modes under uncertainty. The purpose of their model was to minimize total costs, maximize employment, and minimize emissions, and for this end, they formulated a multi-objective MILP model. They developed an intelligent simulation approach to generate data and examined the performance of their proposed model using simulated data. It should be noted that they used a fuzzy goal programming approach to deal with uncertainty and to solve the multi-objective model.

Table 1 presents a review of the recent reverse supply chain network design literature. This thorough review shows some research gaps in the literature for CLSCNs with LIR problems, and carbon tax policy. This is the first study for designing a circular CLSCN for LIR problems with demand uncertainty, vehicle scheduling problem, carbon tax policy, and posteriori methods to the best of the authors' knowledge.

3. Problem statement and proposed model

In this section, a bi-objective MILP model is formulated to manage production, distribution, inventory, and waste in a cable and wire industry by considering carbon emissions control. For this purpose, a multi-period and multi-product CLSCN with forward flow considering suppliers, manufacturing centers, central warehouses and automotive wiring centers, and reverse flow including disposal, recycling, and collection centers is developed. Manufacturing centers produce three products including AV, AVS, and AVSS automotive wires. “8 mm copper wire” and “polyvinyl chloride (PVC) granules” are used to produce these products. The manufactured products are moved to central warehouses to be delivered to automotive wiring centers through the planning of heterogeneous vehicles. Considering vehicle scheduling reduces the waiting time of vehicles at the site of automotive wiring centers; for this purpose, this assumption is considered. Fig. 1 shows the general structure of network under study. In order to clarify the details of the SCN under study, the following assumptions are given.

- The network under study is multi-period and multi-product.
- The network under study simultaneously considers the forward flow including suppliers, manufacturing centers, central warehouses and automotive wiring centers, and the reverse flow including collection, recycling, and disposal centers.
- The vehicles are heterogeneous. In other words, the capacity, the amount of fuel consumption and the supply cost of vehicles are different from each other.
- The capacity of the vehicles, suppliers, and centers are considered definite.

Table 4
Demands of automotive wiring centers for each time period and scenario.

α_{pati}^{CP}		$t=1$			$t=2$			$t=3$			$t=4$		
		$i=1$	$i=2$	$i=3$	$i=1$	$i=2$	$i=3$	$i=1$	$i=2$	$i=3$	$i=1$	$i=2$	$i=3$
$p=1$	$a=1$	0	0	0	0	0	0	0	0	0	0	0	0
	$a=2$	23	19	17	22	20	17	26	22	20	30	25	23
	$a=3$	20	17	15	24	21	18	23	19	17	26	22	20
	$a=4$	24	20	18	22	18	16	20	17	15	23	19	17
	$a=5$	23	19	17	23	19	17	26	22	20	30	25	23
	$a=6$	23	19	17	29	24	23	31	26	23	35	29	26
	$a=7$	34	28	25	31	26	23	23	21	19	28	25	21
$p=2$	$a=1$	0	0	0	0	0	0	0	0	0	0	0	0
	$a=2$	23	19	17	23	19	17	22	18	16	24	20	18
	$a=3$	19	16	14	20	17	15	22	18	16	24	20	18
	$a=4$	28	23	21	23	19	17	20	17	15	24	20	18
	$a=5$	23	19	16	25	21	19	28	23	21	31	26	23
	$a=6$	23	19	18	22	18	16	27	25	23	29	24	22
	$a=7$	26	22	20	19	16	14	23	20	19	24	20	18
$p=3$	$a=1$	0	0	0	0	0	0	0	0	0	0	0	0
	$a=2$	20	18	15	20	17	15	26	22	20	29	24	22
	$a=3$	22	18	16	24	20	18	24	20	18	26	22	20
	$a=4$	19	17	16	18	15	14	23	19	17	26	22	20
	$a=5$	19	16	14	22	18	16	26	22	20	28	24	22
	$a=6$	21	18	17	23	19	17	22	18	16	24	21	19
	$a=7$	22	19	17	20	17	15	23	21	18	26	24	23

Table 5
The lower and upper bounds of objective functions (payoff table).

	Z_1^*	Z_2^*
Z_1^L: Minimize only the objective function 1	12,628,551	–
Z_2^L: Minimize only the objective function 2	–	0
Z_1^U: Minimize the objective function 1 subject to $Z_2 \le Z_2^L$	15,183,917	–
Z_2^U: Minimize the objective function 2 subject to $Z_1 \le Z_1^L$	–	473

- The location of manufacturing, collection, disposal, and recycling centers and central warehouses are determined by model.
- Split-delivery is considered. In other words, it is possible that the demand of an automotive wiring center is provided by more than one vehicle.
- The multi-depot vehicle routing problem is considered between central warehouses and automotive wiring centers.
- Storage capabilities and lost sales are allowed.
- Carbon tax policy is applied to control carbon emissions.
- There is uncertainty in the amount of demand.
- The vehicle scheduling is considered to reduce waiting time of vehicles at the automotive wiring centers.

Indices	
$r \in \{1,2,...,R\}$	Raw material
$p \in \{1,2,...,P\}$	Product
$s \in \{1,2,...,S\}$	Supplier
$m \in \{1,2,...,M\}$	Manufacturing center
$w \in \{1,2,...,W\}$	Central warehouse
$a, a' \in \{1,2,...,A\}$	Automotive wiring center
$c \in \{1,2,...,C\}$	Collection center
$e \in \{1,2,...,E\}$	Recycling center
$d \in \{1,2,...,D\}$	Disposal center
$v, v' \in \{1,2,...,V\}$	Vehicle
$t \in \{1,2,...,T\}$	Time period
$i \in \{1,2,...,I\}$	Scenario
Parameters	
δ_{rst}^{CP}	Maximum capacity of suppliers (kg)
ξ_{pmt}^{CP}	Maximum capacity of manufacturing centers (Number)
φ_{pwt}^{CP}	Maximum capacity of central warehouses (Number)
β_{pct}^{CP}	Maximum capacity of collection centers (Number)
ψ_{ret}^{CP}	Maximum capacity of recycling centers (Number)
ϖ_{dt}^{CP}	Maximum capacity of disposal centers (m^3)
τ_{v}^{CP}	Maximum capacity of vehicles (m^3)
α_{pati}^{CP}	Demands of automotive wiring centers for products in each time period, under each scenario (Number)
κ_r	Volume of raw materials (m^3)
κ'_p	Volume of products (m^3)
θ_{rp}	Amount of raw material r used to produce one unit of product p
δ_{rst}^{PR}	Cost of purchasing one unit of raw material r
ξ_{pmt}^{PR}	Cost of manufacturing one unit of product p
φ_{pwt}^{PR}	Cost of processing products at central warehouses
β_{pct}^{PR}	Cost of processing returned products at collection centers
ψ_{ret}^{PR}	Cost of recycling raw materials at recycling centers
ϖ_{rdt}^{PR}	Cost of disposing raw materials at disposal centers
α_{pat}^{PR}	Cos of holding products at warehouses of automotive wiring centers
δ_{st}^{FX}	Cost of ordering to suppliers
ξ_{m}^{FX}	Cost of opening manufacturing center m
φ_{w}^{FX}	Cost of opening central warehouse w
β_{c}^{FX}	Cost of opening collection center c
ψ_{e}^{FX}	Cost of opening recycling center e
ϖ_{d}^{FX}	Cost of opening disposal center d
τ_{v}^{FX}	Cost of supplying vehicle v
$\delta\xi_{rsmt}$	Transportation cost among suppliers and manufacturing centers
$\xi\varphi_{pmwt}$	Transportation cost among manufacturing centers and central warehouses
$\alpha\beta_{pact}$	Transportation cost among automotive wiring centers and collection centers
$\beta\psi_{rcet}$	Transportation cost among collection centers and recycling centers
$\beta\varpi_{rcdt}$	Transportation cost among collection centers and disposal centers
$\psi\xi_{remt}$	Transportation cost among recycling centers and manufacturing centers
$\varphi\alpha_{wa}$	Distance among central warehouses and automotive wiring centers
$\alpha_{a'a}$	Distance among automotive wiring center a' and a
$T\varphi\alpha_{vwa}$	Time distance among central warehouses and automotive wiring centers by vehicles
$T\alpha_{va'a}$	Time distance among automotive wiring center a' and a by vehicles
ζ_{at}	Products unload time
χ_{pat}	Rate of returned products
χ'_{rct}	Recyclable raw materials rate
PR_i	Occurrence probability of the scenario i

Table 6
The optimal value of objective functions obtained AUGMECON.

