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S.I. : OR FOR SUSTAINABILITY IN SUPPLY CHAIN MANAGEMENT

A Benders decomposition approach for a new sustainable pharmaceutical supply chain network: a case study in France

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Abstract
Recently, sustainable supply chains have emerged to emphasize the importance of social and environmental concerns along with economic factors in supply chain management. In this context, there is a necessity for mathematical models that indicate environmental aspects and the social effects of the supply chain network. In the present study, a new multi-product production, distribution, and transportation, in which the economic, environmental, and social effects under CO_2 emission to fill this gap are presented. Additionally, service technology under various criteria in the social aspects and time window for the earliest and latest arrival time of products to main distribution centers are provided. Also, other novelties of this paper, the environmental effects to open main and local distribution centers, warehouses, and pharmacies are considered as environmental effects. So, the main contributions of this paper are to develop a multi objective, dynamic production and distribution planning using time windows in service technology of sustainable pharmaceutical supply Chain Network. In this regard, the mathematical model is formulated as a mixed-integer linear programming model. Moreover, a Benders decomposition approach is appropriately extended to solve the presented model. In the proposed approach, the problem is decomposed into two models of sub-problem and a master. The master problem is developed by means of preprocessing and valid inequalities. The general and relative efficiency of the model and approach is experimentally assessed. The pharmaceutical production and distribution system of France is considered as a real case study in this paper. Eventually, the results indicate that the proposed approach considerably outperforms, and the efficiency of the developed model is verified through a set of sensitivity analyses.

Keywords Supply chain design · Networks · Sustainable pharmaceutical supply chain network · Time windows · CO_2 emission · Benders decomposition approach · Case study

1 Introduction

Supply chain management assures multi factors of competitiveness through a well-organized interconnected network, which enables the companies to improve their potential and enrich

Extended author information available on the last page of the article other actors of the supply chain (Govindan et al., 2019; Taghipour & Frayret, 2013). Supply chain forms a virtual enterprise with well-structured functional areas such as production, distribution, and consumption, which are managed to achieve targeted goals (Yolmeh & Saif, 2020). Trivially, the actual supply chain management approaches are not completely feasible for the present environmental depletion. Political pressure and legislative rules & regulations have urged supply chain managers to design and adopt the closed-loop supply chain (CLSC) network (Fakhrzad et al., 2019). The CLSC Management is to identify the service facility for end-of-use (EOU) and end-of-life (EOL) products by collecting from end-users and treating them for further required services such as recycling, refurbishing, and incineration facility, etc. (Badiezadeh et al., 2018; Qian et al., 2020). Because of the effectiveness of closed-loop supply chain management, many researchers and practitioners presented various potential research studies comprising with the SCM and CLSC network [see (Jindal & Sangwan, 2014; Arampantzi et al., 2019; Vafaei et al., 2020; Ites et al., 2020; Rajesh, 2020; Pexas et al., 2020; Sun et al., 2020; Vosooghdizaji et al., 2020)].

Over the past few decades, significant attention has been put on sustainability in supply chain design (Tahipour & Frayret, 2013; Vosooghdizaji et al., 2020; Goodarzian et al., 2020, 2021; Benders, 1962; Zahiri et al., 2017). As the production and consumption processes of products involve various phases in which environmental impacts are very severe and harmful. Therefore, a sustainable supply chain management (SSCM) network is designed and implemented efficiently by many researchers to overcome social issue and environmental impacts (Dubey et al., 2017; Aboytes-Ojeda et al., 2020; Tliche et al., 2019, 2020). The SSCM contemplates over three objectives such as economic cost, social issues and environmental impacts, known as TBL (Tripple Bottom Line) objectives for sustainable development (Wang et al., 2020).

The main contributions of this paper are to develop a multi objective, dynamic production and distribution planning using time windows and service technology for sustainable pharmaceutical supply chain network. therefore, according to the mentioned considerations to the PSCN and SCM, this paper develops a sustainable production and distribution network design integrated with time windows under CO_2 emission that is a four-echelon PSCN including producers, warehouses, local and main DCs, and pharmacies. The present paper goals in finding the best pharmaceutical network design according to the three pillars of sustainability. The traits of the proposed problem of this paper are defined according to the real case study of a pharmaceutical production and distribution network in France. Moreover, a Benders decomposition approach is extended to solve the presented model. Hence, the problem is decomposed into two models of sub-problem and master. A real case study of France based pharmaceutical company has been done along with the significant findings. The principal innovations that distinguish this paper from the current studies follow as:

- Extending a mixed-integer linear programming (MILP) model to design a sustainable PSCN under CO_2 emission, which can optimize network total costs, environmental impacts, and social effects simultaneously;
- Considering service technology under various criteria in the social aspects for the first time in this network;
- Considering time windows for the earliest and latest arrival time of pharmaceutical products to main distribution centers;
- Integrating production and distribution problem with time windows into the PSCN problem;
- Developing a Benders approach to efficiently solve the PSCN model for the first time;
- Validation the efficiency of the proposed model by several sensitivity analyses;

- Applying the proposed model in a real case study in France.

The rest of the paper is organized as follows: In Sect. 2, problem descriptions and modeling approach for sustainable PSCN with time windows under CO_2 emission have been developed. Section 3 represents the solution methodology to solve the presented model. Section 4 evaluates the performance of the algorithm as well as a case study based on real data has been examined that shows the applicability and validity of the proposed approach efficiently. Finally, concluding remarks and findings have been highlighted based on the present work in Sect. 5.

2 Literature review

In this section, we focus on the selected literature related to pharmaceutical supply chain networks, sustainable supply chain networks. Respecting the main contributions of this paper, which are to develop a multi objective, dynamic production and distribution planning using time windows and service technology for sustainable pharmaceutical supply chain network, the selected papers are those who focus on sustainable pharmaceutical supply chain networks and have similarities with our methodological approach. Among one of the recent researches works we can mention the approach proposed by (Goodarzian et al., 2020). These authors believe that pharmaceutical supply chain management needs to combine the minimization of costs with service standards while considering risks due to uncertainty. In this work, a multi-objective multi-echelon multi-product multi-period pharmaceutical supply chain network is developed for production–distribution–purchasing–ordering–inventory holding-allocation-routing problem under uncertainty. From the methodological point of view, a Mixed-Integer Non-Linear Programming model is designed and they proposed a robust fuzzy programming method to cope with uncertainty parameters. To find a solution, several multi-objective meta-heuristic algorithms and multi-objective assessment metrics are used. The results confirm a near-optimal solution within a logical time. They paper ignored to integrate the sustainability in the decisions.

The other interesting research work is realized by Goodarzian et al. (2021). In this paper, the authors presented a mathematical model for the allocation, location, and inventory control problems of medicine in the conditions of COVID-19. The main novelties of the proposed model were the resilience and sustainability of their proposed model. Minimizing environmental costs along with transportation costs has been their main goal. Their model was solved using multi-objective teaching–learning-based optimization and particle swarm optimization approaches. This study does not consider uncertainty in the modelling. As a development to previous research works, Gooderzian et al. (2022) formulated a mathematical model for vaccine supply chain management in the conditions of COVID-19. The main contribution of their research was considering Internet-of-Things in their proposed model. Gray Wolf Optimization (GWO) and Variable Neighborhood Search (VNS) approaches have been used for solving. To validate their model, they utilized a real case study in Iran. The paper does not consider transportation and routing in the decision. A real case of distributed flexible job shop scheduling problem with minimizing maximum completion time is presented by Naderi et al. (2020). Four mixed integer linear programming models as well as a constraint programming model are proposed and a logic-based Benders decomposition algorithm is developed as the solution methodology. The showed that the proposed model is efficient, and the proposed CP model is effective for the both the small-sized and large-sized instances. Finally, they suggested a wheat distribution system of Iran as the case study. Alkaabneh et al.

(2020) studied the problem of inventory routing in perishable products. They found near-optimal replenishment scheduling and vehicle routes by maximizing the supplier's profit and minimize the costs of fuel consumption, inventory holding, and greenhouse gas emissions. To solve the problem, they proposed two different algorithms: Benders decomposition and a two-stage meta-heuristic. Acceleration strategies are also proposed to enhance the convergence rate of the Benders decomposition algorithm. The results of the test show that savings in fuel can be achieved by utilizing the model. Merkuryeva et al. (2019) presented a study on demand forecasting in the for the pharmaceutical supply chain planning problem. An integrated procedure for product demand forecasting and purchase order generation is developed. A case study of a wholesaler to a distribution company located in an emerging market is presented. The different optional forecasting scenario has been calculated using the SMA model, multiple regression and symbolic regression with the aid of a genetic algorithm. Karimi et al. (2019) proposed a multi-objective multi-facility model of green closed-loop supply chain (GCLSC) under uncertain environment. They considered three classes in case of the leading chain and three classes in terms of the recursive chain. The objectives are to maximize the total profit of the green closed-loop supply chain, satisfaction of demand, the satisfactions of the customers and getting to the proper cost of the consumers, distribution centers and recursive centers. The presented uncertain model is solved by using two metaheuristic approaches, namely; Non-dominated Sorting Genetic Algorithm-II (NSGA-II) and Non-Dominated Rank Genetic Algorithm (NRGA). The technique of Order Preference Similarity for Ideal Solution (TOPSIS) ranking method is also designed to rank the different solution sets. Nasrollahi and Razmi (2019) studied an integrated Pharmaceutical Supply Chain design with maximum expected coverage, in which different hospitals with specific reliability value for different pharmaceutical substances are studied. A four-layer multi-period supply chain including manufacturers, Distribution Centers, hospitals and patients is considered. The multi-objective Particle Swarm Optimization (PSO) and NSGA-II have been suggested to solve the propounded model. A computational study based on the private medical sector in the remote provinces has been presented to validate the model and solution algorithm. Results showed that when reliability level is considered, better results in terms of unsatisfied demand without an increase in costs are obtained. They showed also that the proposed approach is able to provide solutions to improve the supply chain reliability in a practical pharmaceutical supply network. Singh and Goh (2019) also presented a mixed-integer linear programming problem under the intuitionistic fuzzy environment and applied it to solve the pharmaceutical SCM planning problem. They considered the imprecise nature of some of the critical factors used in the modelling, which can influence the effectiveness of the model. The uncertainty and the hesitation are represented by intuitionistic fuzzy numbers. The model is converted into a crisp model, using defuzzification strategies to create a single objective problem. The proposed method is applied to several cases and a management model with self-generated random data. Ahmadi et al. (2018) identified the challenges pharmaceutical supply chain at three different decision levels of strategic, tactical, and operational decisions. They incorporated the optimization mechanism in pharmaceutical supply chain management. The integrated component of pharmaceutical supply chain has emerged into a good practice scheme for managerial points of view. Aa real practical case study is described and investigated and a number of avenues for further research are finally suggested. All the above studies have their limitations and can be overcome by introducing the most real aspects and problem-oriented modeling approach. Aigbogun et al. (2018) discussed an analytical study on "halal" pharmaceutical SCM in Malaysia. Afterward, quantitative empirical research has developed by justifying the measurement of supply chain dimensions. They applied a quantitative cross-sectional design by means of self-administered structured questionnaire survey, using the Supply Chain Resilience Assessment and Management instrument. Partial least square-based structural modelling was used to analyze the data. The results showed that the psychometric properties of the supply chain resilience dimensions (vulnerabilities and capabilities) in the context of the present study are reliable and valid. Hulea et al. (2018) recently suggested the optimal distribution of pharmaceutical products and presented a solution for pharmaceutical cold chain management using distributed ledger technology. They proposed an application for shipment tracking which will deliver information to all stakeholders. They used Hyperledger Sawtooth distributed ledger framework to collect data. The modeling of data and communication of system entities have well performed in the proposed study. Fathollahi-Fard and Hajiaghaei-Keshteli (2018) also included the environmental objective in CLSC and transformed the model into the two-stage stochastic multi-objective model. The epsilon-constraint method has been used to validate the performance of the different nature-inspired algorithms for small size along with their comparative study. They used a comparative study to confirm the efficiency and effectiveness of Virus Colony Search with other metaheuristics. Results showed the importance of controlling the uncertainty to improve the environmental and economic aspects of Closed-loop Supply Chain. Chung and Kwon (2016) discussed the PSCM for perishable products. They considered the impact of product perishability on a broad scale, which includes manufacturers, distributors centers, wholesalers, and customers. The exclusive feature of the proposed study dynamically captures the significant managerial insight. The computational study based on the multinational pharmaceutical company has been made to reveal the real insight of the perishable medical products. Pishvaee and Razmi (2012) discussed the environmental effects of EOL products in supply chain management under uncertainty. The assessment of environmental impact has been done using the Eco-indicator 99 (LCA-based method) based on the proposed supply chain design. A case study based on pharmaceutical companies has been presented under uncertainty. They used an interactive fuzzy solution approach to solve the proposed multi-objective fuzzy optimization model. The result showed the significance and applicability of the developed model and the usefulness of their approach. Sousa et al. (2011) also effectively captured the global pharmaceutical SCM planning model from the primary sector to secondary sectors. The influence on distribution policy over different circumstances have been addressed along with potential findings for the decision-making scheme. They studied a dynamic allocation/planning problem and they tried to optimize the global supply chain planning of a pharmaceutical company. The model considered different costs and tax rates at different locations in order to maximize the company's net profit value. To solve the problem, they used two decomposition algorithms. Table 1 shows the literature on sustainable pharmaceutical supply chain network.

