**RESEARCH ARTICLE**

# Green dynamic multimodal logistics network design problem considering financing decisions: a case study of cement logistics

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## Abstract
Logistics network is one of the most important parts of supply chains with significant share in achieving sustainability across them. In this paper, we investigate a new multi-objective mixed integer linear programming model for the design of multimodal logistics network. A bi-objective mathematical model is introduced and two conflicting objectives including the minimization of total cost and the total environmental impact are taken into account. Effective environmental life cycle assessment–based method is incorporated in the model to estimate the relevant environmental impacts. Due to budget constraints, financing decisions for facility construction are considered in the proposed model. To cope with the model objective functions, the augmented $\varepsilon$-constraint method is applied. Computational analysis is also provided by using a cement multimodal rail-road logistics network case study to present the significance of the proposed model. Results show that utilizing the proposed multi-period optimization model influences the location of multimodal terminals and their construction time. Also, the results show that the use of the proposed model enhances the efficiency of terminals. On the other hand, computational results indicate that preferences of decision-makers and the importance of environmental objective have significant impacts on the topology of transportation network.

**Keywords** Multimodal logistics network design · Augmented $\varepsilon$-constraint method · Life cycle assessment · Transportation · Emissions

## Introduction

In recent years, due to the globalization of markets, producers and consumers are geographically far apart (Fazayeli et al. 2018). Therefore, forming an efficient and effective supply chain is a key competitive factor in various industries. Despite the traditional business view, now, the performance of supply chain is assessed in environmental and social aspects beside economic dimension. Accordingly, the concept of sustainable supply chain becomes critically important both in academic and industrial contexts (Muñoz-Torres et al. 2020; Sherafati et al. 2019). Among different functions of a supply chain, transportation generated a significant part of environmental burden and damages. Thus, improving the efficiency of freight logistics systems plays a key role in covering the environmental concerns as well as supporting the needs of the manufacturers (Park and Regan 2005), specifically for manufacturers who, in addition to reducing costs and improving the quality of their products, are looking for an economical solution to transport their products over long distances (Ghane-Ezabadi and Vergara 2016). The transportation sector contributes to the economic development of communities; but, on the other hand, it has significant negative impacts on human health, climate change, and the natural environment (Merchan et al. 2019).

Railway transportation is a cost-effective solution to carry large volumes of goods at long distances, while road transportation is convenient for fast shipping goods and has high

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availability for collecting and distributing goods in short to medium distances (Wang et al. 2018). Both railway and road transportation connect freight logistic hubs in multimodal rail-road transportation systems (Chimba et al. 2019). Multimodal rail-road transportation involving two modes of transportation provides an economical solution for the cargo delivery for long-distance transportation, especially at distances greater than 300 km (Mostert et al. 2018) and increases the flexibility and efficiency of the freight transportation process (Park et al. 2017). In addition, having a significant impact on the economic and social development of societies, multimodal transportation is an essential factor in environmental considerations (Zhao et al. 2017). This transportation method has a significant impact on reducing the environmental impact of freight transportation. In 2017, multimodal transportation has been used to carry 10% of the total freight in the USA and is forecasted that this volume will increase by 30% by 2040 (Fotuhi and Huynh 2018).

There has been a significant growth in research on multimodal freight logistics system as a key component in increasing the efficiency of supply chains since the 1990s. Some relevant research works can be found in SteadieSeifi et al. (2014) and Agamez-Arias and Moyano-Fuentes (2017). In the last decade, researchers have focused on the modeling of multimodal logistics systems using optimization approaches. Multimodal transportation planning problems can be classified in three categories in terms of the planning horizons including strategic, tactical, and operational levels. In strategic planning problems, investment decisions, design, and expansion of a multimodal logistics network are considered. Woxenius (2007) proposes six different topologies for transportation network design problem including direct link, corridor, hub-and-spoke, connected hubs, static routes, and dynamic routes. According to the literature, a multimodal logistics network design problem can be essentially formulated as a multimodal hub-and-spoke or connected hubs network (Yang et al. 2016). In these many-to-many distribution networks, hub facilities serve as sorting, transshipment, and consolidation points (Kartal et al. 2017). Ishfaq and Sox (2011) develop a mathematical model using the multiple-allocation $p$-hub median approach for intermodal logistics network design problem. Each hub facility has the access and the capability of handling rail and road transportation. Also, a discount factor is considered for inter-hub transportation costs. This model makes location-allocation decisions and minimizes the total transportation cost. Ghane-Ezabadi and Vergara (2016) proposes a single-allocation hub location model for an intermodal logistics network. In this mathematical model, in addition to locating hubs and allocating the load flows, the transportation mode selection is also considered. Correia et al. (2018) studied the optimization of the intermodal hub-and-spoke network focusing on minimizing the expected value of total transportation cost and the maximization of travel time. An intermodal

network design problem was studied in Mostert et al. (2018). This problem involves determining the modal split between three transportation modes: road, intermodal rail, and intermodal inland waterway (IWW) transport. The developed model is tested in Belgium network with the aim of minimizing of operational cost and $CO_2$ emissions. To illustrate economies of scale, the results of the model have been analyzed using a fleet with different capacities for each intermodal rail and intermodal IWW transportation.

Wang et al. (2018) present a bi-objective model for the connected hub-based road-rail intermodal transportation network design problem under uncertainty, where the economic objective and service objective are considered. To illustrate the applicability of proposed model, Turkey has been selected as a case study. Typically, multimodal transportation network design studies use one of two hub-and-spoke or connected hub topologies. While depending on the real-world application, each of these network topologies can be used for transportation systems (SteadieSeifi et al. 2014). In Wang et al. (2018), the design of a rail-road multimodal transportation network has been investigated using a hybrid topology, the load flow can be assigned to the rail-road multimodal transportation network, using three topologies from origins to destinations. On the other hand, one of the most important measures affecting high transportation costs over long distances is the lack of connectivity between the origin of the goods or their destinations to the railway network. Only research works by Fotuhi and Huynh (2018) and Gelareh et al. (2015) consider the construction and development of railway lines in the multimodal transportation network beside locating the multimodal terminals and allocating the load flows to the transportation network. This literature gap is the main motivation of the current research and therefore, this paper focuses on integrated modeling of railway network expansion and the design of a multimodal transportation network.