Grid point	ε_2	Objective function 1	Objective function 2
GP1	$0 + 0 \times 43 = 0$	15,183,917	0
GP2	$0 + 1 \times 43 = 43$	14,763,038	42.25
GP3	$0 + 2 \times 43 = 86$	14,601,682	86
GP4	$0 + 3 \times 43 = 129$	14,349,547	127.75
GP5	$0 + 4 \times 43 = 172$	13,922,526	169.25
GP6	$0 + 5 \times 43 = 215$	13,936,115	207.75
GP7	$0 + 6 \times 43 = 258$	13,475,744	251
GP8	$0 + 7 \times 43 = 301$	13,584,006	289.25
GP9	$0 + 8 \times 43 = 344$	13,167,674	336
GP10	$0 + 9 \times 43 = 387$	12,834,639	381.5
GP11	$0 + 10 \times 43 = 430$	12,974,645	425.5
GP12	$0 + 11 \times 43 = 473$	12,628,551	472.25

φ_{pt}	Shortage penalty cost
$E\delta\xi_{rsmt}$	Carbon emissions per unit of shipping raw materials from suppliers to manufacturing centers
$E\xi\varphi_{pmwt}$	Carbon emissions per unit of shipping products from manufacturing centers to central warehouses
$E\alpha\beta_{pact}$	Carbon emissions per unit of shipping products from automotive wiring centers to collection centers
$E\beta\psi_{rcet}$	Carbon emissions per unit of shipping raw materials from collection centers to recycling centers
$E\beta\varpi_{rcdt}$	Carbon emissions per unit of shipping raw materials from collection centers to disposal centers
$E\psi\xi_{remt}$	Carbon emissions per unit of shipping raw materials from recycling centers to manufacturing centers
$E\tau_v$	Carbon emissions per unit of consuming fuel by vehicles
$E\xi_{pm}$	Carbon emissions per unit of manufacturing products at manufacturing centers
$E\varphi_{pw}$	Carbon emissions per unit of processing products at central warehouses
$E\beta_{pc}$	Carbon emissions per unit of processing products at collection centers
$E\psi_{re}$	Carbon emissions per unit of recycling raw materials at recycling centers
$E\varpi_{rd}$	Carbon emissions per unit of disposing raw materials at disposal centers
Ψ	Carbon unit price
$F\tau_v$	Fuel consumption per unit of distance by vehicles
PF	Fuel price
$bigm$	A large number

Variables

$\eta\delta_{rsti}\begin{cases}1\\0\end{cases}$	Binary	In case of selecting supplier s to purchase raw material r in time period t, under scenario i Otherwise
$\eta\xi_m\begin{cases}1\\0\end{cases}$	Binary	In case of opening manufacturing center m Otherwise
$\eta\varphi_w\begin{cases}1\\0\end{cases}$	Binary	In case of opening central warehouse w Otherwise
$\eta\beta_c\begin{cases}1\\0\end{cases}$	Binary	In case of opening collection center c Otherwise
$\eta\psi_e\begin{cases}1\\0\end{cases}$	Binary	In case of opening recycling center e Otherwise
$\eta\varpi_d\begin{cases}1\\0\end{cases}$	Binary	In case of opening disposal center d Otherwise
$\eta\tau_v\begin{cases}1\\0\end{cases}$	Binary	In case of purchasing vehicle v Otherwise
$\eta_{vw}\begin{cases}1\\0\end{cases}$	Binary	If vehicle v is assigned to central warehouse w Otherwise
$\gamma_{va'ati}\begin{cases}1\\0\end{cases}$	Binary	If route between automotive wiring center a' and a is assigned to vehicle v in time period t, under scenario i Otherwise
$\mu_{v'vati}\begin{cases}1\\0\end{cases}$	Binary	If vehicle v' visits automotive wiring center a before vehicle v in time period t, under scenario i Otherwise
$Y\delta\xi_{rsmti}$	Positive	Amount of raw materials moved from suppliers to manufacturing centers
$Y\xi\varphi_{pmwti}$	Positive	Amount of products moved from manufacturing centers to central warehouses
$Y\varphi\alpha_{pvwati}$	Positive	Amount of products moved from central warehouses to automotive wiring centers by vehicles
$Y\alpha\beta_{pacti}$	Positive	Amounts of returned products moved from automotive wiring centers to collection centers
$Y\beta\psi_{rceti}$	Positive	Amount of raw materials moved from collection centers to recycling centers
$Y\beta\varpi_{rcdti}$	Positive	Amount of raw materials moved from collection centers to disposal centers
$Y\psi\xi_{remti}$	Positive	Amount of raw materials moved from recycling centers to manufacturing centers
σ_{vati}	Positive	Arrival time of vehicle v to site of automotive wiring center a in time period t, under scenario i
ϑP_{pati}	Positive	Amount of product p in warehouse of automotive wiring center a in time period t, under scenario i
ϑN_{pati}	Positive	Amount of product p shortage for automotive wiring center a in time period t, under scenario i
ϑ_{pati}	Free	Inventory level in warehouse of automotive wiring center a in time period t, under scenario i
ZS	Positive	Total strategic costs
ZO	Positive	Total operational costs

Objective functions

$$Min\ \ Z_1 = ZS + ZO \tag{1}$$

$$Min\ \ Z_2 = \sum_{p,a,t,i} PR_i \times \vartheta N_{pati} \tag{2}$$

s.t.

$$ZS = \sum_m \xi_m^{FX} \times \eta\xi_m + \sum_w \varphi_w^{FX} \times \eta\varphi_w + \sum_c \beta_c^{FX} \times \eta\beta_c + \sum_e \psi_e^{FX} \times \eta\psi_e$$
$$\sum_v \tau_v^{FX} \times \eta\tau_v$$

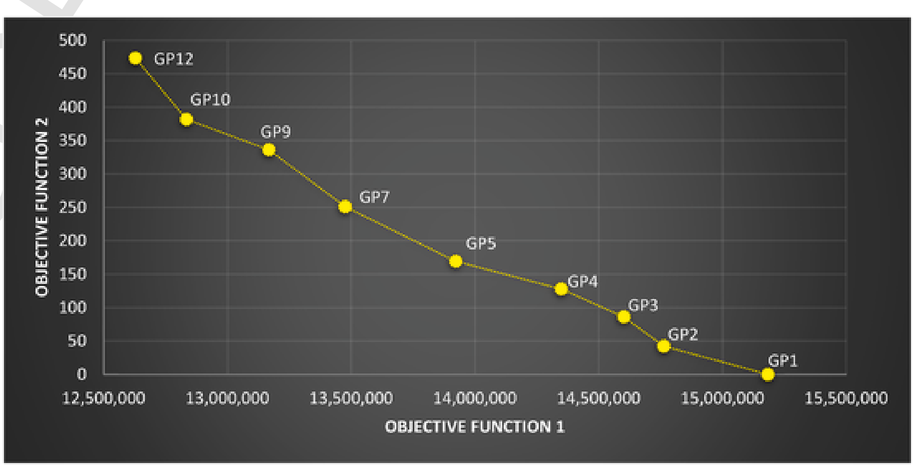

Fig. 2. The Pareto frontier obtained AUGMECON.