In this paper, the production–distribution–transportation problem as a four-echelon network was utilized to develop the sustainability PSCN problem. The main difference of this research, in addition to the network configuration and solution method, can be found in the social impacts of service technology under various criteria and time windows at the earliest and latest arrival time of pharmaceutical products to main distribution centers which were neglected in the previous paper. We also develop a multi objective, dynamic production and distribution planning using time windows in service technology of sustainable pharmaceutical supply Chain Network.

Table 1 A review of literature on sustainable pharmaceutical supply chain network

No.	References	Number of objective functions (Single/Multi Objective)	Planning horizon (Static, Dynamic)	Optimization method (Deterministic/Stochastic/Robust, Fuzzy Optimization)	Service technology	Sustainable PSCN	Time windows	Production and distribution planning
1	Goodarzian et al. (2022)	MO	D	D	–	–	–	–
2	Goodarzian et al. (2021)	MO	D	S	–	*	–	–
3	Goodarzian et al. (2020)	MO	D	D	–	–	–	–
4	Naderi et al. (2020)	SO	S	D	–	–	–	*
5	Alkaabneh et al. (2020)	SO	D	St	–	–	–	–
6	Merkuryeva et al. (2019)	SO	S	D	–	–	–	*
7	Karimi et al. (2019)	MO	D	Ro	–	–	*	–
8	Nasrollahi and Razmi (2019)	MO	D	St	–	–	–	*
9	Singh and Goh (2019)	MO	S	St	–	–	*	*
10	Ahmadi et al. (2018)	SO	S	D	–	–	–	–
11	Aigbogun et al. (2018)	MO	S	D	–	–	*	–
12	Hulea et al. (2018)	SO	S	D	–	–	–	–

Table 1 (continued)

No.	References	Number of objective functions (Single/Multi Objective)	Planning horizon (Static, Dynamic)	Optimization method (Deterministic/Stochastic/Robust, Fuzzy Optimization)	Service technology	Sustainable PSCN	Time windows	Production and distribution planning
13	Fathollahi-Fard and Hajiaghaei-Keshteli (2018)	MO	D	St	–	–	*	*
14	Chung and Kwon (2016)	SO	S	D	–	–	*	–
15	Pishvaee and Razmi (2012)	SO	S	St	–	–	–	–
16	Sousa et al. (2011)	SO	S	D	–	–	–	*
17	This Study	MO	D	D	*	*	*	*

3 Problem description

The suggested multi-product, multi-objective, and multi-period PSCN of this paper are indicated and the communication amid its chain members in Fig. 1. The principal purpose of the present paper is to optimize the decision variables of the proposed model by several proper heuristic algorithms according to the three factors of sustainability. First of all, the total cost objective function contains (i) the fixed cost of opening main and local distribution centers (DCs), (ii) transportation cost between producer and main and local DCs and between main and local DCs and pharmacies, (iii) the storage costs in the main and local DCs, (IV) the inventory holding costs in the warehouse, main and local DC, and (V) the production cost in the producer. Next, environmental effects contain the most harmful Greenhouse Gases emissions, i.e., CO_2, which are related to transporting pharmaceutical products throughout the network by using vehicles. Also, the social aspect contains generating work opportunities at the main and local DCs, warehouses, and pharmacies based on the regional factor (unemployment ratio).

In this network, several producers transport several sorts of pharmaceutical products through main and local DCs to various quantities of pharmacies. The transfer of products from producers to main and local DCs and from main and local DCs to pharmacies is fulfilled by vehicles through the available routes. Routing the vehicle from producers to main and local DCs and from main and local DCs to pharmacies and also scheduling the vehicles to recognize the time windows are operational decisions.

In this regard, there are some assumptions according to the proposed model including:

- The demand of the pharmaceutical products by main and local DCs, vehicles, warehouses, and pharmacies must be investigated on time;
- Soft-time windows for the earliest and latest arrival time of pharmaceutical products are considered;
- The number and location of facilities in each echelon (producer, main and local DCs, and pharmacy) are predetermined;
- There is a route between the main and local DCs;
- There is not any route direct between producer and pharmacy;
- Finally, at most one service technology is used for each pharmacy.

Service technology refers to the use of digital services for decision making. Services technologies are autonomous, platform agnostic software components that operate within an ecosystem. In this research, three types of service technology for pharmacies are considered

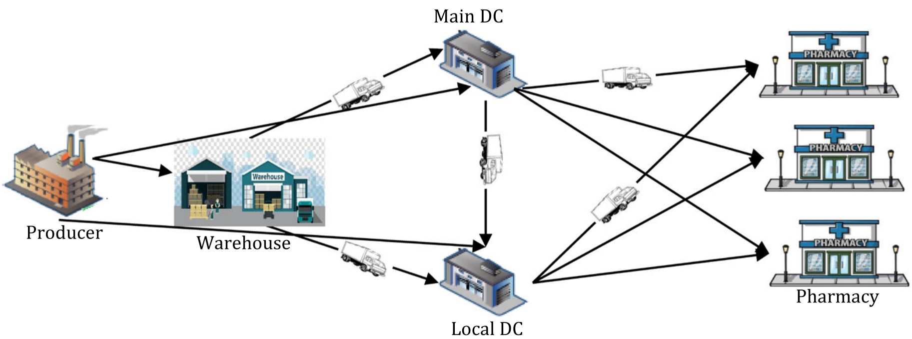


Fig. 1 A framework of four-level pharmaceutical supply chain network

as follows: E-Verification Systems, which are provide digital images that make it easier for pharmacist to verify the prescription; Battling Substance Abuse system, which show excessive prescriptions for certain drugs can be identified and flagged by this system, alerting a pharmacy to at-risk customers; Tele-pharmacy Services for Rural Areas, which bring pharmacy services to the internet. Individuals in remote locations can fill prescriptions, which will be mailed to their location.

The sets and indices, parameters, and decision variables of the presented mathematical model are explained as follows:

Sets and indices	*Description*
S	The set of producers; $s \in S$
m	Index of main distribution centers;$m \in \{1, 2, \ldots, M\}$
n	Index of local distribution centers;$n \in \{1, 2, \ldots, N\}$
k	Index of pharmacies;$k \in K$
w	Index of warehouses;$w \in W$
b	Technology choice criteria $b \in \{1, 2, \ldots, B\}$
e	Technology sorts $e \in \{1, 2, \ldots, E\}$
V	The set of vehicles;$v \in V$
P	The set of products;$p \in P$
t	Index of periods of time;$t \in T$
Parameters	
α_m	The fixed cost of opening main DC m
β_n	The fixed cost of opening local DC n
μ^1_{VPSm}	The transportation cost of product P from producer S to main DC m by vehicle V
μ^2_{VPSw}	The transportation cost of product p from producer S to warehouse w by vehicle V
μ^3_{VPwm}	The transportation cost of product p from warehouse w to main DC m by vehicle V
μ^4_{VPwn}	The transportation cost of product p from warehouse w to local DC n by vehicle V
μ^4_{VPSn}	The transportation cost of product P from producer S to local DC n by vehicle V
μ^5_{VPmn}	The transportation cost of product P from main DC m to local DC n by vehicle V
μ^6_{VPmk}	The transportation cost of product P from main DC m to pharmacy k by vehicle V
μ^7_{VPnk}	The transportation cost of product P from local DC n to pharmacy k by vehicle V

Sets and indices	Description
I^1_{Pwt}	Inventory holding cost of product P in the warehouse w at period t
I^2_{Pmt}	Inventory holding cost of product P in the main distribution center m at period t
I^3_{Pnt}	Inventory holding cost of product P in the local distribution center n at period t
P^t_{PS}	Production cost of product P in the producer S at period t
Δ^1_{kPt}	The demand of pharmacy k for product P at period t
Δ^2_{mPt}	The demand of main DC m for product P at period t
Δ^3_{nPt}	The demand of local DC n for product P at period t
Δ^4_{wPt}	The demand of warehouse w for product P at period t
φ^1_{Pm}	The storage cost of product P at the end of each period in the main DC m
φ^2_{Pn}	The storage cost of product P at the end of each period in the local DC n
φ^3_{Pwt}	The storage cost of product P at the period t in the warehouse w
ω^1_m	The storage capacity of product in the main DC m
ω^2_n	The storage capacity of product in the local DC n
ω^3_w	The storage capacity of product in the warehouse w
IC_b	Importance of criteria b
ST_{eb}	A score of service technology e from criteria b
δ_P	The relative significance of product P
τ^1_m	Regional factor (unemployment ratio) in the main DC m
τ^2_n	Regional factor (unemployment ratio) in the local DC n
τ^3_w	Regional factor (unemployment ratio) in the warehouse w
τ^4_k	Regional factor (unemployment ratio) in the pharmacy k
ϑ^1_m	The number of works generated at the main DC m
ϑ^2_n	The number of works generated at the local DC n
ϑ^3_w	The number of works generated at the warehouse w
ϑ^4_k	The number of works generated at the pharmacy k
θ^1_{VPSm}	CO_2 emission per unit product P transported from the producer S to the main DC m by vehicle V
θ^2_{VPSn}	CO_2 emission per unit product P transported from the producer S to the local DC n by vehicle V
θ^3_{VPmn}	CO_2 emission per unit product P transported from the main DC m to the local DC n by vehicle V
θ^4_{VPmk}	CO_2 emission per unit product P transported from the main DC m to the pharmacy k by vehicle V

Sets and indices	*Description*
θ^5_{VPnk}	CO_2 emission per unit product P transported from the local DC n to the pharmacy k by vehicle V
e^1_m	The environmental effects of opening main DC m
e^2_n	The environmental effects of opening local DC n
e^3_w	The environmental effects of opening warehouse w
e^4_k	The environmental effects of opening pharmacy k
ρ^1_m	The earliest arrival time of the time window for the main DC m
ρ^2_n	The Latest arrival time of the time window for the main DC m
γ	The vehicle capacity
ξ^t_m	Waiting penalty cost in the main DC m at the period t
ϑ^t_m	Lateness penalty cost in the main DC m at the period t
$\aleph_m(\sigma_m)$	Time windows violation penalty function for the main DC m $$\aleph_m(\sigma_m) = \left\{ \begin{array}{cc} \xi^t_m(\rho_m - \sigma_m), & if \sigma_m < \rho_m \\ 0, & if \rho_m < \sigma_m < \rho_n \\ \vartheta^t_m(\sigma_m - \rho_n), & if \rho_n < \sigma_m \end{array} \right\} \quad \forall m \in M \quad (1)$$
σ_m	Arrival time of vehicle to the main DC m
M	The big number
N	The upper limit of the number of distribution centers
Decision variables	
χ^1_{VPSmt}	Quantity of product P traveled from the producer S to the main DC m using vehicle V in period t
χ^2_{VPSnt}	Quantity of product P traveled from the producer S to the local DC n using vehicle V in period t
χ^3_{VPmnt}	Quantity of product P traveled from the main DC m to the local DC n using vehicle V in period t
χ^4_{VPmkt}	Quantity of product P traveled from the main DC m to the pharmacy k using vehicle V in period t
χ^5_{VPnkt}	Quantity of product P traveled from the local DC n to the pharmacy k using vehicle V in period t
χ^6_{VPSwt}	Quantity of product P traveled from the producer S to the warehouse w using vehicle V in period t
χ^7_{VPwmt}	Quantity of product P traveled from the warehouse w to the main DC m using vehicle V in period t
χ^8_{VPwnt}	Quantity of product P traveled from the warehouse w to the local DC n using vehicle V in period t