Multimodal logistics network design decisions have a strategic nature since in addition to the high cost of constructing and setting up facilities, these decisions have long-term effects on supply chain performance (John et al. 2018). Therefore, the development of multimodal logistics networks requires significant investments in the construction of the required network infrastructure, which, due to budget constraints, is usually not available at the beginning of the planning period. Multi-period planning makes it possible for the network facilities to be built up during the planning horizon and when they are needed, while helping to properly manage the resources available in the decision-making process; on the other hand, it helps to make more realistic decisions (Correia et al. 2018). Gelareh et al. (2015) studied a multi-period incapacitated multiple allocation hub location problem for a multimodal maritime—land transportation network. They consider the minimization of total cost including installing, repairing, and removing the hub nodes and hub edges costs as the objective function. In the

presented model, in each period, there is limited budget for the development and maintenance of network facilities or closing existing facilities.

24.2% of greenhouse gas emissions in the European Union have been caused by transportation according to 2019 statistics. Within the whole transportation sector, road represents 72.8%, while rail only contributed to 0.6% (European Commission 2019). In Iran also, transportation is one the most significant sectors in GHG emission since this sector is responsible for about 22% of total GHG emission (IPRC 2017). Iran plays an important role in international transportation network as it connects the West of Asia to the East of Europe and North Africa. Iran has built a vast transportation network both in road and rail modes in order to respond the internal and external transportation demand. Intermodal rail-road transportation is highly used for freight transportation for many products including cement and steel. In the whole transportation sector, all means of transportation including road, rail, aviation, and navigation, is responsible for approximately 28% of the total energy demand worldwide according to 2016 statistics (IEA 2019). The ratios of oil, natural gas, and electricity that provide the energy demand for transportation are 95, 4, and 1%, respectively. Seventy-six percent of the energy produced from oil and used in the transportation sector is used for road transportation, while rail transportation only consumes 1% (Bilgili et al. 2019). Mostert et al. (2018) use the $CO_2$ emission index to measure and model environmental impact especially on climate change across freight transportation network in an intermodal transportation network design problem. Demir et al. (2017) developed a multi-objective optimization model in an intermodal transportation service network design problem and environmental impact of transportation measured in the form of $CO_2$ emissions.

By the aid of more comprehensive environmental impact assessment methods, i.e., life cycle assessment (LCA)–based methods, Pishvaee and Razmi (2012) developed a bi-objective optimization model to consider the environmental burden in forward/reverse supply chain network design problem. Pishvaee et al. (2014) integrated two LCA-based impact assessment methods to formulate and measure the environmental and social impacts of different supply chain network configurations. To achieve an eco-friendly multimodal logistics network, we need to have methods and tools to measure the environmental impact of different transportation services served by different transportation modes. LCA is known as the most credible methodology to quantify and assess the total environmental and social impacts of a product or service during its life cycle (SAIC 2006). Ashtineh and Pishvaee (2019) use the LCA to assess the economic and environmental impacts of different transportation fuels during production, distribution, and consumption stages. They show that load, distance, speed, and transmission gear ratio are the main factors affecting the amount emissions. Skrucany et al.

(2017) compared rail and road transport vehicles in terms of energy consumption and greenhouse gas emissions. Merchan et al. (2019) studied the inland freight transport in Belgium and used the LCA method to indicate the share of road and railway transport of total greenhouse gas emissions. They evaluated the railway versus to an operating highway from the environmental viewpoint considering both the construction and operation phase. Merchan et al. (2019) compared externalities and external costs for inland freight transport on the Belgium case study regarding three negative effects including climate change, photochemical ozone formation, and particulate matter. The purpose of this study is to compare the decisions made on the basis of two criteria externalities and external costs. Fridell et al. (2019) investigate the emissions related to transportation infrastructure and terminals for freight transport under different modes. The existed data from different LCA reports are used and analyzed. Heinold (2020) study the performance and precision of emission estimation models on rail freight transportation. The impact of trip and train parameters on estimation results is investigated and analyzed.

The purpose of this paper is to design a green dynamic rail-road logistics network while considering financing and development of railways network decisions. This problem involves decision-making at both strategic and tactical levels. The main contributions of this paper include (1) developing a model for multimodal rail-road transportation network with simultaneous decision-making for railways development; (2) using a multi-period planning approach to design a multimodal rail-road transportation network; (3) considering the possibility of financing for construction multimodal terminals and development of railway lines and receiving loans in any time period; (4) applying LCA-based impact assessment methods to formulate a bi-objective optimization model to multimodal rail-road transportation network; (5) the developed model has been used for the real industry case of the design of the cement multimodal transportation network in Iran.

## Problem definition

In this section, we discuss the green multimodal rail-road logistics network design (GMLND), present our bi-objective optimization model, and also outline the solution methodology we use to generate set of Pareto solutions for bi-objective optimization problem.

### Problem definition

The GMLND problem described in this section is formed based on a real industrial case. The case study is a logistics network used for cement transportation at the national level in Iran. Road transportation is currently being used to distribute a

significant amount of cement produced in factories. Shipping cost includes 30% of the cement final price. Therefore, due to the high cost of carrying this strategic product over long distances, cement producers do not use their whole capacity. The efficiency of cement manufacturing plants depends on how economically the cement is transported from the cement factories to the consignee centers. This process necessitates developing an integrated logistics network that efficiently connects origin plants to destination nodes with proper transportation modes. The structure of the actual transportation network investigated in this study is illustrated in Fig. 1. As previously mentioned, to allocate freight flows to the transportation network, hybrid multimodal rail-road transportation paths are taken into account.