Table 7
Amount of products delivered to automotive wiring centers by vehicles.

$Y\varphi\alpha_{pvwati}$				$t = 1$			$t = 2$			$t = 3$			$t = 4$		
				$i = 1$	$i = 2$	$i = 3$	$i = 1$	$i = 2$	$i = 3$	$i = 1$	$i = 2$	$i = 3$	$i = 1$	$i = 2$	$i = 3$
$p = 1$	$v = 2$	$w = 2$	$q = 2$	21	0	0	10	18	0	0	21	19	0	22	0
			$q = 3$	0	14	7	0	19	0	0	7	16	0	19	19
			$q = 4$	0	0	17	20	0	15	19	0	0	22	0	0
			$q = 5$	20	0	0	0	5	0	0	0	20	0	0	21
			$q = 6$	0	0	16	25	0	19	15	0	0	29	0	0
			$q = 7$	0	0	0	24	0	0	20	0	0	25	0	0
	$v = 4$	$w = 2$	$q = 2$	0	0	0	0	0	0	24	0	0	10	0	0
			$q = 3$	0	0	0	22	0	0	0	12	0	25	0	0
			$q = 4$	10	18	0	0	0	0	0	0	0	0	16	0
			$q = 5$	0	0	0	20	0	0	13	21	0	15	0	0
			$q = 6$	14	9	0	0	0	0	0	0	0	0	23	0
			$q = 7$	12	24	0	0	0	0	0	0	0	0	18	0
	$v = 5$	$w = 2$	$q = 2$	0	18	16	11	0	16	0	0	0	0	0	21
			$q = 3$	19	0	7	0	0	0	22	0	0	0	0	0
			$q = 4$	0	0	0	0	16	0	0	14	13	0	0	0
			$q = 5$	0	19	17	0	0	0	0	0	0	0	23	0
			$q = 6$	0	0	0	0	21	0	0	20	19	0	0	20
			$q = 7$	0	0	0	0	22	20	0	17	16	0	0	0
	$v = 6$	$w = 2$	$q = 2$	0	0	0	0	0	0	0	0	0	19	0	0
			$q = 3$	0	2	0	0	0	16	0	0	0	0	0	0
			$q = 4$	11	0	0	0	0	0	0	0	0	0	0	14
			$q = 5$	0	0	0	0	13	17	12	0	0	14	0	0
			$q = 6$	7	9	0	0	0	0	16	0	0	0	0	0
			$q = 7$	16	0	22	0	0	0	0	0	0	0	0	16
$p = 2$	$v = 2$	$w = 2$	$q = 2$	0	19	0	21	17	0	0	18	16	0	19	0
			$q = 3$	17	0	0	0	15	0	10	17	16	0	20	17
			$q = 4$	0	0	0	21	0	15	18	0	0	22	0	0
			$q = 5$	5	0	16	0	0	0	0	0	0	0	0	21
			$q = 6$	0	0	17	19	0	15	0	0	0	24	0	0
			$q = 7$	0	0	0	17	0	0	19	0	0	22	0	0
	$v = 4$	$w = 2$	$q = 2$	0	0	0	0	0	0	11	0	0	0	0	0
			$q = 3$	0	0	0	0	0	0	0	0	0	24	0	0
			$q = 4$	0	21	0	0	0	0	0	0	0	0	18	0
			$q = 5$	16	0	0	0	0	0	27	20	0	20	0	0
			$q = 6$	18	17	0	0	0	0	0	0	0	0	19	0
			$q = 7$	9	19	0	0	0	0	0	0	0	0	15	0
	$v = 5$	$w = 2$	$q = 2$	19	0	16	0	0	15	21	0	0	0	0	18
			$q = 3$	0	0	14	19	0	0	0	0	0	0	0	0
			$q = 4$	0	0	0	0	16	0	0	13	13	0	0	0
			$q = 5$	0	18	0	21	0	0	0	0	0	0	24	0
			$q = 6$	0	0	0	0	16	0	0	18	17	0	0	17
			$q = 7$	0	0	0	0	15	14	0	15	15	0	0	0
	$v = 6$	$w = 2$	$q = 2$	0	0	0	0	0	0	0	0	0	23	0	0
			$q = 3$	0	16	0	0	0	15	0	0	0	0	0	0
			$q = 4$	23	0	19	0	0	0	0	0	0	0	0	16
			$q = 5$	0	0	0	0	19	17	0	0	19	8	0	0
			$q = 6$	0	0	0	0	0	0	22	0	0	0	0	0
			$q = 7$	15	0	18	0	0	0	0	0	0	0	0	15
$p = 3$	$v = 2$	$w = 2$	$q = 2$	16	7	0	0	16	0	0	21	20	0	0	0
			$q = 3$	8	10	0	0	17	0	0	0	0	0	21	18
			$q = 4$	0	0	6	17	0	13	20	0	0	21	0	0
			$q = 5$	6	0	0	0	0	0	0	0	0	0	0	20
			$q = 6$	0	0	7	19	0	16	9	0	0	19	0	0
			$q = 7$	0	0	7	18	0	0	19	0	0	20	0	0
	$v = 4$	$w = 2$	$q = 2$	0	0	0	0	0	0	10	0	0	23	0	0
			$q = 3$	0	0	0	21	0	0	0	19	0	9	0	0
			$q = 4$	16	13	0	0	0	0	0	0	0	0	17	0
			$q = 5$	12	0	0	10	0	0	0	21	0	12	0	0
			$q = 6$	0	0	0	0	0	0	0	0	0	0	16	0
			$q = 7$	18	16	0	0	0	0	0	0	0	0	18	0
	$v = 5$	$w = 2$	$q = 2$	0	8	13	19	0	8	14	0	0	0	21	22
			$q = 3$	12	0	0	0	0	0	23	0	17	0	0	0
			$q = 4$	0	0	0	0	14	0	0	15	14	0	0	0
			$q = 5$	0	15	0	9	0	0	0	0	0	0	23	0
			$q = 6$	0	0	0	0	18	0	0	15	14	0	0	15
			$q = 7$	0	0	0	0	16	14	0	13	15	0	0	0
	$v = 6$	$w = 2$	$q = 2$	0	0	0	0	0	6	0	0	0	4	0	0

(continued on next page)

Table 7 (*continued*)

$Y\varphi\alpha_{pvwati}$	$t = 1$			$t = 2$			$t = 3$			$t = 4$		
	$i = 1$	$i = 2$	$i = 3$	$i = 1$	$i = 2$	$i = 3$	$i = 1$	$i = 2$	$i = 3$	$i = 1$	$i = 2$	$i = 3$
$q = 3$	0	7	15	0	0	16	0	0	0	16	0	0
$q = 4$	0	0	6	0	0	0	0	0	0	0	0	17
$q = 5$	0	0	14	0	17	15	25	0	19	13	0	0
$q = 6$	20	15	7	0	0	0	10	0	0	0	0	0
$q = 7$	0	0	6	0	0	0	0	0	0	0	0	17