Sets and indices	Description
η^1_{Pmt}	Inventory level of product P in the main DC m at the end of period t
η^2_{Pnt}	Inventory level of product P in the local DC n at the end of period t
η^3_{Pwt}	Inventory level of product P in the warehouse w at the period t
Q^4_{Pwt}	The quantity of inventory of product P in the warehouse w at period t
Q^1_{Pmt}	The quantity of inventory of product P in the main DC m at period t
Q^2_{Pnt}	The quantity of inventory of product P in the local DC n at period t
Q^3_{PSt}	The production quantity of product P in the producer S at the period t
ϕ^2_n	If the local DC n is opened 1; otherwise 0
ϕ^1_m	If the main DC m is opened 1; otherwise 0
ϕ^3_w	If the warehouse w is opened 1; otherwise 0
ϕ^4_k	If the pharmacy k is opened 1; otherwise 0
ϕ^5_{ke}	If the pharmacy k with technology e is opened 1; otherwise 0
Ω^1_{mk}	If main DC m is served pharmacy k equal to 1; otherwise 0
Ω^2_{nk}	If local DC n is served pharmacy k equal to 1; otherwise 0
Ω^3_{wk}	If warehouse w is served pharmacy k equal to 1; otherwise 0

3.1 The mathematical model

A multi-objective, multi-product multi-period MILP model is presented to decrease the economic and environmental impacts and also to increase the social aspects of a PSCN by specifying the optimal level of different decision variables. The formulation of the proposed mathematical model, including objective functions and constraints is illustrated as follows.

$$
\begin{aligned}
Min\ OF_1 = & \sum_m \alpha_m \phi^1_m + \sum_n \beta_n \phi^2_n + \sum_t \sum_P \Big(\sum_S \sum_m \sum_V \mu^1_{VPSm} \chi^1_{VPSmt} \\
& + \sum_S \sum_n \sum_V \mu^4_{VPSn} \chi^2_{VPSnt} + \sum_m \sum_n \sum_V \mu^5_{VPmn} \chi^3_{VPmnt} \\
& + \sum_m \sum_k \sum_V \mu^6_{VPmk} \chi^4_{VPmkt} + \sum_n \sum_k \sum_V \mu^7_{VPnk} \chi^5_{VPnkt} \\
& + \sum_S \sum_w \sum_V \mu^2_{VPSw} \chi^6_{VPSwt} + \sum_w \sum_m \sum_V \mu^3_{VPwm} \chi^7_{VPwmt} \\
& + \sum_w \sum_n \sum_V \mu^4_{VPwn} \chi^8_{VPwmt} + \sum_m \varphi^1_{Pm} \eta^1_{Pmt} + \sum_n \varphi^2_{Pn} \eta^2_{Pnt} + \sum_w \varphi^3_{Pwt} \eta^3_{Pwt} \\
& + \sum_w I^1_{Pwt} Q^4_{Pwt} + \sum_m I^2_{Pmt} Q^1_{Pmt} + \sum_n I^3_{Pnt} Q^2_{Pnt} + \sum_S P^t_{PS} Q^3_{Pst} \Big)
\end{aligned}
\tag{2}
$$

$$Min\ OF_2 = \sum_t (\sum_P \sum_m \sum_k \sum_V \theta^4_{VPmk} \chi^4_{VPmkt} + \sum_P \sum_n \sum_k \sum_V \theta^5_{VPnk} \chi^5_{VPnkt} + \sum_P \sum_S \sum_m \sum_V \theta^1_{VPSm} \chi^1_{VPsmt} + \sum_P \sum_S \sum_n \sum_V \theta^2_{VPSn} \chi^2_{VPsnt} + \sum_P \sum_m \sum_n \sum_V \theta^3_{VPmn} \chi^3_{VPmnt}) + \sum_m e^1_m \phi_m + \sum_n e^2_n \phi^2_n + \sum_k e^4_k \phi^4_k + \sum_w e^3_w \phi^3_w \quad (3)$$

$$Max\ OF_3 = \sum_m \tau^1_m \vartheta^1_m \phi^1_m + \sum_n \tau^2_n \vartheta^2_n \phi^2_n + \sum_w \tau^3_w \vartheta^3_w \phi^3_w + \sum_k \tau^4_w \vartheta^4_k \phi^4_k + \sum_b \sum_k \sum_e IC_b \times ST_{eb} \times \phi^5_{ke} \quad (4)$$

Subject to

$$\sum_n \eta^2_{Pnt} = \sum_{n-1} \eta^2_{Pn-1,t} + \sum_m \sum_V \left(\sum_n \chi^3_{VPmnt} - \sum_S \chi^1_{VPsmt} - \sum_k \chi^4_{VPmkt} \right);\ \forall P, t \quad (5)$$

$$\sum_P \eta^1_{Pmt} \le \omega^1_m \phi^1_m;\ \forall m, t \quad (6)$$

$$\sum_P \left(\eta^2_{Pn-1,t} + \sum_m \sum_V \chi^3_{VPmnt} \right) \le \omega^2_n \phi^2_n;\ \forall n, t \quad (7)$$

$$\sum_P \eta^3_{Pwt} \le \omega^3_w \phi_w;\ \forall w, t \quad (8)$$

$$\sum_V \sum_n \chi^5_{VPnkt} \ge \Delta^1_{kPt} \forall P, k, t \quad (9)$$

$$\sum_V \sum_S \chi^1_{VPsmt} \ge \Delta^2_{mPt};\ \forall P, m, t \quad (10)$$

$$\sum_V \sum_S \chi^2_{VPsnt} \ge \Delta^3_{nPt} \forall P, n, t \quad (11)$$

$$\phi^1_m \le N \forall m \in M \quad (12)$$

$$\sum_k \Omega^1_{mk} \le \mathrm{M} \times \phi^1_m;\ \forall m \quad (13)$$

$$\sum_k \Omega^1_{nk} \le \mathrm{M} \times \phi^2_n;\ \forall n \quad (14)$$

$$\sum_k \Omega^3_{wk} \le \mathrm{M} \times \phi^3_w;\ \forall w \quad (15)$$

$$\sum_k \Omega^1_{mk} = 1;\ \forall m \quad (16)$$

$$\sum_k \Omega^2_{nk} = 1;\ \forall n \quad (17)$$

$$\sum_w \Omega^3_{wk} = 1;\ \forall w \quad (18)$$

$$\sum_k \left(\Omega^1_{mk} \times \sum_P \Delta^1_{kPt} \right) \le \omega^1_m;\ \forall m, t \quad (19)$$

$$\sum_k \left(\Omega^2_{nk} \times \sum_P \Delta^1_{kPt} \right) \le \omega^2_n;\ \forall n, t \quad (20)$$

$$\sum_{k}\left(\Omega_{wk}^{3} \times \sum_{P} \Delta_{wPt}^{4}\right) \leq \omega_{w}^{3};\ \forall w,\ t \tag{21}$$

$$\sum_{k} \phi_{ke}^{5} \leq 1; \quad \forall e \tag{22}$$

$$\begin{array}{ll} \chi_{VPSmt}^{1},\ \chi_{VPsnt}^{2},\ \chi_{VPmnt}^{3},\ \chi_{VPmkt}^{4},\ \chi_{VPnkt}^{5},\ \chi_{VPSwt}^{6},\ \chi_{VPwmt}^{7}, & \\ \chi_{VPwnt}^{8},\ \eta_{Pmt}^{1},\ \eta_{Pnt}^{2},\ \eta_{Pwt}^{3},\ Q_{Pmt}^{1},\ Q_{Pnt}^{2},\ Q_{Pst}^{3},\ Q_{Pwt}^{4} & \geq 0 \\ \phi_{m}^{1},\ \phi_{w}^{3},\ \phi_{k}^{4},\ \phi_{ke}^{5},\ \Omega_{mk},\ \Omega_{mk}^{1},\ \Omega_{nk}^{2},\ \Omega_{wk}^{3},\ \phi_{m}^{1},\ \phi_{n}^{2},\ \phi_{w}^{3},\ \phi_{k}^{4},\ \phi_{ke}^{5} & \in \{0,\ 1\} \end{array} \tag{23}$$

The economic effect's objective (2) is to decrease the total costs of PSCN. It contains five components: fixed costs, storage costs, transportation costs, inventory holding costs, and production cost. Fixed costs consist of two components, containing the opening main and local DCs costs, transportation costs consist of five components, containing the transportation cost of pharmaal pcts from producers to warehouses, main and local DCs, the transportation cost of pharmaceutical products from warehoused to main and local DCs, the transportation cost of pharmaceutical products from main DCs to local DCs, the transportation cost of pharmaceutical products from main DCs to pharmacies, and the transportation cost of pharmaceutical products from local DCs to pharmacies, storage costs consist of three components, including the storage cost of pharmaceutical product at the end of each period in the local and main DCs and in the warehouses at the each period, inventory holding costs consist of three components, containing the inventory costs in the warehouse, main and local DCs, and the production cost in the producer.

The environmental impact's objective (3) is to decrease the environmental aspects of PSCN. It involves the CO_2 emission through vehicles per unit pharmaceutical product transported from the producer to the main and local DC, from the main and local DC to the pharmacy, and from the main DC to local DC and environmental effects related to opening a main DC, Local DC, pharmacy, and warehouse, respectively.

The social effect's objective (4) is to increase the work generation at the main and local DCs, warehouses, and pharmacies in fewer extended regions of the PSCN as well as the total technology score of pharmacies for choosing suitable service technology under different criteria. Then, it selects the local and main DCs, warehouses, and pharmacies that have a higher superiority to generate works. In other words, the local and main DCs, warehouses, and pharmacies with the high unemployment rate as the regional factor or more work requirement has a better chance to be selected in this flow. Additionally, service technologies were scored under various criteria. Technology with higher total scores is introduced as the best technology.

- Constraint (5) ensures the flow balance of different pharmaceutical products at each local DC in various periods. The inventory level at the local DC at the end of the period equals the inventory level of the prior period and the amount of the medicine that is received from the main DCs minus the amount of the medicine that is transferred from producers to main DCs and from the local DC to the pharmacy. Constraints (6–8) show storage capacity for the main and local DCs and warehouses, sequentially. The inventory levels of main and local DCs requirements are not greater than the capacity of any DC. Constraints (9–11) guarantee that the flow of various pharmaceutical products to the pharmacy, main and local DCs be able to comply with the demand of each region. Constraint (12) identified the upper limit of the number of distribution centers. Constraints (13–15) illustrate those pharmacies are able to relate only to open main and local DCs and warehouses. Each pharmacy is allocated to only one local and main DCs and warehouses is ensured by constraints (16–18). Constraints (19–21) guarantee the capacity of each main and local

DCs and warehouses. Constraint (22) guarantees that each pharmacy uses maximum one service technology (in this research, E-Verification Systems, Battling Substance Abuse system, Tele-pharmacy Services for Rural Areas). Eventually, constraint (24) indicates the sort of decision variables.

Using the coefficients w_1, w_2, and w_3 as the degree of significance of the objective functions, we can define the aggregated objective function follow as:

$$
\begin{aligned}
MinOF = & \Bigg[w_1 \Bigg(\sum_m \alpha_m \phi_m^1 + \sum_n \beta_n \phi_n^2 + \sum_t \sum_P \Big(\sum_S \sum_m \sum_V \mu_{VPSm}^1 \chi_{VPSmt}^1 + \sum_S \sum_n \sum_V \mu_{VPSn}^4 \chi_{VPSnt}^2 \\
& + \sum_m \sum_n \sum_V \mu_{VPmn}^5 \chi_{VPmnt}^3 + \sum_m \sum_k \sum_V \mu_{VPmk}^6 \chi_{VPmkt}^4 + \sum_n \sum_k \sum_V \mu_{VPnk}^7 \chi_{VPnkt}^5 \\
& + \sum_S \sum_w \sum_V \mu_{VPSw}^2 \chi_{VPSwt}^6 + \sum_w \sum_m \sum_V \mu_{VPwm}^3 \chi_{VPwmt}^7 + \sum_m \sum_w \varphi_{Pm}^1 \eta_{Pwt}^3 \eta_{Pmt}^1 \\
& + \sum_n \sum_w \varphi_{Pn}^2 \eta_{Pwt}^3 \eta_{Pnt}^2 + \sum_w \varphi_{Pwt}^3 \eta_{Pwt}^3 + \sum_w I_{Pwt}^1 \varphi_{Pwt}^3 + \sum_m I_{Pmt}^2 Q_{Pmt}^1 + \sum_n I_{Pnt}^3 Q_{Pnt}^2 \\
& + \sum_S P_{PS}^t Q_{Pst}^3 \Big) \Bigg) \Bigg] + \Bigg[w_2 \Bigg(\sum_t \Big(\sum_P \sum_m \sum_k \sum_V \theta_{VPmk}^4 \chi_{VPmkt}^4 \\
& + \sum_P \sum_n \sum_k \sum_V \theta_{VPnk}^5 \chi_{VPnkt}^5 + \sum_P \sum_S \sum_m \sum_V \theta_{VPSm}^1 \chi_{VPSmt}^1 + \sum_P \sum_S \sum_n \sum_V \theta_{VPSn}^2 \chi_{VPSnt}^2 \\
& + \sum_P \sum_m \sum_n \sum_V \theta_{VPmn}^3 \chi_{VPmnt}^3 \Big) + \sum_m e_m^1 \phi_m^1 + \sum_n e_n^2 \phi_n^2 + \sum_k e_k^4 \phi_k^4 + \sum_w e_w^3 \phi_w^3 \Bigg) \Bigg] \\
& - \Bigg[w_3 \Bigg(\sum_m \tau_m^1 \vartheta_m^1 \phi_m^1 + \sum_n \tau_n^2 \vartheta_n^2 \phi_n^2 + \sum_w \tau_w^3 \vartheta_w^3 \phi_w^3 + \sum_k \tau_k^4 \vartheta_k^4 \phi_k^4 \Bigg) \Bigg] \qquad (24)
\end{aligned}
$$

Regarding the degree of importance of objective functions, it is worth mentioning that these coefficients include the degree of importance of co-scaling of objective functions.