Direct link, hub-and-spoke, and connected hubs topologies are applied to efficiently route shipments between many origins (cement factories) and destinations nodes. Our objective is to find the best planning decisions for the following decisions:

- Development decisions of potential railway stations and locating the rail-road multimodal transportation terminals;
- Decisions about construction of railways;

- Allocation of load flow to the multimodal logistics network using hub-and-spoke topology, in addition to locating rail-road multimodal transportation terminals, the cement factories or consignee centers should be connected to the railway network.
- Financing decisions required for the construction and development of multimodal transportation network facilities

LCA methodology as a systemic approach not only evaluates the direct processes associated with transportation such as energy consumption and exhaust emissions, but also other related processes including electricity and fuel production, vehicles, and infrastructure. Already several studies have applied the LCA methodology to investigate the environmental burden of different modes of inland freight transport (Merchan et al. 2019). The development of ISO 14000 series on LCA by the International Standard Organization resulted in extensive acceptance of this methodology by researchers and practitioners in various industries (Pishvaee et al. 2014). ISO identify four stages for LCA including goal and scope definition, inventory analysis, impact assessment, and interpretation (ISO 2006). According to ISO14040 and ISO 14044 (ISO 2006), life cycle impact assessment (LCIA) stage includes three

**Fig. 1** The underlying structure of the concerned multimodal transportation
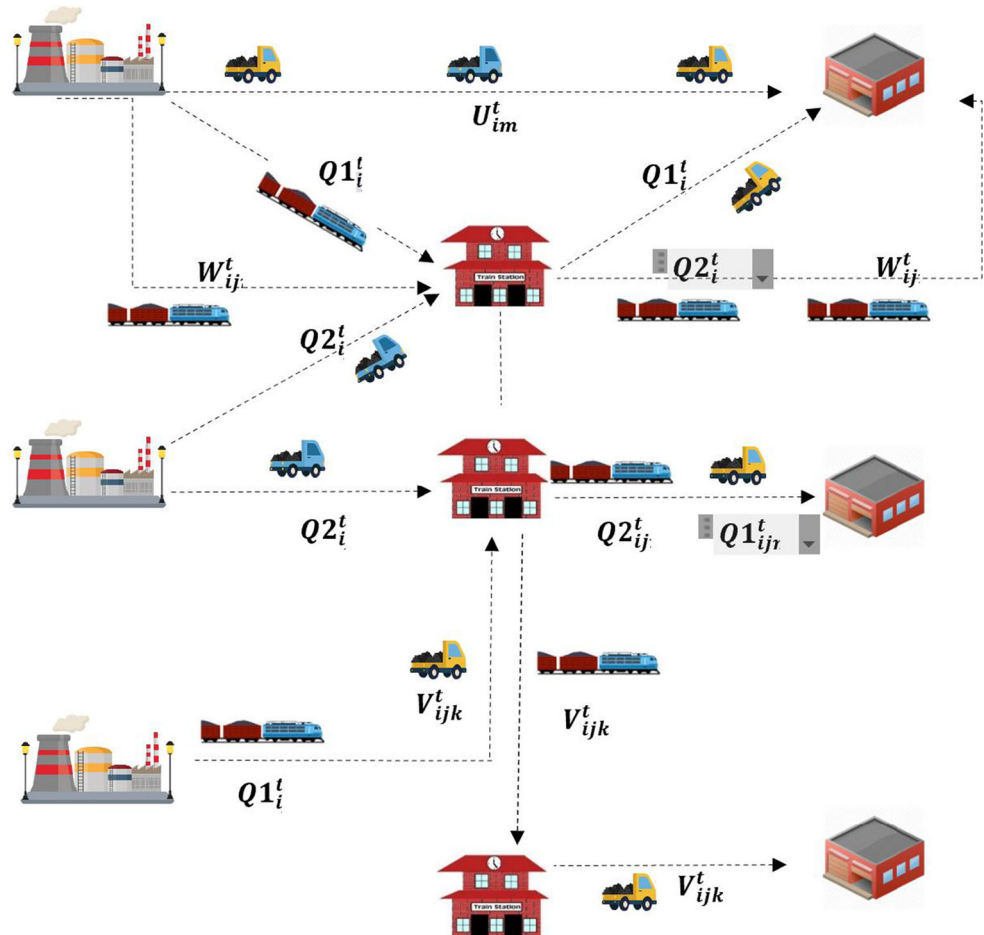
mandatory steps: (1) selection, (2) classification, and (3) characterization. Also, normalization and weighting are the two optional steps of this phase.

Using the LCA methodology directly is a complex, time-consuming, and costly process. For this reason, many standard methods have been developed based on the LCA methodology that has simplified this process for users. In this study, the ReCiPe 2016 method is used to calculate the environmental impacts of road and rail transportation methods. ReCiPe is a damage-oriented LCA-based impact assessment tool. Using this method, the environmental burden can be calculated as a single number by aggregating the environmental impacts in three impact categories including (1) human health, (2) ecosystem diversity, and (3) resource availability (Pishvaee et al. 2014). Using an appropriate weighting method, the final score can be represented in the form of a single number. ReCiPe provides three distinct weighting methods according to different cultural perspectives including hierarchist, individualist, or egalitarian approaches. The hierarchist version is applied more than the other versions as the more moderate method to aggregate the results. In this approach, human health, ecosystem diversity, and resource availability contribute 40%, 40%, and 20% in the final score, respectively.

To use the ReCiPe method, users must complete the following four steps:

1. The scope and mission of the studied system and the purpose of using ReCiPe method should be determined in detail.
2. The life cycle stages of product/service should be defined.
3. The number of inventories for each stage must be calculated.
4. Environmental burden is calculated via multiplying the amounts of inventories by the corresponding environmental indicator values.