$$ZO = \sum_i PR_i \times \Big(\sum_{r,s,t} \delta^{FX}_{st} \times \eta\delta_{rsti} + \sum_{r,s,m,t} \delta^{PR}_{rst} \times Y\delta\xi_{rsmti} + \sum_{p,m,w,t} \xi^{PR}_{pmt}$$
$$\sum_{p,v,w,a,t} \varphi^{PR}_{pwt} \times Y\varphi\alpha_{pvwati} + \sum_{p,a,c,t} \beta^{PR}_{pct} \times Y\alpha\beta_{pacti} + \sum_{r,c,e,t} \psi^{PR}_{ret} \times Y\beta\psi_{rc}$$
$$\sum_{p,a,t} \alpha^{PR}_{pat} \times \vartheta P_{pati} + \sum_{r,s,m,t} \delta\xi_{rsmt} \times Y\delta\xi_{rsmti} + \sum_{p,m,w,t} \xi\varphi_{pmwt} \times Y\xi\varphi_{pmwt}$$
$$\sum_{r,c,e,t} \beta\psi_{rcet} \times Y\beta\psi_{rceti} + \sum_{r,c,d,t} \beta\varpi_{rcdt} \times Y\beta\varpi_{rcdti} + \sum_{r,e,m,t} \psi\xi_{remt} \times Y\psi$$
$$\sum_{p,a,t} \varphi_{pt} \times \vartheta N_{pati} + PF \times \sum_{v,w,a>1,t} F\tau_v \times \varphi\alpha_{wa} \times \eta_{vw} \times (\gamma_{v1ati} + \gamma_{va1ti}) +$$
$$PF \times \sum_{v,a'>1,a>1,t} F\tau_v \times \alpha_{a'a} \times \gamma_{va'ati} + \sum_{r,s,m,t} \Psi \times E\delta\xi_{rsmt} \times Y\delta\xi_{rsmti} +$$
$$\sum_{p,m,w,t} \Psi \times E\xi\varphi_{pmwt} \times Y\xi\varphi_{pmwti} + \sum_{p,a,c,t} \Psi \times E\alpha\beta_{pact} \times Y\alpha\beta_{pacti} +$$
$$\sum_{r,c,e,t} \Psi \times E\beta\psi_{rcert} \times Y\beta\psi_{rceti} + \sum_{r,c,d,t} \Psi \times E\beta\varpi_{rcdt} \times Y\beta\varpi_{rcdti} +$$
$$\sum_{r,e,m,t} \Psi \times E\psi\xi_{remt} \times Y\psi\xi_{remti} + \sum_{v,w,a>1,t} \Psi \times E\tau_v \times F\tau_v \times \varphi\alpha_{wa} \times \eta_{vw}$$
$$\sum_{v,a'>1,a>1,t} \Psi \times E\tau_v \times F\tau_v \times \alpha_{a'a} \times \gamma_{va'ati} + \sum_{p,m,w,t} \Psi \times E\xi_{pm} \times Y\xi\varphi_{pmwt}$$
$$\sum_{p,v,w,a,t} \Psi \times E\varphi_{pw} \times Y\varphi\alpha_{pvwati} + \sum_{p,a,c,t} \Psi \times E\beta_{pc} \times Y\alpha\beta_{pacti} +$$
$$\sum_{r,c,e,t} \Psi \times E\psi_{re} \times Y\beta\psi_{rceti} + \sum_{r,c,d,t} \Psi \times E\varpi_{rd} \times Y\beta\varpi_{rcdti}\Big)$$

$$\sum_s Y\delta\xi_{rsmti} \geq \theta_{rp} \times \sum_w Y\xi\varphi_{pmwti} \forall r,p,m,t = 1,i \tag{5}$$

$$\sum_s Y\delta\xi_{rsmti} + \sum_e Y\psi\xi_{remti} \geq \theta_{rp} \times \sum_w Y\xi\varphi_{pmwti} \forall r,p,m,t>1,i \tag{6}$$

$$\sum_m Y\xi\varphi_{pmwti} \geq \sum_{v,a} Y\varphi\alpha_{pvwati} \forall p,w,t,i \tag{7}$$

$$\vartheta_{pati} = \sum_{v,w} Y\varphi\alpha_{pvwati} - \alpha^{CP}_{pati} - \sum_c Y\alpha\beta_{pacti} \forall p,a,t = 1,i \tag{8}$$

$$\vartheta_{pati} = \vartheta_{pa(t-1)i} + \sum_{v,w} Y\varphi\alpha_{pvwati} - \alpha^{CP}_{pati} - \sum_c Y\alpha\beta_{pacti} \forall p,a,t>1,i \tag{9}$$

$$\vartheta_{pati} = \vartheta P_{pati} - \vartheta N_{pati} \forall p,a,t,i \tag{10}$$

$$\sum_c Y\alpha\beta_{pacti} = \sum_{v,w} \chi_{pat} \times Y\varphi\alpha_{pvwati} \forall p,a,t,i \tag{11}$$

$$\sum_a Y\alpha\beta_{pacti} \times \theta_{rp} = \sum_e Y\beta\psi_{rceti} + \sum_d Y\beta\varpi_{rcdti} \forall r,p,c,t,i \tag{12}$$

$$\sum_c Y\beta\psi_{rceti} = \sum_m Y\psi\xi_{remti} \forall r,e,t,i \tag{13}$$

$$\sum_e Y\beta\psi_{rceti} = \sum_a \chi'_{rct} \times Y\alpha\beta_{pacti} \times \theta_{rp} \forall r,p,c,t,i \tag{14}$$

$$\sum_m Y\delta\xi_{rsmti} \leq \delta^{CP}_{rst} \forall r,s,t,i \tag{15}$$

$$\sum_w Y\xi\varphi_{pmwti} \leq \xi^{CP}_{pmt} \forall p,m,t,i \tag{16}$$

$$\sum_{v,a} Y\varphi\alpha_{pvwati} \leq \varphi^{CP}_{pwt} \forall p,w,t,i \tag{17}$$

$$\sum_a Y\alpha\beta_{pacti} \leq \beta^{CP}_{pct} \forall p,c,t,i \tag{18}$$

$$\sum_c Y\beta\psi_{rceti} \leq \psi^{CP}_{ret} \forall r,e,t,i \tag{19}$$

$$\sum_{r,c} Y\beta\varpi_{rcdti} \times \kappa_r \leq \varpi^{CP}_{dt} \forall d,t,i \tag{20}$$

$$\sum_{p,a} Y\varphi\alpha_{pvwati} \times \kappa'_p \leq \tau^{CP}_v \forall v,w,t,i \tag{21}$$

$$\sigma_{vati} + \left(1 - \gamma_{va'ati}\right) \times bigm \geq \sigma_{va'ti} + T\alpha_{va'a} \forall v,a',a>1,t,i \tag{22}$$

$$\sigma_{v1ti} + \left(1 - \gamma_{va1ti}\right) \times bigm \geq \sigma_{vati} + T\varphi\alpha_{vwa} \times \eta_{vw} \forall v,w,a>1,t,i \tag{23}$$

$$\sum_{a'} \gamma_{va'ati} - \sum_{a'} \gamma_{vaa'ti} = 0 \forall v,a,t,i \tag{24}$$

$$\sum_{a'} \gamma_{va'ati} \leq 1 \forall v,a,t,i \tag{25}$$

$$Y\varphi\alpha_{pvwati} \leq bigm \times \eta\tau_v \forall p,v,w,a,t,i \tag{26}$$

$$Y\varphi\alpha_{pvwati} \leq bigm \times \sum_{a'} \gamma_{va'ati} \forall p,v,w,a,t,i \tag{27}$$

$$Y\varphi\alpha_{pvwati} \leq bigm \times \eta_{vw} \forall p,v,w,a,t,i \tag{28}$$

$$\sum_v \eta_{vw} \leq bigm \times \eta\varphi_w \forall w \tag{29}$$

$$\sum_w \eta_{vw} \leq 1 \forall v \tag{30}$$

$$Y\delta\xi_{rsmti} \leq bigm \times \eta\delta_{rst} \forall r,s,m,t,i \tag{31}$$

$$Y\delta\xi_{rsmti} \leq bigm \times \eta\xi_m \forall r,s,m,t,i \tag{32}$$

$$Y\xi\varphi_{pmwti} \leq bigm \times \eta\xi_m \forall p,m,w,t,i \tag{33}$$

$$Y\psi\xi_{remti} \leq bigm \times \eta\xi_m \forall r,e,m,t,i \tag{34}$$

$$Y\xi\varphi_{pmwti} \leq bigm \times \eta\varphi_w \forall p,m,w,t,i \tag{35}$$