4 A benders decomposition algorithm

In this section, it can be also indicated that the model is NP-hard, from an analytical viewpoint. To reduce the computational complexity (Goodarzian et al. 2020), in this section a Benders decomposition approach (BDA) is developed. The solution method is coded in GAMS24.1 software and all the tests are carried out on an Intel(R) Core i5 CPU with a 2.5 GHz processor and 6 GB of RAM. It is right that the Benders decomposition algorithm can be implemented using various software packages such as GAMS, AMPL, and CPLEX. These packages provide solvers and modelling languages that can be used to formulate and solve optimization problems, including those that involve Benders decomposition. However, the specific implementation details may vary depending on the software package and the problem being solved.

The BDA to a wide range of difficult optimization problems has been successfully applied. The reasons for using this method, the BDA was originally presented in MILP models with continuous sub problems, and it has since been developed to handle a wider range of problems such as integer, nonlinear, constraint programming, and multi-stage problems (Rahmaniani et al., 2017; Tapia-Ubeda et al., 2018). BDA was introduced by Benders (1962) for the first time, is now known as an effective approach to solving large-scale MILP problems. The Benders decomposition algorithm is dependent on the decomposition of a mixed-integer programming model into one master problem and one sub-problem that is repeatedly solved using each other's solution. The sub-problem contains the continuous variables and their constraints, while the master problem contains the integer variables and one continuous variable that connects the two problems. The optimal solution to the master problem provides a lower limit for the available objective. By using the solution obtained by the master problem, it is solved by proving the correct variables as the input of a dual sub-problem for the sub-problem; utilizing this solution could define an upper limit for the overall objective of the problem. Also, solve the dual sub-problem is used to construct a bender cut that contains continuous variables added to the master problem. In the next iteration of this cut to the master problem added by solving this problem a new lower bound for the general problem is obtained, which is guaranteed not to be worse than the current lower bound. As such, the master problem and sub-problem are repeatedly solved until we reach an end condition, which is to reduce the distance between the upper limit and the lower limit of a small number. Benders decomposition method in the finite iterations reaches the optimal solution. Before developing the master problem and sub-problem in the Banders framework, a general problem formulation is presented, which can be expressed as follows:

$$
\begin{aligned}
MinOF = & \left[w_1 \left(\sum_m \alpha_m \phi_m^1 + \sum_n \beta_n \phi_n^2 \right) \right] \\
& + \left[w_2 \left(\sum_m e_m^1 \phi_m^1 + \sum_n e_n^2 \phi_n^2 + \sum_k e_k^4 \phi_k^4 + \sum_w e_w^3 \phi_w^3 \right) \right] \\
& - \left[w_3 \left(\sum_m \tau_m^1 \vartheta_m^1 \phi_m^1 + \sum_n \tau_n^2 \vartheta_n^2 \phi_n^2 + \sum_w \tau_w^3 \vartheta_w^3 \phi_w^3 + \sum_k \tau_k^4 \vartheta_k^4 \phi_k^4 \right) \right] \\
& + BSP\left(x, \eta, Q | \widehat{\varnothing}, \widehat{\Omega}\right)
\end{aligned} \tag{25}
$$

Subject to

$$\phi_m^1 \leq N; \quad \forall m \in M \tag{26}$$

$$\sum_k \Omega_{mk}^1 \leq \mathrm{M} \times \phi_m^1; \quad \forall m \tag{27}$$

$$\sum_k \Omega_{nk}^2 \leq \mathrm{M} \times \phi_n^2; \quad \forall n \tag{28}$$

$$\sum_k \Omega_{wk}^3 \leq \mathrm{M} \times \phi_w^3; \quad \forall w \tag{29}$$

$$\sum_k \Omega_{mk}^1 = 1; \quad \forall m \tag{30}$$

$$\sum_k \Omega_{nk}^2 = 1; \quad \forall n \tag{31}$$

$$\sum_w \Omega_{wk}^3 = 1; \quad \forall w \tag{32}$$

$$\sum_k \left(\Omega_{mk}^1 \times \sum_P \Delta_{kPt}^1 \right) \leq \omega_m^1; \quad \forall m, t \tag{33}$$

$$\sum_k \left(\Omega_{nk}^2 \times \sum_P \Delta_{kPt}^1 \right) \leq \omega_n^2; \quad \forall n, t \tag{34}$$

$$\sum_{k}\left(\Omega_{wk}^{3}\times\sum_{P}\Delta_{wPt}^{4}\right)\leq\omega_{w}^{3};\quad\forall w,\,t \tag{35}$$

where $BSP\left(x,\,\eta,\,Q|\widehat{\varnothing},\,\widehat{\Omega}\right)$ is the sub-problem of Benders that will be discussed in detail below.

4.1 Sub problem

The sub-problem $BSP\left(x,\,\eta,\,Q|\widehat{\varnothing},\,\widehat{\Omega}\right)$ is a minimization problem that obtains the optimal value of continuous variables $(x,\,\eta,\,Q)$ for the fixed variables $\left(\widehat{\varnothing},\,\widehat{\Omega}\right)$. This sub-problem can be stated as follows:

$$\Bigg[w_1\Bigg(\sum_t\sum_P(\sum_S\sum_m\sum_V\mu^1_{VPSm}\chi^1_{VPSmt}+\sum_S\sum_n\sum_V\mu^4_{VPSn}\chi^2_{VPSnt}+\sum_m\sum_n\sum_V\mu^5_{VPmn}\chi^3_{VPmnt}$$
$$+\sum_m\sum_k\sum_V\mu^6_{VPmk}\chi^4_{VPmkt}+\sum_n\sum_k\sum_V\mu^7_{VPnk}\chi^5_{VPnkt}+\sum_S\sum_w\sum_V\mu^2_{VPSw}\chi^6_{VPSwt}$$
$$+\sum_w\sum_m\sum_V\mu^3_{VPwm}\chi^7_{VPwmt}+\sum_w\sum_n\sum_V\mu^4_{VPwn}\chi^8_{VPwnt}+\sum_m\varphi^1_{Pm}\eta^1_{Pmt}+\sum_n\eta^2_{Pnt}\varphi^2_{Pn}+\sum_w\varphi^3_{Pwt}\eta^3_{Pwt}$$
$$+\sum_w I^1_{Pwt}Q^4_{Pwt}+\sum_m I^2_{Pmt}Q^1_{Pmt}+\sum_n I^3_{Pnt}Q^2_{Pnt}+\sum_S P^t_{PS}Q^3_{Pst})\Bigg)\Bigg]$$
$$+\Bigg[w_2\Bigg(\sum_t(\sum_P\sum_m\sum_k\sum_V\theta^4_{VPmk}\chi^4_{VPmkt}+\sum_P\sum_n\sum_k\sum_V\theta^5_{VPnk}\chi^5_{VPnkt}+\sum_P\sum_S\sum_m\sum_V\theta^1_{VPSm}\chi^1_{VPSmt}$$
$$+\sum_P\sum_S\sum_n\sum_V\theta^2_{VPSn}\chi^2_{VPSnt}+\sum_P\sum_m\sum_n\sum_V\theta^3_{VPmn}\chi^3_{VPmnt})\Bigg)\Bigg] \tag{36}$$

Subject to

$$\sum_n\eta^2_{Pnt}\leq\sum_{n-1}\eta^2_{Pn-1t}+\sum_m\sum_V\left(\sum_n\chi^3_{VPmnt}-\sum_S\chi^1_{VPSmt}-\sum_k\chi^4_{VPmkt}\right);\quad\forall P,\,t \tag{37}$$

$$\sum_n\eta^2_{Pnt}\geq\sum_{n-1}\eta^2_{Pn-1,t}+\sum_m\sum_V\left(\sum_n\chi^3_{VPmnt}-\sum_S\chi^1_{VPSmt}-\sum_k\chi^4_{VPmkt}\right);\quad\forall P,\,t \tag{38}$$

$$\sum_P\eta^1_{Pmt}\leq\omega^1_m\widehat{\phi}^1_m;\forall m,\,t \tag{39}$$

$$\sum_P\left(\eta^2_{Pn-1t}+\sum_m\sum_V\chi^3_{VPmnt}\right)\leq\omega^2_n\widehat{\phi}^2_n;\quad\forall n,\,t \tag{40}$$

$$\sum_P\eta^3_{Pwt}\leq\omega^3_w\widehat{\phi}^3_w;\quad\forall w,\,t \tag{41}$$

$$\sum_V\sum_n\chi^5_{VPnkt}\geq\Delta^1_{kPt};\quad\forall P,\,k,\,t \tag{42}$$

$$\sum_V\sum_S\chi^1_{VPSmt}\geq\Delta^2_{mPt};\quad\forall P,\,m,\,t \tag{43}$$

$$\sum_V\sum_S\chi^2_{VPSnt}\geq\Delta^3_{nPt};\quad\forall P,\,n,\,t \tag{44}$$

$$\chi^1_{VPSmt},\ \chi^2_{VPsnt},\ \chi^3_{VPmnt},\ \chi^4_{VPmkt},\ \chi^5_{VPnkt},\ \chi^6_{VPSwt},\ \chi^7_{VPwmt},\ \chi^8_{VPwnt},\ \eta^2_{Pnt},\ \eta^1_{Pmt},\ \eta^3_{Pwt},\ Q^4_{Pwt},\ Q^1_{Pmt},\ Q^2_{Pnt},\ Q^3_{Pst} \geq 0 \tag{45}$$

According to the constraint (4) in the presented model, which is equal, without changing the solution space and the optimal solution has been transformed into two less-equal and more-equal constraints in (37) and (38) that to obtain easier, the dual problem has been done. Dual problem $BSP(x, \eta, Q|\widehat{\varnothing}, \widehat{\Omega})$ is used to produce Benders cuts for the master problem. Moreover, to obtain dual of this problem we use dual variables π^1_{Pt}, π^2_{Pt}, π^3_{mt}, π^4_{nt}, π^5_{Pkt}, π^6_{Pmt} and π^7_{Pnt} for each constraint (30–36). By considering these variables, the dual problem of sub-problem the name $DBSP(\pi^1, \pi^2, \pi^3, \pi^4, \pi^5, \pi^6, \pi^7|\widehat{\varnothing}, \widehat{\Omega})$ be as follows:

$$\begin{aligned} MaxU = &\left[-\sum_P\sum_t \pi^1_{Pt}\left(\sum_{n-1}\eta^2_{Pn-1,t} + \sum_m\sum_V\left(\sum_n \chi^3_{VPmnt} - \sum_S \chi^1_{VPSmt} - \sum_k \chi^4_{VPmkt}\right)\right)\right. \\ &\left.\sum_P\sum_t \pi^2_{Pt}\left(\sum_{n-1}\eta^2_{Pn-1,t} + \sum_m\sum_V\left(\sum_n \chi^3_{VPmnt} - \sum_S \chi^1_{VPSmt} - \sum_k \chi^4_{VPmkt}\right)\right)\right] \\ &-\left[\sum_m\sum_t \pi^3_{mt}\left(\omega^1_m\widehat{\phi}^1_m\right)\right] - \left[\sum_n\sum_t \pi^4_{nt}\left(\omega^1_n\widehat{\phi}^2_n\right)\right] \end{aligned} \tag{46}$$