In this study, SimaPro 8.2.3.0 is used to compare the environmental impacts of freight transportation by rail and road. This software is developed based on the four steps mentioned above and is used to implement ReCiPe method.

## Model formulation

In order to provide a precise expression of the concerned GMLND problem, the following indices, parameters, and decision variables are used. It should be noted that in this study, the hub is meant to be a multimodal rail-road terminal.

Indices:

$i$     index of fixed locations of cement factories $i=1, \ldots I$

$m$    index of fixed locations of consignee centers $m=1, \ldots M$

$j, k$    index of candidate locations for multimodal terminals $j, k=1, \ldots J$

$q$     $q$ index of capacity level of multimodal terminals $q=1, \ldots Q$

$t$      index of yearly time periods $t=1, \ldots T$

Parameters:

$D_m^t$    demand of consignee center $m$ at time period $t$

$\alpha_j^q$    capacity of multimodal terminal $j$ with level $q$

$\beta_{ij}$    maximum capacity of candidate rail link from cement factory $i$ to multimodal terminal $j$

$\eta_{jm}$    maximum capacity of candidate rail link from multimodal terminal $j$ to consignee center $m$

$\delta_{jk}$    maximum capacity of rail link from first multimodal terminal $j$ to second multimodal terminal $k$

$\rho_i^t$    maximum capacity of factory $i$ at time period $t$

$r_{im}^t$    Direct road transportation cost per tonne from cement factory $i$ to consignee center $m$ at time period $t$

$s_{ij}^t$    road transportation cost per tonne from cement factory $i$ to multimodal terminal $j$ at time period $t$

$e_{jm}^t$    road transportation cost per tonne from multimodal terminal $j$ to consignee center $m$ at time period $t$

$\rho_{im}^t$    rail transportation cost per tonne from cement factory $i$ to multimodal terminal $j$ at time period $t$

$\sigma_{jm}^t$    rail transportation cost per tonne from multimodal terminal $j$ to consignee center $m$ at time period $t$

$\tau_{jk}^t$    rail transportation cost per tonne from multimodal terminal $j$ to multimodal terminal $k$ at time period $t$

$\upsilon_{im}^t$    rail transportation cost per tonne from cement factory $i$ to consignee center $m$ at time period $t$

$\varphi_{jq}^t$    handling operational costs per tonne at the multimodal terminal $j$ with capacity level $q$ at time period $t$

$f_{jq}^t$    fixed cost of opening candidate terminal $j$ with capacity level $q$ at time period $t$

$g_i^t$    fixed cost required to connect factory $i$ to the rail network at time period $t$

$h_{jm}^t$    fixed cost of rail link construction from multimodal terminal $j$ to consignee center $m$ at time period $t$

$AB^t$   Annual budget at time period $t$

$IC$    Initial capital

$A_t$    The amount of loan received at the time period $t$

$cb_{tt'}$   The repayment rate of the loan received in the time period $t'$ which is paid in the time period $t$

$R$     Interest rate of loan received

$N$    Number of loan repayment periods

$er_{im}$   environmental burden of long haul road transportation per tonne from cement factory $i$ to consignee center $m$ at time period $t$

$es_{ij}$   environmental burden of road transportation per tonne from cement factory $i$ to multimodal terminal $j$ at time period $t$

$ee_{jm}$   environmental burden of road transportation per tonne from multimodal terminal $j$ to consignee center $m$ at time period $t$

$e\rho_{im}$   environmental burden of rail transportation per tonne from cement factory $i$ to multimodal terminal $j$ at time period $t$

$e\sigma_{jm}$   environmental burden of rail transportation per tonne from multimodal terminal $j$ to consignee center $m$ at time period $t$

$e\tau_{jk}$   environmental burden of rail transportation per tonne from multimodal terminal $j$ to multimodal terminal $k$ at time period $t$

$e\upsilon_{im}$   environmental burden of rail transportation per tonne from cement factory $i$ to consignee center $m$ at time period $t$

Variables:

$u_{im}^t$     The amount of cement shipped directly from the factory $i$ to consignee center $m$, using the road transportation mode, at time period $t$

$V_{ijkm}^t$     Load flow originated at factory $i$ and destined to consignee center $m$, uses the railway hub link from hub $j$ to hub $k$ with road-rail-road transportation mode, at time period $t$

$p_{ijm}^t$     Load flow originated at factory $i$ and destined to consignee center $m$, uses the hub $j$ for transshipment from rail to road, at time period $t$

$q_{ijm}^t$     Load flow originated at factory $i$ and destined to consignee center $m$, uses the hub $j$ for transshipment from road to rail, at time period $t$

$\gamma_{ijm}^{lt}$     Load flow originated at factory $i$ and destined to consignee center $m$, uses the rail transportation mode (factory $i$ and consignee center $m$ are connected to the hub $j$ by railway), at time period $t$

$A_t$     The amount of loan received at the time period $t$

$x_{jq}^t = \begin{cases} 1 \\ 0 \end{cases}$ if a hub is established at node $j$ with capacity level $q$ at time period $t$ otherwise

$y_i^t = \begin{cases} 1 \\ 0 \end{cases}$ if a railway link is established to connect factory $i$ to the rail network at time period $t$ otherwise

$z_{jm}^t = \begin{cases} 1 \\ 0 \end{cases}$ if a railway link is established from multimodal hub $j$ to consignee center $m$ at time period $t$ otherwise

$w_{im}^t = \begin{cases} 1 \\ 0 \end{cases}$ if a railway path is established from factory $i$ to consignee center $m$ at time period otherwise

## Objective functions

As mentioned in the "Introduction" section, two important and conflicting objective functions are considered in the formulation of GMLND problem:

Objective 1: *Minimize the overall transportation cost throughout the multimodal transportation network*

The first objective is to minimize the total transportation cost of the overall multimodal transportation network which consists of following sections:

Fixed cost of opening candidate terminal and construction of rail links

- Total transportation costs of direct road transportation
- Total transportation costs of rail-road multimodal transportation
- Total transshipment costs between road and rail (operation cost)

$$\text{Min Cost } W_1 = \sum_t (TR\text{Cost} + OPR\text{Cost} + FSC\text{Cost})$$

$$FS\text{Cost(Fixed Setup costs)} = \sum_t \sum_q \sum_j f_{jq}^t x_{jq}^t + \sum_t \sum_i g_i^t y_i^t + \sum_t \sum_j \sum_m h_{jm}^t z_{jm}^t$$

$$OPR\text{Cost(material handling and transshipment costs)} = \sum_t \sum_i \sum_q \sum_j \sum_m \varphi_{jq}^t \left(q_{ijm}^t + p_{ijm}^t\right) + \sum_t \sum_i \sum_q \sum_j \sum_k \sum_m \left(\varphi_{jq}^t + \varphi_{kq}^t\right) V_{ijkm}^t$$

$$TR\text{Cost(Transportation costs)} = \sum_t \sum_i \sum_m r_{im}^t u_{im}^t + \sum_t \sum_i \sum_j \sum_m \left(\rho_{ij}^t + e_{jm}^t\right) p_{ijm}^t + \sum_t \sum_i \sum_j \sum_m \left(s_{ij}^t + \sigma_{jm}^t\right) q_{ijm}^t + \sum_t \sum_i \sum_j \sum_k \sum_m \left(s_{ij}^t + \tau_{jk}^t + e_{km}^t\right) v_{ijkm}^t + \sum_t \sum_i \sum_j \sum_m \upsilon_{im}^t w_{ijm}^t$$

(1)

*Notably, the transportation costs between facilities are calculated by multiplying the transportation cost of one unit of load flow per unit of distance (i.e., one kilometer) by the corresponding shipping distance.*

Objective 2: *Minimize the overall transportation emission burdens throughout the multimodal transportation network*

The second objective is to minimize the total transportation emission of the overall multimodal transportation network which consists of following sections:

Min *Env* impact $W_2$

$$= \sum_t (\text{Transportation Environmental Burden})$$

$$= \sum_t \sum_i \sum_m er_{im}^t u_{im}^t + \sum_t \sum_i \sum_j \sum_m \left( e\rho_{ij}^t + ee_{jm}^t \right) p_{ijm}^t$$

$$+ \sum_t \sum_i \sum_j \sum_m \left( es_{ij}^t + e\sigma_{jm}^t \right) q_{ijm}^t$$

$$+ \sum_t \sum_i \sum_j \sum_k \sum_m \left( es_{ij}^t + e\tau_{jk}^t + ee_{km}^t \right) v_{ijkm}^t$$

$$+ \sum_t \sum_i \sum_j \sum_m ev_{im}^t w_{ijm}^t \qquad (2)$$

## Constraints

**Demand satisfaction constraints** Constraints (3) ensure that the demands of all consignee centers are satisfied:

$$D_m^t = \sum_i u_{im}^t + \sum_i \sum_j \sum_k V_{ijkm}^t + \sum_i \sum_j p_{ijm}^t + \sum_i \sum_j q_{ijm}^t$$

$$+ \sum_i \sum_j w_{ijm}^t, \qquad \forall m, t \qquad (3)$$

**Capacity constraints** All relevant capacity constraints are summarized as follows.

$$v_{ijkm}^t \le \sum_q \alpha_j^q x_{jq}^t, \qquad \forall i, j, k, m, t \qquad (4)$$

$$v_{ijkm}^t \le \sum_q \alpha_k^q x_{kq}^t, \qquad \forall i, j, k, m \qquad (5)$$

$$p_{ijm}^t \le \sum_q \alpha_j^q x_{jq}^t, \qquad \forall i, j, m, t \qquad (6)$$

$$q_{ijm}^t \le \sum_q \alpha_k^q x_{jq}^t, \qquad \forall i, j, m, t \qquad (7)$$

$$\sum_i \sum_k \sum_m \left( v_{ijkm}^t + p_{ijm}^t + q_{ijm}^t \right) \le \sum_q \alpha_j^q x_{jq}^t, \qquad \forall j, t \qquad (8)$$

$$\sum_i \sum_j \sum_m \left( v_{ijkm}^t + p_{ikm}^t + q_{ikm}^t \right) \le \sum_q \alpha_k^q x_{kq}^t, \qquad \forall k, t \qquad (9)$$

$$p_{ijm}^t \le \beta_{ij} y_i^t, \qquad \forall i, j, m, t \qquad (10)$$

$$q_{ijm}^t \le \eta_{jm} z_{jm}^t, \qquad \forall i, j, m, t \qquad (11)$$

$$v_{ijkm}^t \le \delta_{jk}, \qquad \forall i, j, k, m, t \qquad (12)$$

$$\gamma_{ijm}^t \le \beta_{ij} y_i^t, \qquad \forall i, j, m, t \qquad (13)$$

$$\gamma_{ijm}^t \le \eta_{jm} z_{jm}^t, \qquad \forall i, j, m, t \qquad (14)$$

$$\sum_m \left( p_{ijm}^t + \gamma_{ijm}^t \right) \le \beta_{ij} y_i^t, \qquad \forall i, j, t \qquad (15)$$

$$\sum_i \left( q_{ijm}^t + \gamma_{ijm}^t \right) \le \eta_{jm} z_{jm}^t, \qquad \forall j, m, t \qquad (16)$$

$$\sum_i \sum_m v_{ijkm}^t \le \delta_{jk}, \qquad \forall j, k, t \qquad (17)$$

$$\sum_m u_{im}^t + \sum_j \sum_m \left( p_{ijm}^t + q_{ijm}^t \right) + \sum_m \sum_k \sum_j v_{ijkm}^t$$

$$+ \sum_m \sum_j \gamma_{ijm}^t \le \rho_i, \qquad \forall i, t \qquad (18)$$

Constraints (4) to (18) are capacity constraints on multi-modal transportation hub, railway links, and cement factories respectively.