$$Y\varphi\alpha_{pvwati} \leq bigm \times \eta\varphi_w \forall p,v,w,a,t,i \tag{36}$$

$$Y\alpha\beta_{pacti} \leq bigm \times \eta\beta_c \forall p,a,c,t,i \tag{37}$$

$$Y\beta\psi_{rceti} \leq bigm \times \eta\beta_c \forall r,c,e,t,i \tag{38}$$

$$Y\beta\varpi_{rcdti} \leq bigm \times \eta\beta_c \forall r,c,d,t,i \tag{39}$$

$$Y\beta\psi_{rceti} \leq bigm \times \eta\psi_e \forall r,c,e,t,i \tag{40}$$

$$Y\psi\xi_{remti} \leq bigm \times \eta\psi_e \forall r,e,m,t,i \tag{41}$$

$$Y\beta\varpi_{rcdti} \leq bigm \times \eta\varpi_d \forall r,c,d,t,i \tag{42}$$

$$\sigma_{v'ati} - \sigma_{vati} + bigm \times \mu_{v'vati} \geq \zeta_{at} \forall v' \neq v,a>1,t,i \tag{43}$$

$$\sigma_{vati} - \sigma_{v'ati} + bigm \times (1 - \mu_{v'vati}) \geq \zeta_{at} \forall v' \neq v,a > 1,t,i \tag{44}$$

The first objective function minimizes the total costs including strategic and operational costs. Strategic and operational costs are given in constraints (3) and (4), respectively.

The second objective function minimizes the lost sales.

Constraint (3) calculates strategic costs. These costs include costs of opening manufacturing centers, central warehouses, collection, recycling, and disposal centers.

Constraint (4) calculates operational costs. These costs include ordering cost to suppliers, cost of purchasing raw materials, costs of processing raw materials/products in central warehouses, manufacturing, collection, recycling, and disposal centers, cost of holding products in warehouses of automotive wiring centers, transportation costs, shortage cost, cost of fuel consumption by vehicles, and carbon tax.

Constraints (5) and (6) guarantee the inventory balance in manufacturing centers. Similarly, the inventory balance for central warehouses is considered in constraint (7). Constraints (8) and (9) calculate the inventory level at warehouses of automotive wiring centers, and relations between inventory level, shortage, and storage are determined by constraint (10). The noteworthy point in constraint (8) is that because both variables ϑP_{pqti} and ϑN_{pqti} are positive, variable ϑ_{pqti} must be defined as

Fig. 3. Sequence of routes assigned to vehicle 2.

a free variable. Constraint (11) calculates the amount of returned products from automotive wiring centers to collection centers. Inventory balance in collection and recycling centers are controlled by constraints (12) and (13), respectively. Amount of returned products shipped from collection centers to recycling centers are calculated by constraint (14). Capacity constraints of suppliers, manufacturing centers, central warehouses, collection, recycling, disposal, and vehicles are represented in constraints (15) to (21), respectively. Sub-tour elimination constraint is considered in constraints (22) and (23). Constraint (24) guarantees that if vehicles enter an automotive wiring center, they should leave it. Each

Table 8
The optimal value of objective functions obtained AUGMECON.

Grid point	Objective function 1	Objective function 2
GP1	15,183,917	0
GP2	14,802,729	42.5
GP3	14,601,682	86
GP4	14,328,125	128.25
GP5	14,400,437	170.25
GP6	14,385,926	209.5
GP7	13,701,662	255
GP8	13,591,731	291
GP9	13,120,152	341.25
GP10	13,255,174	378.5
GP11	12,883,251	429.25
GP12	12,925,226	468.5

vehicle is allowed to serve each automotive wiring center at most once, in each time period and scenario. This issue is controlled by constraint (25). To deliver the products to automotive wiring centers, vehicles should be purchased, vehicles should visit the automotive wiring centers, and the purchased vehicles should be assigned to central warehouses; these conditions are considered in constraints (26) to (28), respectively. Constraint (29) states that if a central warehouse is not opened, vehicles should not be allocated to it. Each vehicle is allowed to be dedicated to a maximum of one central warehouse. This condition is managed by constraint (30). The condition of ordering raw materials to suppliers is considered in constraint (31). The condition of location for manufacturing centers is controlled by constraints (32) to (34). Similarly, the condition of location for central warehouses is managed by constraints (35) and (36). Also, constraints (37) to (42) represent the condition of location for collection, recycling, and disposal centers, respectively. Vehicles scheduled for serving the automotive wiring centers are guaranteed by constraints (43) and (44).

3.1. Linearization process

Multiplying the two binary variables η_{vw} and $\gamma_{va'ati}$ in the constraint (4) creates a nonlinear term in the proposed model. To linearize this term, we use the technique presented by Govindan et al. (2022). For this purpose, an auxiliary binary variable (i.e., $X_{vwa'ati}$) is defined and replaced with the nonlinear term, which is as follows:

$$ZO' = \sum_i PR_i \times \Big(\sum_{r,s,t} \delta_{st}^{FX} \times \eta\delta_{rsti} + \sum_{r,s,m,t} \delta_{rst}^{PR} \times Y\delta\xi_{rsmti} + \sum_{p,m,w,t} \xi_{pm}^{PF}$$
$$\sum_{p,v,w,a,t} \varphi_{pwt}^{PR} \times Y\varphi\alpha_{pvwati} + \sum_{p,a,c,t} \beta_{pct}^{PR} \times Y\alpha\beta_{pacti} + \sum_{r,c,e,t} \psi_{ret}^{PR} \times Y\beta\psi_{rce}$$
$$\sum_{p,a,t} \alpha_{pat}^{PR} \times \vartheta P_{pati} + \sum_{r,s,m,t} \delta\xi_{rsmt} \times Y\delta\xi_{rsmti} + \sum_{p,m,w,t} \xi\varphi_{pmwt} \times Y\xi\varphi_{pmwt}$$
$$\sum_{r,c,e,t} \beta\psi_{rcet} \times Y\beta\psi_{rceti} + \sum_{r,c,d,t} \beta\varpi_{rcdt} \times Y\beta\varpi_{rcdti} + \sum_{r,e,m,t} \psi\xi_{remt} \times Y\psi$$
$$\sum_{p,a,t} \varphi_{pt} \times \vartheta N_{pati} + PF \times \sum_{v,w,a>1,t} F\tau_v \times \varphi\alpha_{wa} \times (X_{vw1ati} + X_{vwa1ti}) +$$
$$PF \times \sum_{v,a'>1,a>1,t} F\tau_v \times \alpha_{a'a} \times \gamma_{va'ati} + \sum_{r,s,m,t} \Psi \times E\delta\xi_{rsmt} \times Y\delta\xi_{rsmti} +$$
$$\sum_{p,m,w,t} \Psi \times E\xi\varphi_{pmwt} \times Y\xi\varphi_{pmwti} + \sum_{p,a,c,t} \Psi \times E\alpha\beta_{pact} \times Y\alpha\beta_{pacti} +$$
$$\sum_{r,c,e,t} \Psi \times E\beta\psi_{rcert} \times Y\beta\psi_{rceti} + \sum_{r,c,d,t} \Psi \times E\beta\varpi_{rcdt} \times Y\beta\varpi_{rcdti} +$$
$$\sum_{r,e,m,t} \Psi \times E\psi\xi_{remt} \times Y\psi\xi_{remti} + \sum_{v,w,a>1,t} \Psi \times E\tau_v \times F\tau_v \times \varphi\alpha_{wa} \times (X_{vi}$$
$$\sum_{v,a'>1,a>1,t} \Psi \times E\tau_v \times F\tau_v \times \alpha_{a'a} \times \gamma_{va'ati} + \sum_{p,m,w,t} \Psi \times E\xi_{pm} \times Y\xi\varphi_{pmwt}$$
$$\sum_{p,v,w,a,t} \Psi \times E\varphi_{pw} \times Y\varphi\alpha_{pvwati} + \sum_{p,a,c,t} \Psi \times E\beta_{pc} \times Y\alpha\beta_{pacti} +$$
$$\sum_{r,c,e,t} \Psi \times E\psi_{re} \times Y\beta\psi_{rceti} + \sum_{r,c,d,t} \Psi \times E\varpi_{rd} \times Y\beta\varpi_{rcdti}\Big)$$