Subject to

$$\begin{aligned} &-\pi^1_{Pt} + \pi^2_{Pt} - \pi^4_{nt} + \pi^5_{Pkt} + \pi^6_{Pmt} + \pi^7_{Pnt} \\ &\quad \leq w_1\left(\mu^1_{VPSm} + \mu^4_{VPSn} + \mu^5_{VPmn} + \mu^6_{VPmk} + \mu^7_{VPnk} + \mu^2_{VPSw} + \mu^3_{VPwm} + \mu^4_{VPwn}\right) \\ &\quad + w_2\left(\theta^4_{VPmk} + \theta^5_{VPnk} + \theta^1_{VPSm} + \theta^2_{VPSn} + \theta^3_{VPmn}\right)\forall P, m, n, k, S, V, w, t \end{aligned} \tag{47}$$

$$\pi^1_{Pt} - \pi^2_{Pt} - \pi^3_{mt} - \pi^4_{nt} \leq w_1\left(\eta^1_{Pmt} + \eta^2_{Pnt}\right)\forall P, m, n, t \tag{48}$$

$$\pi^1_{Pt}, \pi^2_{Pt}, \pi^3_{mt}, \pi^4_{nt}, \pi^5_{Pkt}, \pi^6_{Pmt} \text{and} \pi^7_{Pnt} \geq 0 \tag{49}$$

4.2 Master problem

In this section, the master problem of Banders is modeled as follows:

$$\min_{\phi, \Omega} z \tag{50}$$

Subject to

$$\begin{aligned} z \geq &\left[w_1\left(\sum_m \alpha_m\phi^1_m + \sum_n \beta_n\phi^2_n\right)\right] + \left[w_2\left(\sum_m e^1_m\phi^1_m + \sum_n e^2_n\phi^2_n + \sum_k e^4_k\phi^4_k + \sum_w e^3_w\phi^3_w\right)\right] \\ &-\left[w_3\left(\sum_m \tau^1_m\vartheta^1_m\phi^1_m + \sum_n \tau^2_n\vartheta^2_n\phi^2_n + \sum_w \tau^3_w\vartheta^3_w\phi^3_w + \sum_k \tau^4_k\vartheta^4_w\phi^4_k\right)\right] \\ &+\left[-\sum_P\sum_t \widehat{\pi}^{1f\prime}_{Pt}\left(\sum_{n-1}\eta^2_{Pn-1,t} + \sum_m\sum_V\left(\sum_n \chi^3_{VPmnt} - \sum_S \chi^1_{VPSmt} - \sum_k \chi^4_{VPmkt}\right)\right)\right. \end{aligned}$$

$$\sum_{P}\sum_{t}\widehat{\pi}_{Pt}^{2f\prime}\left(\sum_{n-1}\eta_{Pn-1,t}^{2}+\sum_{m}\sum_{V}\left(\sum_{n}\chi_{VPmnt}^{3}-\sum_{S}\chi_{VPSmt}^{1}-\sum_{k}\chi_{VPmkt}^{4}\right)\right)\Bigg]$$

$$-\left[\sum_{m}\sum_{t}\widehat{\pi}_{mt}^{3f\prime}(\omega_{m}^{1}\widehat{\phi}_{m}^{1})\right]-\left[\sum_{n}\sum_{t}\widehat{\pi}_{nt}^{4f\prime}(\omega_{n}^{2}\widehat{\phi}_{n}^{2})\right]\forall f\prime=1,\ldots,F\prime \tag{51}$$

$$\Bigg[-\sum_{P}\sum_{t}\widehat{\pi}_{Pt}^{1l\prime}\left(\sum_{n-1}\eta_{Pn-1,t}^{2}\right. \tag{52}$$

$$\left.+\sum_{m}\sum_{V}\left(\sum_{n}\chi_{VPmnt}^{3}-\sum_{S}\chi_{VPSmt}^{1}-\sum_{k}\chi_{VPmkt}^{4}\right)\right)\sum_{P}\sum_{t}\widehat{\pi}_{Pt}^{2l\prime}\left(\sum_{n-1}\eta_{Pn-1,t}^{2}\right.$$

$$\left.+\sum_{m}\sum_{V}\left(\sum_{n}\chi_{VPmnt}^{3}-\sum_{S}\chi_{VPSmt}^{1}-\sum_{k}\chi_{VPmkt}^{4}\right)\right)\Bigg]$$

$$-\left[\sum_{m}\sum_{t}\widehat{\pi}_{mt}^{3l\prime}\left(\omega_{m}^{1}\widehat{\phi}_{m}^{1}\right)\right]-\left[\sum_{n}\sum_{t}\widehat{\pi}_{nt}^{4l\prime}\left(\omega_{n}^{2}\widehat{\phi}_{n}^{2}\right)\right]\leq 0\quad\forall l\prime=1,\ldots,L\prime$$

$$\phi_{m}^{1}\leq N;\forall m\in M \tag{53}$$

$$\sum_{k}\Omega_{mk}^{1}\leq \mathrm{M}\times\phi_{m}^{1};\quad\forall m \tag{54}$$

$$\sum_{k}\Omega_{nk}^{2}\leq \mathrm{M}\times\phi_{n}^{2};\quad\forall n \tag{55}$$

$$\sum_{k}\Omega_{wk}^{3}\leq \mathrm{M}\times\phi_{w}^{3};\quad\forall w \tag{56}$$

$$\sum_{k}\Omega_{mk}^{1}=1;\quad\forall m \tag{57}$$

$$\sum_{k}\Omega_{nk}^{2}=1;\quad\forall n \tag{58}$$

$$\sum_{w}\Omega_{wk}^{3}=1;\quad\forall w \tag{59}$$

$$\sum_{k}\left(\Omega_{mk}^{1}\times\sum_{P}\Delta_{kPt}^{1}\right)\leq\omega_{m}^{1}\widehat{\phi}_{m};\quad\forall m,t \tag{60}$$

$$\sum_{k}\left(\Omega_{nk}^{2}\times\sum_{P}\Delta_{kPt}^{1}\right)\leq\omega_{n}^{2}\widehat{\phi}_{m};\quad\forall n,t \tag{61}$$

$$\sum_{k}\left(\Omega_{wk}^{3}\times\sum_{P}\Delta_{wPt}^{4}\right)\leq\omega_{w}^{3}\widehat{\phi}_{m};\quad\forall w,t \tag{62}$$

In this model, Eq. (50) shows the objective function of Bender's master problem. Equation (51) is the optimal slices that are added to the master problem after reaching the optimal solution of the sub-problem. $\widehat{\pi}_{Pt}^{1f\prime}$,$\widehat{\pi}_{Pt}^{2f\prime}$, $\widehat{\pi}_{mt}^{3f\prime}$ and $\widehat{\pi}_{nt}^{4f\prime}$ parameters are of the dual variables obtained from the solution of the Benders sub-problem, in which these values are considered as fixed values in the cutting constraints. Equation (52) is to be a feasible cutting that is added to the master problem if the sub-problem is not feasible.$\widehat{\pi}_{Pt}^{1l\prime}$,$\widehat{\pi}_{Pt}^{2l\prime}$, $\widehat{\pi}_{mt}^{3l\prime}$ and $\widehat{\pi}_{nt}^{4l\prime}$ parameters are of the dual variables obtained from the solution of Benders sub-problem, in which these values are considered as fixed values in the cutting constraints.

4.3 The developed Benders decomposition approach

As evident from the pseudo-code in the following algorithm (The framework of developed Benders decomposition algorithm), we must first find a feasible solution to the master problem that using the solving of the master problem without any cutting is performed. Then, the solutions obtained by the master problem are given to sub-problem and the sub-problem is solved. Moreover, if the sub-problem does not become feasible and the solution of dual sub-problem is infinite, an infinitesimal direction taken from the dual is added to the master problem by using this direction to produce a cutting. After that, if the sub-problem does become feasible and has an optimal solution, using the optimal solutions of the dual sub-problem, an optimal cut is generated which is added to the master problem. Therefore, if the obtained solution is achieved a better upper bound, the upper bound is updated. Then, the master problem is solved again by using a new cut as well as the lower bound is updated. This is repeated until the distance between the bound and lower bound is less than a certain value.

We added the feasibility cuts (or unbounded ray) to improve the efficiency and accuracy of the optimization process. To do that, feasibility cuts the constraints are added to the problem to eliminate infeasible solutions. By adding these constraints, the algorithm can quickly eliminate any solutions that do not satisfy the problem's constraints, leading to faster convergence to the optimal solution. In the case of the unbounded ray, the objective function can be improved by respecting all the constraints, and if not, the optimal solution does not exist.

{Initialization}
(ϕ, Ω)=initial feasible integer solution
LB:=$-\infty$
UB:=-∞
$L^{'}$=$F^{'}$=0
While (UB-LB>ε) **do**
{solve sub-problem}
If (sub-problem is infeasible) **then**
Get unbounded ray π
Add cut $[-\sum_P \sum_t \hat{\pi}_{Pt}^{1l^{'}} (\sum_{n-1} \eta_{Pn-1t}^2 + \sum_m \sum_V (\sum_n \chi_{VPmnt}^3 - \sum_S \chi_{VPSmt}^1 - \sum_k \chi_{VPmkt}^4)) \sum_P \sum_t \hat{\pi}_{Pt}^{2l^{'}} (\sum_{n-1} \eta_{Pn-1,t}^2 + \sum_m \sum_V (\sum_n \chi_{VPmnt}^3 - \sum_S \chi_{VPSmt}^1 - \sum_k \chi_{VPmkt}^4))] - [\sum_m \sum_t \hat{\pi}_{mt}^{3l^{'}} (\omega_m^1 \hat{\phi}_m^1)] - [\sum_n \sum_t \hat{\pi}_{nt}^{4l^{'}} (\omega_n^2 \hat{\phi}_n^2)] \leq 0$
to master problem
$L^{'} := L^{'} + 1;$
Else
Get extreme point π
Add cut $z \geq [w_1(\sum_m \alpha_m \phi_m^1 + \sum_n \beta_n \phi_n^2)] + [w_2(\sum_m e_m^1 \phi_m^1 + \sum_n e_n^2 \phi_n^2 + \sum_k e_k^4 \phi_k^4 + \sum_w e_w^3 \phi_w)] - [w_3(\sum_m \tau_m^1 \vartheta_m^1 \phi_m + \sum_n \tau_n^2 \vartheta_n^2 \phi_n + \sum_w \tau_w^3 \vartheta_w^3 \phi_w^3 + \sum_k \tau_k^4 \vartheta_k^4 \phi_k)]$
$[-\sum_P \sum_t \hat{\pi}_{Pt}^{1f^{'}} (\sum_{n-1} \eta_{Pn-1t}^2 + \sum_m \sum_V (\sum_n \chi_{VPmnt}^3 - \sum_S \chi_{VPSmt}^1 - \sum_k \chi_{VPmkt}^4)) \sum_P \sum_t \hat{\pi}_{Pt}^{2f^{'}} (\sum_{n-1} \eta_{Pn-1}^t + \sum_m \sum_V (\sum_n \chi_{VPmnt}^3 - \sum_S \chi_{VPSmt}^1 - \sum_k \chi_{VPmkt}^4))] - [\sum_m \sum_t \hat{\pi}_{mt}^{3f^{'}} (\omega_m^1 \hat{\phi}_m^1 \hat{\phi}_n^2)] - [\sum_n \sum_t \hat{\pi}_{nt}^{4f^{'}} (\omega_n^2 \hat{\phi}_m^1 \hat{\phi}_n^2)]$to master problem
$F^{'} := F^{'} + 1;$

$UB :=\{ min[w_1(\sum_m \alpha_m \phi_m^1 + \sum_n \beta_n \phi_n^2)] + [w_2(\sum_m e_m^1 \phi_m^1 + \sum_n e_n^2 \phi_n^2 + \sum_k e_k^4 \phi_k^3 + \sum_w e_w^3 \phi_w^3)] - [w_3(\sum_m \tau_m^1 \vartheta_m^1 \phi_m^1 + \sum_n \tau_n^2 \vartheta_n^2 \phi_n^2 + \sum_w \tau_w^3 \vartheta_w^3 \phi_w^3 + \sum_k \tau_k^4 \vartheta_k^4 \phi_k^4)] +$
$[-\sum_P \sum_t \hat{\pi}_{Pt}^{1f^{'}} (\sum_{n-1} \eta_{Pn-1,t}^2 + \sum_m \sum_V (\sum_n \chi_{VPmnt}^3 - \sum_S \chi_{VPSmt}^1 - \sum_k \chi_{VPmkt}^4)) \sum_P \sum_t \hat{\pi}_{Pt}^{2f^{'}} (\sum_{n-1} \eta_{Pn-1,t}^2 + \sum_m \sum_V (\sum_n \chi_{VPmnt}^3 - \sum_S \chi_{VPSmt}^1 - \sum_k \chi_{VPmkt}^4))] - [\sum_m \sum_t \hat{\pi}_{mt}^{3f^{'}} (\omega_m^1 \hat{\phi}_m^1 \hat{\phi}_n^2)] - [\sum_n \sum_t \hat{\pi}_{nt}^{4f^{'}} (\omega_n^2 \hat{\phi}_m^1 \hat{\phi}_n^2)]\}$