**Relationship between binary decision variables constraints** The following constraints assure that at any time period, the construction of railways occurs on condition that the multi-modal transportation hubs were built in the previous time periods and already established:

$$z_{jm}^t \le \sum_q \sum_{t'=1}^t x_{jq}^{t'}, \forall j, m, t \qquad (19)$$

Constraints (20) and (21) assure that in the case of connection of factories and consignee centers to the rail network, the load flow can be carried directly through the rail transportation system.

$$\sum_{t'=1}^t y_i^{t'} + \sum_{t'=1}^t z_{jm}^{t'} \ge 2\omega_{im}^t, \forall i, j, m, t \qquad (20)$$

$$\sum_{t'=1}^t y_i^{t'} + \sum_{t'=1}^t z_{jm}^{t'} \le \omega_{im}^t + 1, \forall i, j, m, t \qquad (21)$$

**Construction of facilities in the planning horizon constraints** Constraints (22)–(24) ensure that a potential node of establishing a multimodal transportation terminal can be opened at most once over all expansion periods.

$$\sum_q \sum_t x_{jq}^t \le 1, \qquad \forall j \qquad (22)$$

$$\sum_t y_i^t \le 1, \qquad \forall i, j \qquad (23)$$

$$\sum_t z_{jm}^t \le 1, \qquad \forall j, m \qquad (24)$$

**Financing constraints** Constraints (25) and (26) are considered for financing the necessary funds for the construction and expansion of a multimodal transportation network facilities.

$$IC + AB_t + A_t \geq \sum_q \sum_j f_{jq}^t x_{jq}^t + \sum_j \sum_i g_i^t y_i^t + \sum_m \sum_j h_{jm}^t z_{jm}^t, \quad t$$

$$= 1 \tag{25}$$

$$AB_t + A_t \geq \sum_q \sum_j f_{jq}^t x_{jq}^t + \sum_j \sum_i g_{ij}^t y_i^t + \sum_m \sum_j h_{jm}^t z_{jm}^t$$

$$+ \sum_{t' < t} \sum_t cb_{tt'} A_{t'} (1 + R), \quad \forall t \backslash t$$

$$= 1 \tag{26}$$

$$A_t = 0, \quad \forall t > |T| - N \tag{27}$$

Constraint (27) refers to the need for a full repayment of loans at the end of the horizon. According to this constraint, if the loan repayment period is equal to $N$, then in periods after N- | T | Unable to get a loan. Because it will not be fully refundable.

**Decision variables constraints** The following constraints are related to the binary and non-negativity decision variables:

$$x_{jq}^t, y_{ij}^t, z_{jm}^t \in \{0, 1\} \quad \forall i, j, m, q, t \tag{28}$$

$$u_{ij}^t, v_{ijkm}^t, p_{ijm}^t, q_{ijm}^t, \gamma_{ijm}^t, A_t \geq 0 \tag{29}$$

## Solution methodology

To solve multi-objective problems, several methods have been proposed in the relevant literature. In this study, the developed bi-objective mixed integer linear programming problem solved with the augmented ε-constraint method proposed by Mavrotas and Florios (2013). The ε-constraint method is able to produce a significant number of non-extreme efficient solutions that are useful for decision-maker (Mavrotas, 2009). This method is able to provide an approximation of the Pareto set and prevents the generation of weakly efficient generated in standard ε-constraint technique. After calculation of the best value and the worst value of cost objective function ($W_1$ in Eq. 1) and the environmental emission objective function ($W_2$ in Eq. 2) respectively, the augmented ε-constraint method is used as follows.

$$\text{Min } W_1 - \mu x_s \tag{30}$$

Subject to :
$$W_2 + x_s = W_2^{UP} - \epsilon \tag{31}$$

Eqs.(3)–(29)

A new slack variable ($x_s$) is added to the second objective function and it is set to the upper bound of this objective

function for each ε value in Eq. Therefore, a new $W_1$ value is obtained. Modifications in the optimization model are as follows.

## Case study

In this section, to demonstrate the validity and practicality of the proposed model, the developed GDLND model is implemented for the studied case, i.e., the rail-road multimodal logistics of cement in Iran, and the corresponding numerical results are evaluated and analyzed. As illustrated in the "Problem definition" section, the concerned transportation network includes three stages. The first stage is dedicated to cement factories. In this stage, the 7 cement manufacturers in Iran have been investigated. The location of cement factories is constant and their annual production capacity is clear. None of the 7 cement factories is connected to the rail network. At the second stage, 10 candidate railway stations are considered for establishing rail-road multimodal transportation terminals with three available capacity levels for transshipment operations. At the third stage of the multimodal transportation network, 8 consignee centers with specific annual demand have been investigated. Six of the 8 consignee centers are connected to the rail network. Cement factories (origins) and consignee centers (destinations) are at least 200 km apart and their corresponding demand values are more than 100 tonne per year. These conditions are required to make shipments eligible for multimodal transportation option (Fotuhi and Huynh 2018). On the other hand, for the access of cement factories and consignee centers to the railway network, potential railways with determined annual capacity are specified. It should be noted that currently, potential stations, which are candidates for establishing of rail-road multimodal transportation terminals, are connected through the railway network and these railway links have a limited annual transportation capacity.