Then, the relationship between the new binary variable and the two binary variables η_{vw} and $\gamma_{va'ati}$ are determined using constraints (46) and (47).

$$1.5 \times X_{vwa'ati} - \eta_{vw} - \gamma_{va'ati} \leq 0 \forall v, w, a', a, t, i \quad (46)$$

$$X_{vwa'ati} - \eta_{vw} - \gamma_{va'ati} + 1.5 \geq 0 \forall v, w, a', a, t, i \quad (47)$$

If at least one of the variables η_{vw} or $\gamma_{va'ati}$ is set to zero, the variable $X_{vwa'ati}$ should be zero. Constraint (46) guarantees this issue. Also, if both variables η_{vw} and $\gamma_{va'ati}$ take the value of one at the same time, the variable $X_{vwa'ati}$ should take the value of one. Constraint (47) makes this happen.

4. Solution approach

Hwang et al. (1980) claimed that it is possible to categorize multi-objective optimization solving methods into three classes, namely a priori, interactive, and posteriori methods. In a priori method, DMs are allowed to show their preferences or comment on the weights of objective function before the problem is solved. The second category, that is, interactive methods, is representative of a continuous dialogue existing between DMs and analysts that finally may result in the convergence of the preferences with solutions. In posteriori methods, it is focused on solving the problem and finding the effective Pareto solutions so that DMs can choose from among them in line with their preferences. Considering the preconditions of a priori methods (i.e., infrequency of early knowledge and quantification capability of the preference model already set by DMs) as well as DMs' difficult task in having a full command of the Pareto front along with the interactive methods, the current study aims at solving the proposed bi-objective model through posteriori methods. From among these methods, this is the epsilon-constraint method that focuses on optimizing one objective function. This is so while all the other objective functions are regarded as constraints. In this paper, the proposed bi-objective model is solved using the augmented epsilon-constraint method (AUGMECON) presented by Mardan et al. (2019). The total form of AUGMECON is as follows:

$$\begin{aligned} & Min\ \left(F_1(x) - \Omega \times \left(\frac{\check{}_2}{r_2} + \ldots + \frac{\check{}_p}{r_p}\right)\right) \\ & s.t. \\ & F_2(x) + \check{}_2 = \varepsilon_2 \\ & \vdots \\ & F_j(x) + \check{}_j = \varepsilon_j \\ & \vdots \\ & F_p(x) + \check{}_p = \varepsilon_p \\ & \check{}_2, \ldots, \check{}_p \geq 0 \end{aligned} \quad (48)$$

where Ω represents a small number (usually among 10^{-6} to 10^{-3}). $\check{}_j$ and r_j are the slack variable and the range of the objective function j, respectively. Also, F_p shows the objective function p. It should be noted that the lexicographic optimization method is employed to calculate the lower and upper bounds of objective functions, which is described in detail in the case study section.

5. Case study

In this section, the performance of the proposed circular economy based closed loop supply chain network model and solution approach is examined using the data and experts' knowledge of a wire and cable production and distribution company in Iran. The company under study has an area of about 14,000 square meters and is located near the capital of Iran (i.e., Tehran); it annually produces about 6000 million meters of various wires and cables. This paper applies data related to six automotive wiring centers, four suppliers, three central warehouses, three collection centers, three disposal and three recycling centers, six vehicles, four time periods, and three scenarios including pessimistic, most possible, and optimistic, for the validation of proposed model. This company produces a variety of products, but this paper applies data on three types of automotive wire, including AV, AVS, and AVSS. It should be noted that this company uses 8 mm copper wire and

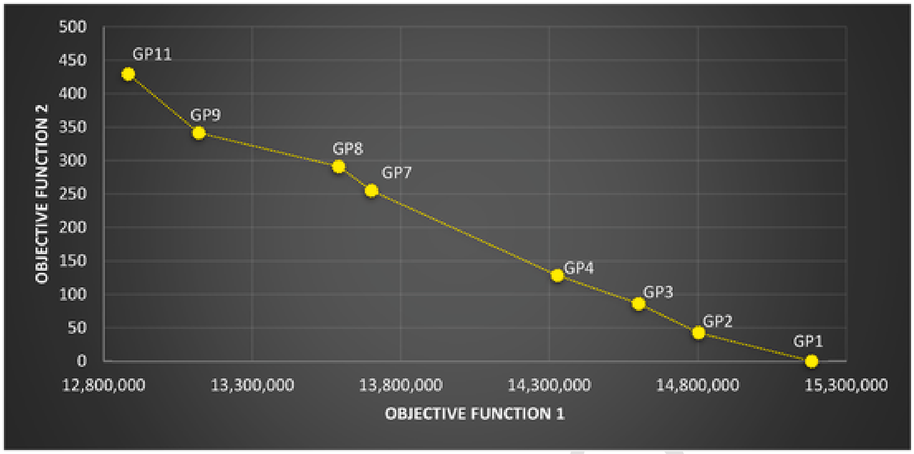

Fig. 4. The Pareto frontier obtained classical epsilon-constraint method.

polyvinyl chloride (PVC) granules to produce its products. The amount of raw materials required to produce the mentioned products is given in Table 2. Also, Tables 3 and 4 provide the distance among automotive wiring centers and the demand of these centers, respectively.

As mentioned, in this paper, the augmented epsilon-constraint method presented by Mardan et al. (2019) is used to solve the proposed bi-objective model. The first step in implementing this method is to calculate the lower and upper bounds of objective functions and form a payoff table. The following lexicographic method is used for this purpose.

- Assume that the second objective function does not exist and the model minimizes only the first objective function. In this case, the optimal value of the objective function is, indeed, the lower bound of the first objective function.
- Similarly, assume that the first objective function does not exist and the model minimizes only the second objective function. In this case, the optimal value of the objective function is, indeed, the lower bound of the second objective function.
- To calculate the upper bound of the second objective function, the second objective function should be minimized subject to the first objective function's non-exceeding its lower bound.
- Similarly, to calculate the upper bound of the first objective function, the first objective function should be minimized subject to the second objective function's non-exceeding its lower bound.

The value of the lower and upper bounds of objective functions are given in Table 5. In this table, the lower and upper bounds of objective function 1 are shown by Z_1^L and Z_1^U, respectively, and Z_2^L and Z_2^U represent the lower and upper bounds of objective function 2, respectively.

After forming the payoff table, the proposed model should be structured based on AUGMECON. For this purpose, the first objective is defined as the main objective function and the second objective function is added to the model constraints. Finally, using the structure presented in Eq. (48), the proposed model is formulated as follows:

$$Min\ \ Z_1 = ZS + ZO' - \Omega \times \frac{\check{\ }_2}{473 - 0} \tag{49}$$

s.t.

$$\sum_{p,a,t,i} PR_i \times \vartheta N_{pati} + \check{\ }_2 = \varepsilon_2 \tag{50}$$

Constraints (3) and (5)-47.

To form a Pareto frontier, the single-objective model should be run by CPLEX solver in GAMS software for different value of ε_2. For this purpose, the amounts of ε_2 are calculated using Eq. (51).

$$\varepsilon_2 = Z_2^L + \frac{Z_2^U - Z_2^L}{GP - 1} \times k \forall k = 0, 1, 2, ..., GP - 1 \tag{51}$$

where GP represents the number of grid points and is determined by DMs. In this paper, 12 grid points are considered to extract the Pareto frontier. The calculated values for ε_2 is shown in Table 6. Also, the optimal values of the objective functions for each grid point are given in this table.