End if
{solve master problem}
LB:=$\overline{z}$// result of master problem
End while

In order to deal with the infeasibility of cuts, the penalty approach has been used. For example, the violation calculation for constraints 13–15 is as Eq. 63–65. It should be noted that p is equal to the number of indices of the objective functions.

$$A_p = Max_m\{0, \sum_k \Omega_{mk}^1 - \mathrm{M} \times \phi_m^1\} \quad \forall p = 1, 2, 3 \tag{63}$$

$$B_p = Max_n\{0, \sum_k \Omega_{nk}^1 - \mathrm{M} \times \phi_n^2\} \quad \forall p = 1, 2, 3 \tag{64}$$

$$C_p = Max_w\{0, \sum_k \Omega_{wk}^3 - \mathrm{M} \times \phi_w^3\} \quad \forall p = 1, 2, 3 \tag{65}$$

Therefore, the amount of the total penalty is equal to Eq. (66).

$$f_p = f_p + penalty * \left(A_p + B_p + C_p\right) \quad \forall p = 1, 2, 3 \tag{66}$$

Therefore, the objective function does not get worse if the penalty amount is zero; but if an amount of penalty is imposed the corresponding solution will have less chance to be selected for the next populations (please see Eqs. 67–69).

$$A_p = Max_m\{0, \sum_k \Omega^1_{mk} - \mathrm{M} \times \phi^1_m\} \quad \forall p = 1, 2, 3 \tag{67}$$

$$B_p = Max_n\{0, \sum_k \Omega^1_{nk} - \mathrm{M} \times \phi^2_n\} \quad \forall p = 1, 2, 3 \tag{68}$$

$$C_p = Max_w\{0, \sum_k \Omega^3_{wk} - \mathrm{M} \times \phi^3_w\} \quad \forall p = 1, 2, 3 \tag{69}$$

5 Experimental evaluations

In this section, we utilize the presented model and solution procedure for a real case study, and also assess and analyze the efficiency and the outputs of the Benders decomposition algorithm. Several randomly created experiment problems are also proposed to compare the efficiency of the developed solution procedure with the efficiency of CPLEX. Ten test problems involving two classifications, i.e. small: SP1 to SP5 and medium: MP6 to MP10 are offered. The size of the problem instances is introduced in Table 2. Moreover, the value of parameters is shown in Table 3. Given the dynamic nature of some of the parameters in planning system, they are mainly estimated based on comments and mental experiences of experts. The solution method is coded in GAMS24.1 software and all the tests are carried out on an Intel(R) Core i5 CPU with a 2.5 GHz processor and 6 GB of RAM (Goodarzian et al. 2020).

In the above Table 3 Given the dynamic nature of some of the parameters in planning system, the intervals are mainly estimated based on comments and mental experiences of experts. As an example, to decide about the capacity of the vehicles, different trucks are considered and the intervals are determined based on the actual norms.

In Table 4, the results of the objective function and computational times per problem utilizing the CPLEX and Benders decomposition algorithm are summarized, respectively. In the Fig. 2 we compared Benders decomposition and CPLEX for all problems to see what are the benefits. The computational times of the CPLEX and Benders decomposition algorithm

Table 2 The size of the instance problems

Problem size	Instance no	Levels (#*S*#*m*#*n*#*k*#*w*#*v*#*P*#*T*)
Small	SP1	(#2#2#3#1#4#1#1#1)
	SP2	(#3#3#2#5#5#1#1#1)
	SP3	(#3#3#3#4#2#2#1#1)
	SP4	(#4#3#4#2#3#3#1#1)
	SP5	(#4#4#6#2#4#2#1#2)
Medium	LP1	(#5#5#5#3#5#4#1#2)
	LP2	(#5#5#6#4#6#6#1#3)
	LP3	(#6#5#7#7#9#6#1#2)
	LP4	(#6#6#8#7#7#8#1#3)
	LP5	(#6#6##7#8#7#8#1#3)

Table 3 Pre-specified intervals to generate parameters based on a uniform distribution

Parameters	Value	Parameters	Value
α_m, β_n	$15000USD$	$I^3_{Pwt}, I^1_{Pmt}, I^2_{Pnt}$	$\sim U(30000, 60000)USD$
P^t_{PS}	$150000USD$	$\Delta^3_{kPt}, \Delta^1_{mPt}, \Delta^2_{nPt}$	35000
$\mu^1_{VPSm}, \mu^2_{VPSw}, \mu^3_{VPwm}, \mu^4_{VPwn}, \mu^4_{VPSn}, \mu^5_{VPmn}, \mu^6_{VPmk}, \mu^7_{VPnk}$	$\sim U(20000, 30000)USD$	$\theta^1_{VPSm}, \theta^2_{VPSn}, \theta^3_{VPmn}, \theta^4_{VPmk}, \theta^5_{VPnk}$	$\sim U(20, 60)$
$\varphi^1_{Pm}, \varphi^2_{Pn}$	$\sim U(10000, 200000)USD$	ω^1_m, ω^2_n	$\sim U(10000, 200000)USD$
δ_P	100	τ^1_m, τ^2_n	[1, 5.5]
$\vartheta^1_m, \vartheta^2_n$	$\sim U(100000, 200000)$	$e^1_m, e^2_n, e^3_w, e^4_k$	$\sim U(200, 400)$
ρ^1_m, ρ^2_n	$\sim U(5, 25)hour$	Big M	10000000
γ	$\sim U(250000, 400000)$	ξ^t_m, ϑ^t_m	$\sim U(250, 650)USD$
$\aleph_m(\sigma_m)$	75	σ_m	$\sim U(5, 25)hour$

Table 4 The results of objective functions and CPU times for each sample problem

Problem size	Objective function	BDA	Upper Bound	Lower Bound	CPU time	CPLEX	CPU time
SP1	of_1	28,352.65	28,227.94	28,394.46	11.78	28,352.65	16.56
	of_2	21,846.07	21,442.13	21,998.45		21,846.07	
	of_3	32,242.90	32,043.01	32,465.77		32,242.90	
SP2	of_1	28,887.56	28,711.50	28,951.32	14.45	28,891.47	22.44
	of_2	24,569.60	24,411.24	24,678.96		24,572.89	
	of_3	35,695.49	35,407.46	35,775.00		35,692.07	
SP3	of_1	29,837.94	29,653.17	29,991.35	22.42	29,838.80	30.64
	of_2	27,497.23	27,254.34	27,679.55		27,499.64	
	of_3	38,169.00	38,005.53	38,565.54		38,164.57	
SP4	of_1	31,434.11	31,108.68	31,754.80	41.00	31,443.54	63.35
	of_2	28,796.84	28,576.35	28,958.76		28,799.00	
	of_3	42,451.10	42,167.76	42,880.32		42,443.72	
SP5	of_1	37,551.12	37,278.56	37,745.98	67.74	37,561.21	84.53
	of_2	33,745.68	33,456.60	33,940.50		33,752.46	
	of_3	49,688.29	49,592.29	49,894.05		49,683.42	
MP1	of_1	39,122.35	39,083.33	39,555.95	549.34	39,125.65	867.34
	of_2	34,256.31	34,109.67	34,479.89		34,245.64	
	of_3	51,788.04	51,547.00	51,985.98		51,787.94	
MP2	of_1	40,473.34	40,190.88	40,592.25	727.04	40,477.70	1114.33
	of_2	36,633.10	36,410.63	36,759.11		36,647.34	
	of_3	52,848.34	52,446.76	52,966.06		52,844.42	
MP3	of_1	42,463.06	42,186.45	42,732.89	1009.40	42,473.89	1628.4
	of_2	37,393.59	37,156.66	37,692.90		37,396.64	
	of_3	53,757.07	53,323.46	53,950.70		53,752.54	
MP4	of_1	44,528.64	44,313.75	44,719.06	1325.67	44,532.85	1954.09
	of_2	38,684.04	38,414.84	38,718.53		38,664.95	
	of_3	54,648.88	54,400.39	54,959.80		54,642.04	
MP5	of_1	45,509.26	45,318.54	45,840.59	1885.67	45,514.85	2419.91
	of_2	39,768.07	39,419.00	39,959.13		39,773.95	
	of_3	56,379.99	56,185.56	56,593.83		56,374.76	

are shown. As a result, the computational time of a Benders algorithm is less than the CPLEX in small and medium sizes of the sample problem.

Therefore, the relative efficiencies are measured to assess the proposed algorithm and model. Accordingly, the relative efficiency is demonstrated by Relative Percentage Deviation (RPD). The RPD is computed according to Eq. (70).

$$RPD = \frac{UB - min}{min} \times 100 \tag{70}$$

where Min is the minimum of obtained UB by the proposed model and algorithm. Thus, RPD shows the relative gap between the two approaches.

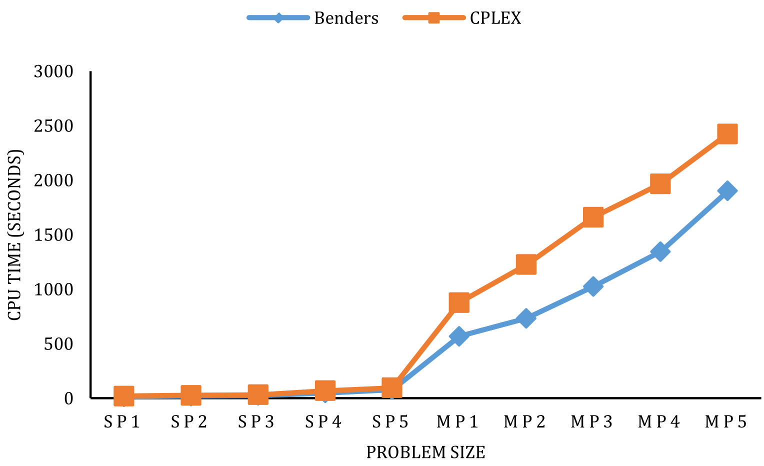


Fig. 2 The CPU time per instance problems

Table 5 indicates the outcome measures of RPD in various problem sizes. It is clear that the BDA approach acts better than CPLEX.

In order to compare the final solution/obtained UB by the two suggested approaches called RPD, BDA achieves the minimum objective in all test problems, and this difference becomes more considerable in medium-sized problems. For instance, the average RPD of the CPLEX goes up from 0.002% for small-sized problems to 5.15% for medium-sized problems. This outcome indicates a larger difference among the CPLEX and BDA in larger sizes. Further, in order to show the convergence of our algorithm in the following figure, we used 50 more instances and we show how lower and upper bounds converge, and we reported the number of cuts and iterations related to Benders' algorithm (Fig. 3):

Table 5 The results of RPD in different problem sizes

Problem size	RPD	
	BDA	CPLEX
SP1	0	0.002
SP2	0	0.002
SP3	0	0.05
SP4	0	0.10
SP5	0	0.14
MP1	0	0.27
MP2	0	0.49
MP3	0	1.06
MP4	0	2.19
MP5	0	5.15

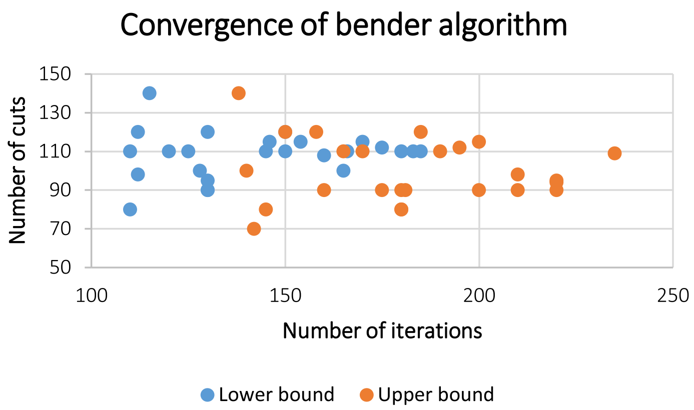


Fig. 3 Convergence of bender algorithm

5.1 Sensitivity analysis

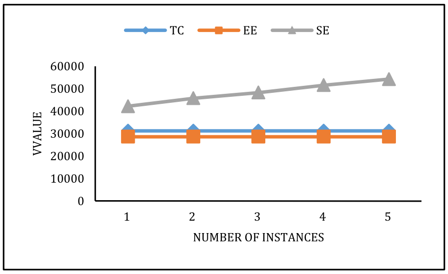
In this section, a sensitivity analysis is performed to survey the impact of changing the main parameters on the presented model outcomes (Fathollahi-Fard et al., 2020). To recognize the behavior of the sustainable PSCN model with the real savings of the problem presented more effectively, several sensitivity analyses have been carried out on the significant parameters of the model. Then, a small test problem such as SP43 involving four producers, four local DCs, three main DCs, two pharmacies, three warehouses, three vehicles, and one product are chosen. To apply the model, the Benders decomposition algorithm as the most effective method in this paper is considered. A set of changes containing the regional factor (unemployment ratio) in the main and local DCs (τ_m and τ_n), The environmental effects of opening in the main and local DCs, warehouses, and pharmacies ($\boldsymbol{e}_{\boldsymbol{m}}^1$,$\boldsymbol{e}_{\boldsymbol{n}}^2$, $\boldsymbol{e}_{\boldsymbol{w}}^3$ and $\boldsymbol{e}_{\boldsymbol{k}}^4$) and the number of used vehicles (V) for developing sustainable PSCN model is analyzed. Each analysis is divided into five instances numbered as i1 to i5. Eventually, all outcomes are shown in Table 4 and also Fig. 4a–c.