As mentioned before, we considered a limited budget available for each period to the expanding existing railway links and development of potential railway stations to the rail-road multimodal transportation terminals. A 10-year planning horizon including 10 periods is considered. The loan repayment period and its repayment rate considered 4 years and 15%, respectively. Figure 2 illustrates the real network. Also, with regard to the consensus sessions of relevant experts and managers, in each period due to limited available budget, there is a possibility to get a loan with certain repayment rate. According to DMs' opinion, values of initial capital, annual budget available, and rate and repayment period of loans received during each period have been determined. Notably, CPLEX 12.6 optimization software is used to implement the model and all the empirical experiments are performed on a desktop computer. Also, SimaPro 8.2.3.0 software which uses

Fig. 2 The illustration of concerned network facilities
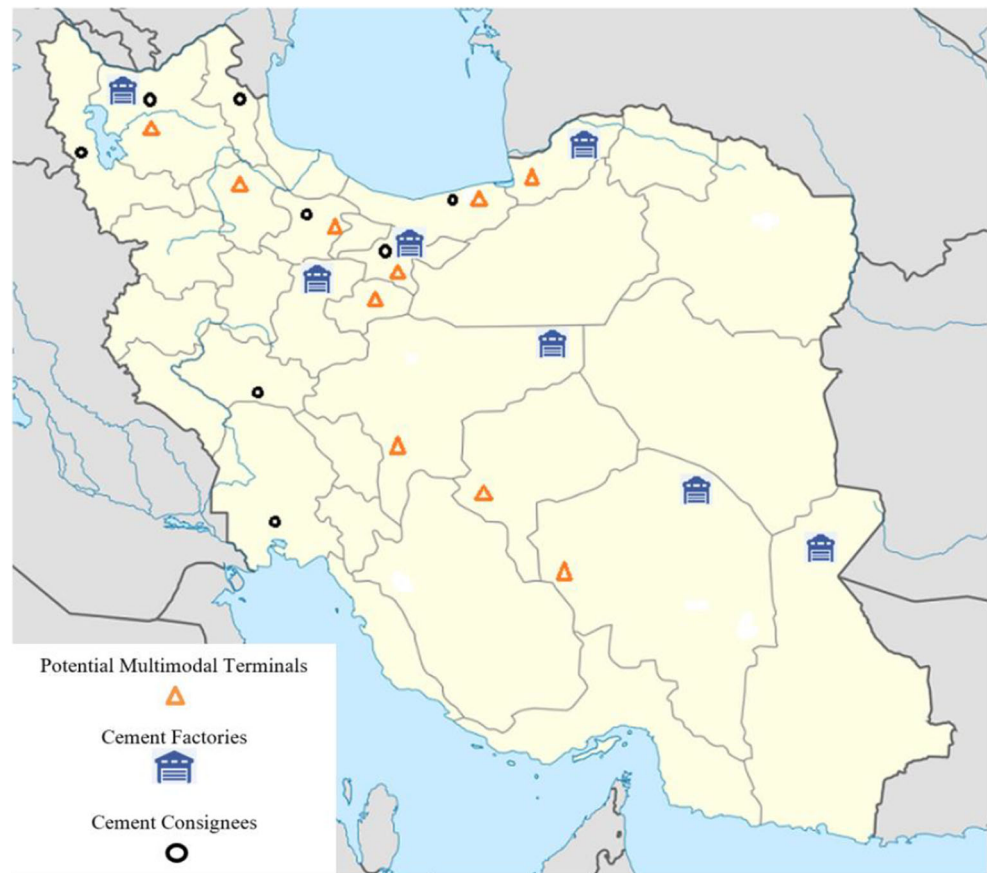


the latest version of ecoinvent database is used to calculate the environmental impact of different inventories via ReCiPe method.

## Results

In this section, the proposed model is applied to the studied cement logistics network and relevant results are reported and analyzed.

### Impact of dynamic modeling on the network structure

To investigate the impact of utilizing multiple expansion time periods to make network expansion decisions including freight transportation network topology, total transportation cost and rail-road multimodal terminal's capacity utilization, a comparison is made against the single-period case which involves only one expansion period. The single-period problem is solved considering average demand and smallest shipping cost which corresponds to the first period of the original problem. The budget for the single-period problem is the sum of the budget of all expansion periods of the original problem.

As depicted in Fig. 3, the optimal solution for single-period model involves opening candidate terminals in 5 potential locations: Tabriz with second capacity level, Esfahan, Qom, Kerman, and Ardakan with first capacity level. In this case, no budget is spent to construction of new rail links between candidate multimodal rail-road terminals and cement factories or cement consignee centers. However, the dynamic framework with ten expansion periods has a different optimal design. It opens six new multimodal rail-road terminals during the planning horizon. Tabriz with second capacity level and Kerman with first capacity level opened in the first time period. Esfahan and Qom with first capacity level opened in the second time period. Ardakan and Gorgan with first capacity level opened in the third time period. Similar to the single-period design, no budget is spent to construction any railway link in the considered network. These results show that a remarkable portion of the budget is spent on development of potential railway stations and deployment of multimodal rail-road terminals rather than building new railway links.

### Impact of dynamic planning on capacity utilization

As mentioned, a significant portion of the budget is dedicated to the development of multimodal rail-road terminals at 5 selected railway stations in the beginning of the 1-year

**Fig. 3** a, b Optimal network
representations of the case study



a)    Dynamic model



b)    Single–period model

planning horizon for the single-period problem. However, the
development of 6 multimodal rail-road terminals in the multi-
period problem is gradually taking place. Therefore, in the

dynamic model, average capacity utilization of all open mul-
timodal terminals improves. These results are reasonable be-
cause the multi-period model adapts to changes in the

different consignees demand over the 10-year planning horizon. That way the extra capacity required for transshipment of freight in multimodal terminals is provided at the appropriate period and the most convenient infrastructure. In average, the yearly utilization is increased by 11%. A yearly 11% increase can generate a huge revenue for the whole planning horizon. Consider a multimodal rail-road terminal with a capacity of handling 1,140,000 tonnes yearly. An 11% increase means handling 125,400 more tonnes in a year and 1,254,000 more tonnes for the whole planning horizon. If handling of one tonne cement between two modes of road and rail transportation can produce 221,000 Rials revenue for the service provider, the total opportunity revenue for the company is about 28 billion Rials. Note that the case study is only considering 7 cement factories and 8 cement consignees. Hence, the overall capacity usage of the multimodal rail-road terminals is low. This will significantly increase by considering all possible cement factories and consignees in the whole Iran. Since there is also a possibility of getting a loan in a number of time periods, it should be noted that in the second period, the loan was received as much as the annual budget.