We should use a set of non-dominated solutions for forming the Pareto frontier. For this purpose, we should identify dominated solutions and exclude them from the set of feasible solutions. As shown in Table 5, GP6, GP8, and GP11 are dominated solutions; because these grid points are dominated by GP5, GP7, and GP10, respectively. Therefore, in order to have Pareto solutions, these grid points should be excluded from the set of feasible solutions. The Pareto frontier obtained from AUGMECON is illustrated in Fig. 2.

DMs can now choose the best grid point from the set of Pareto solutions based on their organizational condition. In this study, given that the maximum available budget is $14,000,000, DMs adopted grid point 5 (GP5) as the optimal decision. In the following, the optimal values of some decision variables related to this grid point are examined.

Suppliers 2 and 3 were selected to purchase raw materials. Central warehouse 2, collection center 1, recycling centers 1 and 3, and disposal center 2 were set up. Vehicles 2, 4, 5, and 6 were purchased for delivering the products to the automotive wiring centers. The amount of products delivered to each automotive wiring center by each vehicle in each time period and scenario are given in Table 7.

For example, the number 21 in the first row of Table 7 states that if scenario 1 occurs, 21 units of product 1 (AV wire) should be transferred from central warehouse 2 to automotive wiring center 2 (Karaj Square) in time period 1. Similarly, the other numbers in this table can be analyzed. One of the important and practical decision variables of the proposed model is the routes traveled by vehicles. Fig. 3 shows the routes taken by vehicle 2 in each time period and each scenario. In addition, the routes traveled by other vehicles are provided in the Appendix.

For example, as shown in Fig. 3, if scenario 1 occurs, vehicle 2 would travel from the central warehouse to the Atmosfer center in time period 1, and then visit the Jahannama and Karaj Square centers, respectively and finally returns to the central warehouse. As mentioned, Table 7 reports the amount of products delivered to each automotive wiring center in each time period and each scenario by each vehicle, and does not provide information on the routes traveled by the vehicles. Therefore, by combining the results presented in Table 7 and Fig. 3, more accurate and practical information can be obtained. For example, in time period 1 and scenario 1, vehicle 2 loads 41 units of product 1, 22 units of product 2, and 30 units of product 3 from the central warehouse, and moves to the Atmosfer center. It delivers 20 units of product 1, 5 units of product 2, and 6 units of product 3 to this center, and heads to the next destination (i.e., Jahannama center), and unloads 17 units of product 2 and 8 units of product 3 at this center. Then the rest of the products, i.e., 21 units of product 1 and 16 units of product 3 will be delivered to Karaj Square center. Similarly, by integrating the results of Table 7 and Fig. 3, all the information related to vehicle routing problem for all vehicles in each time period and each scenario can be extracted.

6. Comparative analysis

In this section, the proposed bi-objective model is solved using the case study data by the classical epsilon-constraint method presented by Chankong and Haimes (1983), and the results from the classical epsilon-constraint method are compared with the AUGMECON results. For this purpose, like AUGMECON, 12 grid points are considered. The optimal values of the objective functions for each grid point obtained from classical epsilon-constraint method are given in Table 8.

The results presented in Table 8 show that GP5, GP6, GP10, and GP12 are dominated solutions, and should be removed from the set of feasible solutions to obtain Pareto efficient solutions. Fig. 4 shows the efficient Pareto frontier obtained from the classical epsilon-constraint method.

The results revealed that under the same conditions (i.e., considering 12 grid points), AUGMECON achieved 9 efficient solutions, while the classical epsilon-constraint method gained 8 efficient solutions. In addition, the comparison of the optimal values of the objective functions obtained from both methods shows that the set of solutions calculated for GP2, GP7, GP8 by the classical epsilon-constraint method are dominated by the AUGMECON. Therefore, it can be concluded that AUGMECON has a more effective performance compared to the classical epsilon-constraint method.

7. Managerial implications

In this paper, a bi-objective MILP model was developed to design a circular CLSC network in the wire and cable industry to achieve circular economy in the value chains. This network was structured based on the needs of a wire and cable industry in Iran, and the proposed model was formulated using real-world assumptions to be provided to DMs as a decision support system. The proposed model allows DMs to identify deserving suppliers and optimal facilities. In addition, it provides vehicle routing and scheduling program for DMs. It should be noted that the proposed model applies the carbon tax policy to reduce emissions. Since both raw materials (i.e., PVC granules and copper wire) used in the wire and cable industry are reusable, the proposed model includes reverse logistics operations to reduce resource consumption in addition to reducing costs. Therefore, the proposed model has a significant contribution to achieving circular economy through environmental protection due to the management of vehicle fuel consumption and reuse of returned products, further which could lead to the speedy achievement of targeted SDGs. One of the advantages of the proposed model is that it does not impose just one optimal solution on DMs; it allows DMs to choose the most appropriate solution from the set of optimal solutions according to the limitations and conditions of their company. The proposed model is flexible and can be easily implemented in industries/SCNs where recycling is important by making minor changes to its structure. For example, the proposed model is easily customized in any of the industries (the automotive parts manufacturing and distribution industry (Gu et al., 2021; Govindan et al., 2020), food supply chains (Salehi-Amiri et al., 2022), plastic and tire industries (Fathollahi-Fard et al., 2021; Santander et al., 2020), and so on) seeking circular advantage in their supply chain.

8. Conclusion

In this paper, a circular CLSCN was structured to manage the production, distribution, and inventory planning in the wire and cable industry for effective implementation of circular economy in their supply chain networks. For this purpose, a bi-objective MILP model was formulated with the aim of optimizing the strategic and operational decisions. The proposed model uses an integrated LIR problem for facilities location, heterogenous vehicle routing, and inventory planning. In addition, the proposed model applies the carbon tax policy to reduce emissions, and the scheduling problem to decrease the waiting time of vehicles. Since demand is inherently uncertain, a scenario-based approach including pessimistic, most possible, and optimistic scenarios was employed to overcome the uncertainty. In order to achieve an efficient optimal solution set and solve the bi-objective model, an augmented epsilon-constraint method (AUGMECON) was employed. To extract the Pareto frontier, the proposed model was run using data from a wire and cable industry for 12 grid points, and the results showed that the solutions for the three grid points were dominated by the other grid points. Finally, the Pareto frontier was depicted using nine grid points, and DMs chose the solutions pertaining to grid point 5 (GP5) according to the available budget. LIR problem is in the category of NP-hard problems and it is not possible to solve it in large sizes by commercial software. Therefore, it is suggested to develop a heuristic or meta-heuristic algorithm to solve the proposed problem in large sizes in future research. Furthermore, this paper does not consider the social aspect of sustainability, which is suggested to be addressed in future research.

Data availability

The data is included in the paper

Appendix.