5.1.1 Impact of τ_m^1 and τ_n^2 on the sustainable PSCN efficiency

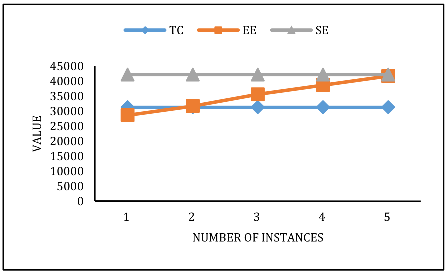
According to the regional factor (unemployment ratio) in the main and local DCs (τ_m and τ_n), sensitivity analyses have been carried out by increasing the amount of this parameter. Table 4 is indicated details. To recognize the behavior of three objective functions, i.e. Economic Effect or Total Cost (TC), Environmental Effect (EE), and Social Effect (SE), simultaneously, Fig. 4a is shown the impact of on τ_m^1 and τ_n^2 values on sustainable PSCN are considered in this comparison. As it can be seen, the outcomes illustrate that although by increasing the amount of this parameter the social effects are increased, these changes have no effect on economic and environmental effects.

5.1.2 Impact of e_m^1,e_n^2, e_w^3 and e_k^4 on the sustainable PSCN efficiency

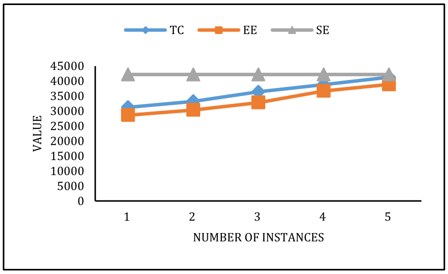
Regarding the environmental effects of opening in the main and local DCs, warehouses, and pharmacies (e_m^1,e_n^2, e_w^3 and e_k^4), the sensitivity analyses on the environmental effects of opening in the main and local DCs, warehouses, and pharmacies have been performed and



a. Impact of regional factor on sustainable PSCN.



b. Impact of the environmental effects of opening on sustainable PSCN.



c. Impact of the number of vehicles on sustainable PSCN.

Fig. 4 The convergence behavior different parameters on objective functions

the outcomes are indicated in Table 4. Moreover, the impact of the three objective functions is displayed in Fig. 4b. It is clear, by increasing the number of environmental effects of opening in the main and local DCs, warehouses, and pharmacies, both TC and SE objective functions have stayed fixed, while the EE is increased gradually.

5.1.3 Impact of V on the sustainable PSCN efficiency

In this section, some sensitivity analyses on the number of vehicles (V) have been carried out by increasing the amount of this parameter. Table 6 and Fig. 4c demonstrate the description of the analyses. As examined before, the outcomes illustrate the conflicting objective functions. While the TC and EE are increased by increasing the number of vehicles, as opposed to the SE is stayed without change. Regarding the managerial insights of the presented sustainable PSCN model, choosing the best strategy to use the most efficient transportation systems is so considerable to manage the effectively total hospital, laboratory, pharmacy, etc. for both patients and doctors' contributors of the hospital, laboratory, pharmacy.

Table 6 The sensitivity analyses on the different parameters

The sensitivity analyses on the regional factor

Number of instances	$\#\tau_m^1\#\tau_n^2$	TC	EE	SE
i1	#1.5#2	31,241.18	28,612.21	42,161.19
i2	#2#2.5	31,241.18	28,612.21	45,712.54
i3	#2.5#3	31,241.18	28,612.21	48,234.12
i4	#3#3.5	31,241.18	28,612.21	51,544.62
i5	#3.5#4	31,241.18	28,612.21	54,253.78

The sensitivity analyses on the environmental effects of opening

Number of instances	$\#e_m^1\#e_n^2\#e_w^3\#e_k^4$	TC	EE	SE
i1	#200#200#200#200	31,241.18	28,612.21	42,161.19
i2	#250#250#250#250	31,241.18	31,645.35	42,161.19
i3	#300#300#300#300	31,241.18	35,572.87	42,161.19
i4	#350#350#350#350	31,241.18	38,666.81	42,161.19
i5	#400#400#400#400	31,241.18	41,652.26	42,161.19

The sensitivity analyses on the vehicle

Number of instances	V	TC	EE	SE
i1	3	31,241.18	28,612.21	42,161.19
i2	4	33,231.13	30,351.24	42,161.19
i3	5	36,378.45	32,819.67	42,161.19
i4	6	38,781.34	36,679.21	42,161.19
i5	7	41,266.26	38,845.32	42,161.19

5.2 Case study

In this research, we have focused on the pharmaceutical industry in France, which is subject to different challenges that make supply chain management particularly difficult. This sector is highly competitive, governed by very strict legislation, with standards throughout the production and distribution. Added to this is an increase in production costs and often a drop in the sale price of drugs following government requests. These specificities make the transport and logistics chain of the pharmaceutical industry very long and complex. In addition, during the health crisis, the industry has had to deal with a sudden explosion in demand for pharmacy drugs, vaccines and other pharmaceutical goods, which has inevitably been accompanied by a massive shortage of warehouse stocks. Added to this were major logistical challenges, with supply and export difficulties. This situation, although exceptional, revealed a number of flaws in the pharmaceutical supply chain. The Covid-19 crisis has thus highlighted the need to optimize the current system to move towards a more resilient and sustainable model, in order to accelerate the marketing of products, improve inventory management, and allow optimization of the entire value chain. To collect the data, we used experts' opinion, based on a semi-directive interview. To do we relied on a structured interview guide which constitutes a framework that will allowed us to conduct the interview.

In this research, 3 types of service technology for pharmacies are considered as follows:

- E1: E-Verification Systems: This technology provides digital images that make it easier for pharmacist to verify the prescription.
- E2: Battling Substance Abuse system: Excessive prescriptions for certain drugs can be identified and flagged by this system, alerting a pharmacy to at-risk customers.
- E3: Tele-pharmacy Services for Rural Areas: This service brings pharmacy services to the internet. Individuals in remote locations can fill prescriptions, which will be mailed to their location.

For each of the presented technologies, two job creation criteria (b_1) and environmental effects (b_2) are considered.

The presented case study evaluates the sustainable PSCN of $Hair-Vit$, considering an optimal balance among the considerable needed investment, and the whole satisfaction of customers in France. Presently, $Hair-Vit$ is only imported from Health Aid Company from the UK to the France. Then, we consider the UK as the only primary producer of producing $Hair-Vit$. According to the experts' knowledge and data from the ministry of health of France, 6, 10, 10, and 12 candidate locations for the establishment of warehouses, main DC, local DC, and for pharmacies are considered, respectively (see Fig. 5). Table 7 indicates the suggested nodes for the case study in France. The values of the input parameter are presented

Fig. 5 Candidate locations of facilities in France

Table 7 Candidate locations of facilities in France and the nodes capacities

ID Node	Capacity (m)	Capacity (n)	Capacity (V)
1 Reims	4960	6700	3540
2 Bayeux	5190	6840	3560
3 Paris	4670	7560	3450
4 Nancy	5220	7810	3340
5 Strasbourg	4560	6540	3700
6 Angers	4370	7230	2970
7 Tours	4820	7100	2890
8 Dijon	4900	7940	3200
9 Lyon	5340	7670	3250
10 Grenoble	4300	6780	3750
11 Cahors	–	–	3680
12 Toulouse	–	–	3100

in Tables 8 and 9. Hence, the offered size is $|S| \times |m| \times |n| \times |k| \times |w| \times |V| \times |P| \times |t| = |1| \times |10| \times |10| \times |12| \times |6| \times |12| \times |1| \times |12|$. The information and parameters used in these tables are from the opinions of Hair-Vit company experts, the French Ministry of Health and Zahiri et al. (2017) is taken.

Table 10 shows service technology scores for each criterion. These points are based on the opinion of experts and based on the Likert scale. Based on this, if the highest amount of job creation is 5 and the lowest amount of job creation is 1. Also, the highest negative environmental effect is equal to 1 and the lowest negative environmental effect is equal to 5

Table 11 indicates the importance of criteria based on experts' opinion. As it is known, the weight of the employment generation criterion is equal to 0.6 and the weight of environmental impact criterion is equal to 0.4

As evident in Fig. 6, for $Hair - Vit$ product, each established warehouse, main & local DCs, and pharmacy fully serve whole demand in that area (named self-service warehouses, main & local DCs, and pharmacy in this paper), while other areas perform their demands by the nearest allocated warehouses and pharmacies to minimize total cost and environmental aspects and to maximize social effects. Moreover, because of several issues (i.e., the capacity of each warehouse, the capacity of each pharmacy, the capacity of each main & local DCs, transportation costs, etc.) for product, warehouses and main & local DCs #1, #2, #4, #5, #6, #8, #9, #10, #12 import the needed product from a producer, while warehouses and main & local DCs #3 trace a various policy for importing product. Interestingly, for warehouses and main & local DCs #3 perform their demands via vehicle. As a result, in the case of disruption of producer, warehouses and main & local DCs #1, #2, #4, #5, #6, #8, #9, #10, #12 are the most vulnerable spots since they only serve their demand by a producer for product; while warehouses and main & local DCs #3 can still be served via vehicle between other warehouses and main & local DCs. Therefore, since the allocation policy of warehouses and main & local DCs #3 for the product is various. Consequently, the concerned zone does not utilize the products as a replacement.

Another important element that has been addressed in this case study is the behavior of the inventory levels at both the main and local DCs. Figure 7a indicates the total number of the inventory level at each period for the $Hair - Vit$ product. In this view of the problem is important for the decision-makers, most especially at main and local DCs, where the

Table 8 Total demand of each pharmacy, main & local DC for product at each time period (Unit)

Δ^1_{kPt}	1	2	3	4	5	6
1	677	1178	1196	956	856	574
2	1045	654	578	908	1032	1076
3	873	1025	1025	1078	1167	765
4	945	956	326	1478	608	456
5	701	1156	354	1145	1634	1067
6	832	367	1289	1267	1067	1678
7	1034	1856	1566	577	804	1677
8	1056	1678	932	1345	677	1072
9	799	788	486	1135	766	845
10	1056	1677	856	1376	1156	1219
11	653	967	923	566	775	806
12	977	993	856	377	1156	773
Δ^1_{kPt}	7	8	9	10	11	12
1	1278	1356	872	1732	1278	1677
2	470	981	1202	1709	804	1451
3	528	1167	582	601	699	1156
4	1375	1388	1354	858	431	513
5	478	1588	1123	941	1233	720
6	1233	1123	910	977	1602	1001
7	845	956	566	715	1208	378
8	677	1671	766	933	1479	1093
9	1289	821	689	739	645	379
10	788	656	1048	900	470	810
11	1610	1455	1408	892	893	965
12	1224	702	1319	1185	1809	1033
Δ^2_{mPt}	1	2	3	4	5	6
1	245	294	368	237	177	266
2	263	306	358	133	412	378
3	309	147	368	279	153	398
4	221	356	376	401	289	143
5	126	143	123	370	128	276
6	165	232	276	345	40	256
7	387	402	298	130	243	152
8	153	195	151	126	173	312
9	274	356	201	393	351	367
10	351	206	382	345	233	283
Δ^2_{mPt}	7	8	9	10	11	12

Table 8 (continued)

Δ^1_{kPt}	1	2	3	4	5	6
1	341	347	193	226	285	267
2	192	253	327	361	218	267
3	184	231	231	265	245	117
4	234	344	212	455	378	119
5	350	221	766	233	901	344
6	671	566	312	504	319	202
7	402	513	788	815	561	332
8	567	344	233	881	221	677
9	881	566	677	914	655	570
10	655	321	721	832	732	455
Δ^3_{nPt}	1	2	3	4	5	6
1	108	156	108	139	245	152
2	500	151	273	143	184	137
3	386	184	167	385	285	274
4	186	116	152	392	381	372
5	341	147	341	274	371	261
6	263	400	352	223	157	376
7	273	118	291	386	178	394
8	195	132	247	339	266	188
9	271	165	389	392	311	354
10	339	167	281	126	353	212
Δ^3_{nPt}	7	8	9	10	11	12
1	164	237	245	338	332	386
2	242	257	221	168	258	269
3	124	176	135	287	158	313
4	317	296	372	386	153	246
5	358	365	193	388	131	137
6	455	212	677	903	158	321
7	203	388	233	389	102	112
8	544	813	566	201	244	514
9	881	432	733	429	502	632
10	322	670	488	591	322	455

inventory levels are shared among products. As indicated in Fig. 7a, when the inventory level at the main DCs is high (see triangle points), the stock level at local DCs is low. Since time windows and CO_2 emission is important in the production and distribution of products in the related chain, the higher inventory level at producers would restrict products' shelf life to be stored at main and local DCs. In other words, when stock levels at producers are high, transportation and storing the products at the same period would become more sensitive to

Table 9 Fixed, production, inventory holding, and storage costs for each producer, main & local DCs, and warehouse (USD)

ID	α_m	β_n	I^1_{Pwt}	I^2_{Pmt}	I^3_{Pnt}	P^t_{PS}	φ^1_{Pm}	φ^2_{Pn}
1	4	5	2	2	3	2	6	7
2	4	5	2	2	3		6	7
3	4	5	3	3	3		6	8
4	5	5	3	3	3		7	8
5	5	6	2	3	3		7	8
6	6	6	3	2	2		7	8
7	6	7	–	2	2		8	9
8	7	7	–	2	3		8	9
9	7	8	–	3	3		9	9
10	8	9	–	3	2		9	9
11			–					
12			–					

Table 10 A score of service technology *e* from criteria *b*

b/e	e_1	e_2	e_3
b_1	2	3	3
b_2	4	4	5

Table 11 Importance of criteria

w/b	b_1	b_2
Weight	0.4	0.6

time windows and CO_2 emission. Moreover, most of the delivered products to the warehouses and main and local DCs will be immediately shipped to demand regions.

Figure 7b displays the total transportation between the DCs at each time period with CPLEX and Benders algorithm. As illustrated, when the product at the Benders method is shipped in huge amounts (i.e., periods #1, #2, #4, #7, #10, #11, and #12), the product is delivered in rather small quantities at the CPLEX method and vice versa. On the other hand, the fluctuation of shipped products resulted in a fixed trend line for the product at both methods. Tracing these trend lines is significant for transport/delivery organizations, whose main limitations are on their existing vehicles and capacities.

The total endured cost in the planning horizon, the minimum environmental aspects and the maximum social effects are shown in Table 12. As displayed, the maximum social effects in the planning horizon are quite low, i.e., $\approx 0.05\%$ of total effects with an appropriate whole cost, while the minimum environmental aspects in this period time are higher than social effects. The proportion of the fixed cost to both the total inventory and transportation costs is around 2.44, which shows the importance of fixed cost in this background. In this regard, the proportion of the production cost to both the total inventory and storage costs is around

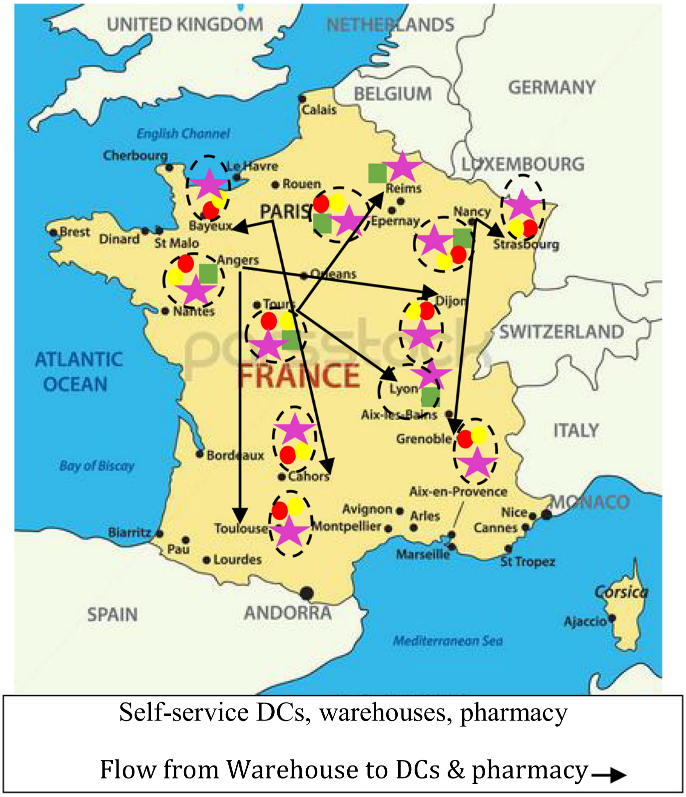
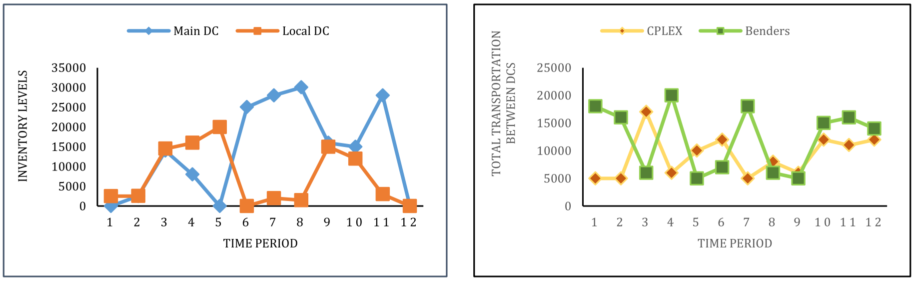


Fig. 6 Established facilities and their interactions for (p = 1)



a. The main and local DCs inventory levels   **b.** The transportation of products between DCs

Fig. 7 The results of inventory levels (**a**) and transportation of products (**b**)

0.34, which indicated the significance of production cost in this field. According to these high fixed and production costs may not indicate the cost-effectiveness of such investment in the short-term, the valence of such cost will be further vindicated as the planning horizon extends.

Table 13 shows the established pharmacy according to Service technology. As indicated,

Table 12 Total cost (USD), minimum environmental effects, and maximum social effects (Unit) in the planning horizon

Fixed cost	35,675,300
Total transportation cost	9,835,670
Total inventory holding cost	4,787,400
Production cost	3,451,950
Storage cost	5,466,800
Minimum environmental effects	141
Maximum social effects	91

Table 13 Established pharmacies with service technology *e*

No	Established pharmacy	Service technology
Pharmacy 1	1	e2
Pharmacy 2	0	–
Pharmacy 3	1	e3
Pharmacy 4	1	e3
Pharmacy 5	1	e1
Pharmacy 6	1	e3
Pharmacy 7	0	–
Pharmacy 8	1	e3
Pharmacy 9	1	e1
Pharmacy 10	1	e3
Pharmacy 11	1	e2
Pharmacy 12	0	–

9 pharmacies have been established. For example, pharmacy 1 has been established with e_1 technology, while e_2 pharmacy has not been established

The difference between case study and problem of the paper is related to the size of the problem. The studied problem concern only small and medium cases, however the case study is in a national scale in France.

5.3 Managerial insights

This research provides further theoretical insights into PSCN strategy development. The results of the current paper potentially assist pharmacies and community pharmacists to understand the operational inefficiencies that they have to face and directs them towards suitable innovative solutions that could enable them to raise levels of efficiency and effectiveness. This paper investigates the pharmaceutical supply chain network in a real case study in France with a $Hair - Vit$ medicine. Therefore, the study's outputs provide information related to the inventory holding of the pharmaceuticals, total costs, environmental and social effects, and transportation of pharmaceutical products. Eventually, the current research highlights the practices within the medicines transportation and inventory holding process, CO_2 emissions through transportation systems, social aspects that need improvements, which can help hospitals, pharmacies, and pharmaceutical industries to investigate a critical issue for decision-makers/managers. In other words, the challenge of how hospitals, pharmacies, and pharmaceutical industries can be more productive utilizing fewer resources.

The obtained results from the presented model are important and significant for several reasons, the most obvious being the minimization of total costs and the environmental effects and maximization social aspects. Since these three are suggested as the main aims of the presented model, the mission of this model does not finish with the optimization of these aims. The presented model makes decision-makers aware of the fact that a sustainable pharmaceutical supply chain considering service technology under various criteria in the social aspects under time windows in the arrival time of pharmaceutical products to main distribution centers can be designed. It is clear that the design of such a pharmaceutical supply chain is costlier. The presented model proposes this condition and specifies that this additional cost can be computed and provided to decision-makers/managers. In terms of inventory visibility, allocation of transportation and warehouses to different levels is also important. Decision-makers/managers must be aware of the different ways, that can constantly improve the pharmaceutical supply chain. Decision-makers can use the proposed model to ensure that pharmaceutical products are transported to their destination without compromising the quality. Therefore, decision-makers/managers can estimate the needed cost, including the fixed cost of opening main and local DC, transportation and inventory holding costs, and production and shortage costs for designing a sustainable pharmaceutical supply chain, one that covers all echelons. In the same way, the presented model tries to bring the obtained results closer to the real-world ones by considering the regional factors (unemployment ratio) in the main & local DCs, warehouses, and pharmacies, CO_2 emission, the environmental effects of opening main &local DCs, warehouses, and pharmacies, and also service technology under various criteria in the social aspects. It should be noted that the suggestion of an efficient mathematical model is a necessary but not sufficient condition for the design of an optimal sustainable pharmaceutical supply chain network. Then, the efficiency and performance of the presented model become more efficient when a proper solution method is presented to it. The presented solution method in the current paper, managers/decision-makers can use for their own aims to minimize the total cost and CO_2 emission and maximize social aspects based on community policies. Also, this possibility has been created for decision-makers/managers to get the desired outcomes based on the considered service technology under various criteria and time windows for the objective functions.

6 Conclusions and future research

Sustainability of supply chains has become more significant because of enhancing concerns about the social and environmental effects of business processes in recent years. Governmental forces and public demand and also amplify the requirement for sustainability in today's business environment. To movement forward the literature review in this paper, this paper developed a multi-objective and multi-period model for a real $Hair - Vit$ sustainable PSCN problem with time windows under CO_2 emissions. The problem traits were defined based on a real case study of the $Hair - Vit$ drug production and distribution network in France, while this pharmaceutical product is produced in the UK. In fact, 12 provinces are regarded as potential warehouses, main & local DCs, and pharmacies in France, while 1 country is considered as a potential producer. Real datasets of $Hair - Vit$ production are considered in the model. The mathematical formulation of the problem as a MILP model is developed. A Benders decomposition algorithm to solve the problem is also suggested. This procedure decomposes the main model divided into two models of master problem and sub-problem. Several generated instances and a practical case study are proposed to demonstrate the applicability of the suggested model and also the performance of the developed solution method. A sensitivity analysis is performed to experiment on the impact of changing the main parameters on the model outcomes. According to the outcomes, we consider that the accelerated Benders decomposition algorithm is considerably more time-effective as compared to CPLEX. Generally, the outcomes and the efficiency analysis can be applied by decision-makers to accept essential components and suitable service strategies to design a sustainable pharmaceutical supply chain network from three economic, environmental, and social effects view.

The present paper can be used as a motivation for subsequent work on several interesting relevant issues. Then, the interested researchers can consider the uncertainty parameters such as costs, demand, and capacities in the presented model as future work, which to cope with the uncertain parameters, robust, fuzzy, stochastic methods, and so on can be used. In terms of solution methods, the interested scholars can develop efficient hybrid meta-heuristic algorithms and logic-based benders to solve large-size models and new heuristic methods for future work. In terms of solution methods, the interested scholars can develop efficient hybrid meta-heuristic algorithms to solve large-size models and new heuristic methods for future work.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose. The authors have no conflicts of interest to declare that are relevant to the content of this article. All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript. The authors have no financial or proprietary interests in any material discussed in this article.

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