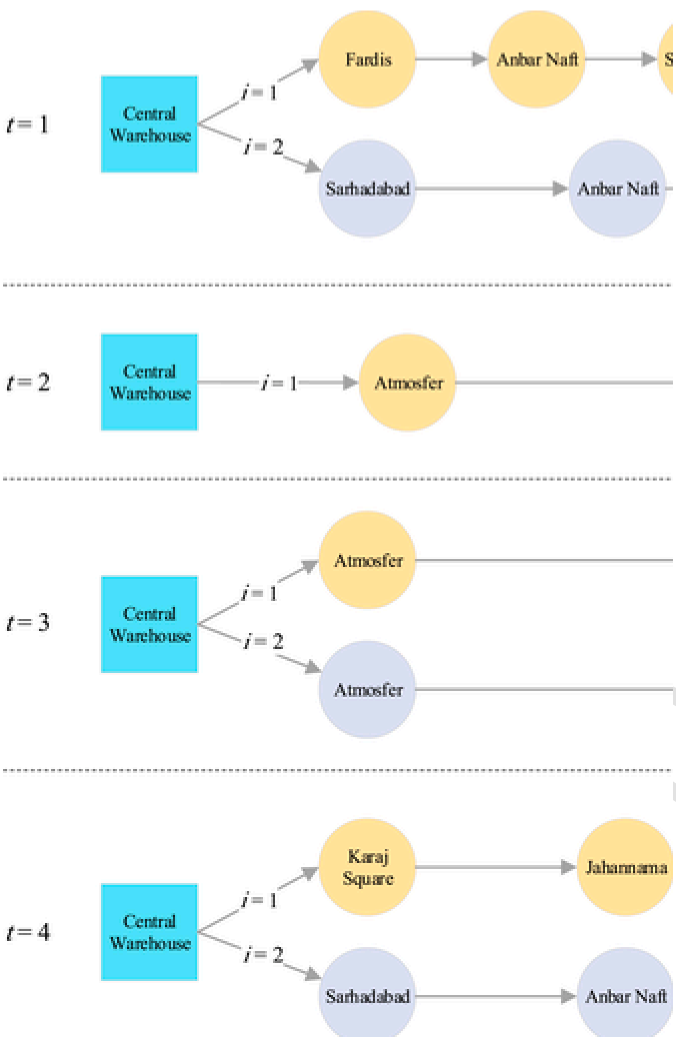

Fig. A1. Sequence of routes assigned to vehicle 4

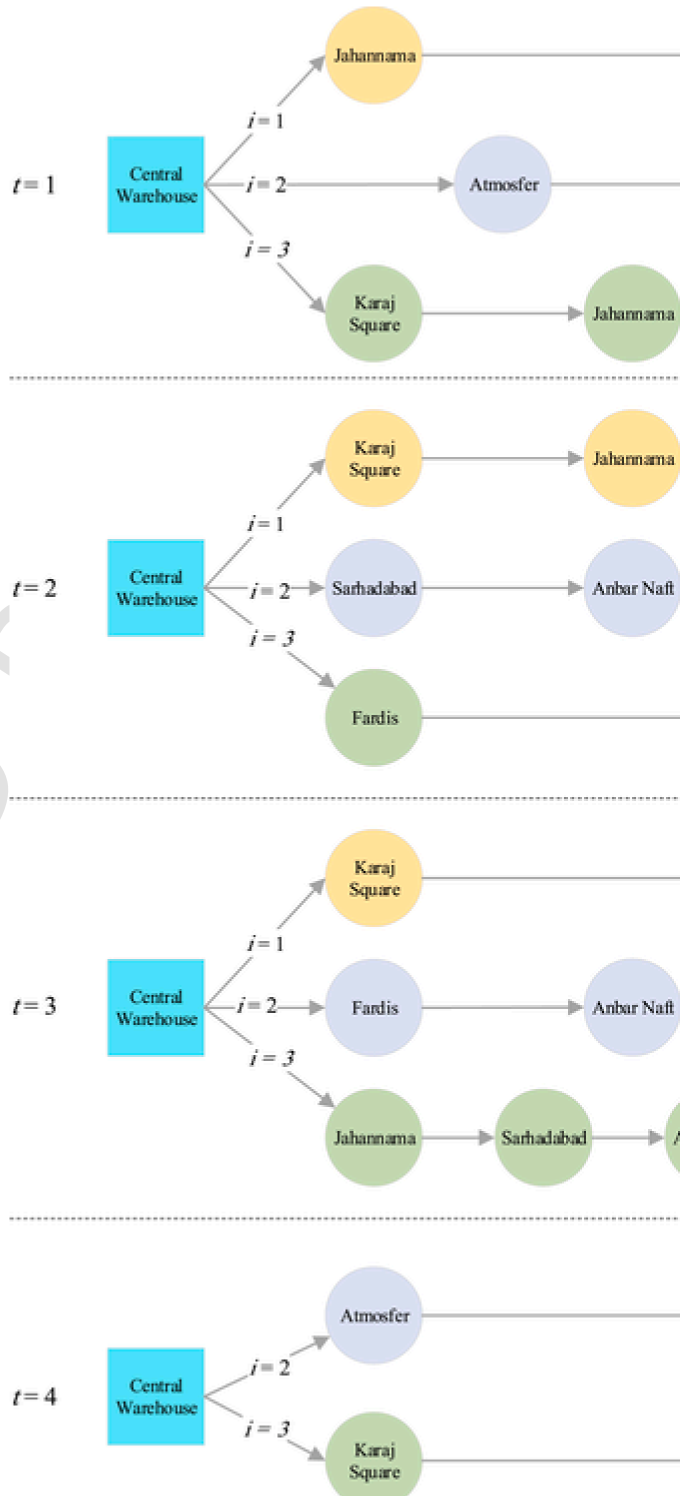

Fig. A2. Sequence of routes assigned to vehicle 5

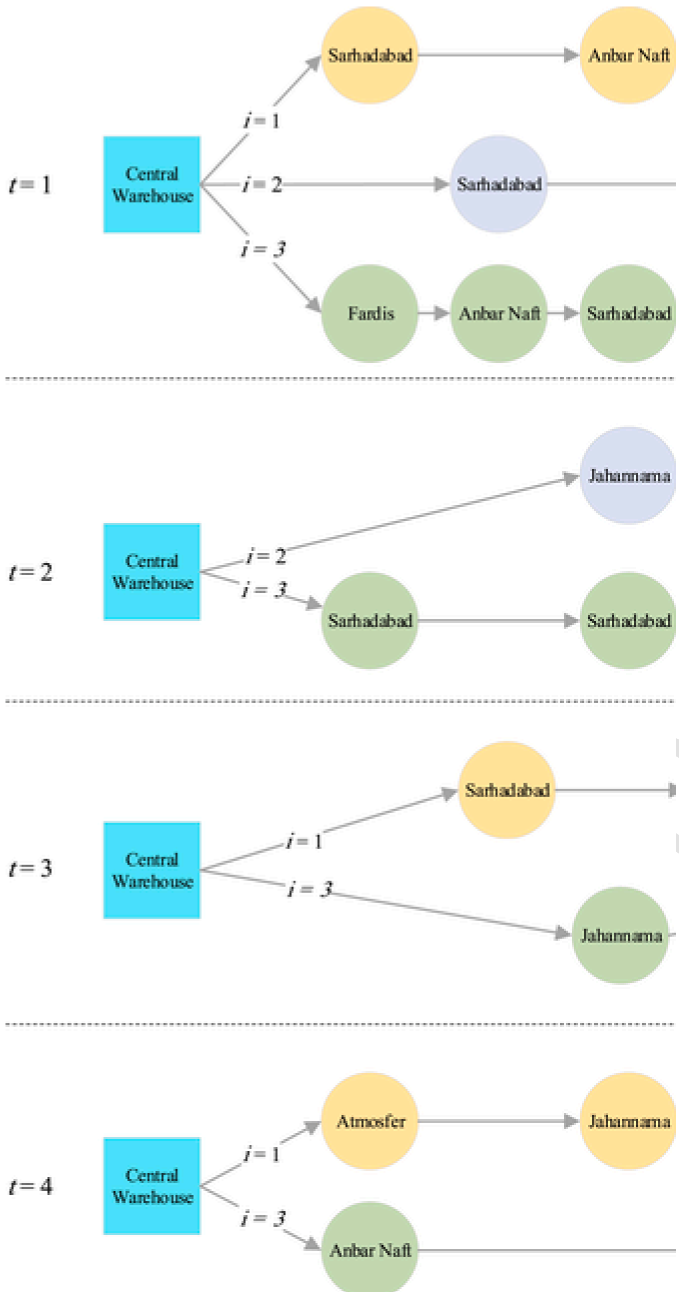

Fig. A3. Sequence of routes assigned to vehicle 6

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