### Results of the bi-objective model

This section aims at presenting the results of the bi-objective model. Solving the bi-objective linear problem with ε-constraint method generates the Pareto front that is shown in Fig. 4. The relative optimal costs-emissions pairs for 8 solutions varying from the minimum transportation cost scenario to the minimum transportation environmental burden scenario are presented. The Pareto front shows that more costs must be borne for the use of environmentally friendly transport methods. As Fig. 4 shows, by reducing 0.01 kg of environmental impacts of the freight transportation process, the total
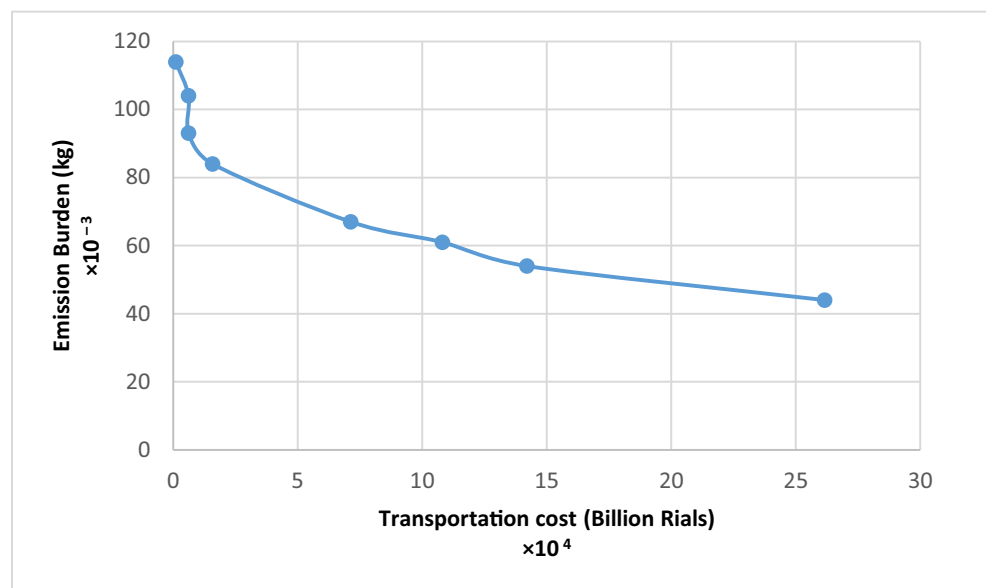
cost of multimodal transportation network design 40% increases.

Table 1 provides the optimal objective values and the flow distribution values under the two extreme points of the Pareto curve. In the cost minimization case, 37% of flow distribution between cement factories and cement consignee centers is allocated to multimodal rail-road transportation.

On the other hand, this freight flow carries the route between the cement factories and the multimodal terminals by road and from the multimodal terminals to the consignee centers, is shipped by railway. The reason for this result is that currently in the network investigated in this study, 6 of the 8 cement consignee centers are connected to the railway network and the developed model decides to connect the other two centers. As Fig. 5 shows, in this case (h), no other two centers were connected to the rail network. The reason for this is obvious. Since the construction of rail between these centers and the rail network is very high, cement rail transport is only between terminals and centers connected to the rail network.

On the contrary, in the environmental impact minimization case, 63% of flow distribution between cement factories and cement consignee centers is allocated to multimodal rail-road transportation. The interesting result is that in this case (a), 4 of the 7 cement factories are connected to the railway network (Fig. 5) and the topology of the multimodal transportation network is changed from the cost minimization case. Therefore, decision-making preferences in choosing economic and environmental considerations affect the topology of the multimodal transportation network rather than changing the number of multimodal terminals built in the transportation network. In the environmental impact minimization case, the reason for the increase in total cost of multimodal transportation network is not due to the construction of more multimodal rail-road transportation terminals and this increase in total cost

**Fig. 4** Pareto front for the bi-objective model

**Table 1** Results of the optimal costs and emissions minimization cases

| | Cost objective (billion Rials) | Emission objective (kg) | Direct road transportation (%) | Multimodal transportation (%) |
|---|---|---|---|---|
| Cost | 1029 | 0.113 | 63 | 37 |
| Emission | 0.044 | 261551 | 32 | 68 |

will be justified due to the change in the transport network topology. By moving from environmental impacts minimization case (a) to total costs minimization case (h), fewer factories are connected to the railway network and road transportation has been used to freight flow transportation between factories and multimodal terminals.

## Conclusions

This paper developed a mixed integer model that addresses the multimodal freight logistics network that integrates with expansion of railway network using a multi-period planning approach. The model incorporated financing for design and expansion decisions. Due to budget limitation, considering financing has improved realistic decision-making. Based on results of the developed mathematical model, it can be concluded that if environmental considerations of freight transportation process are important for decision-maker, the

topology of multimodal rail-road transportation network will be such that many of the cement factories investigated examined in this study are connected to the railway network. On the other hand, if minimizing the total cost has a higher priority for the decision-maker, only consignee centers—that currently connected to the railway network—use multimodal rail-road transportation. In this case, road transportation mode is used to transport cement between multimodal terminals to cement consignee centers or between cement factories to multimodal terminals. The results showed that the multi-period planning approach could significantly improve capacity utilization of multimodal terminals compared to the traditional single period planning approach.

Additionally, many extensions on the presented work could be aimed for future researches. Considering uncertainties in the problem parameters is one of the important areas that can help to make the problem more realistic. In future studies, if the scope of the study extends to international shipping, it will be necessary to consider other modes of
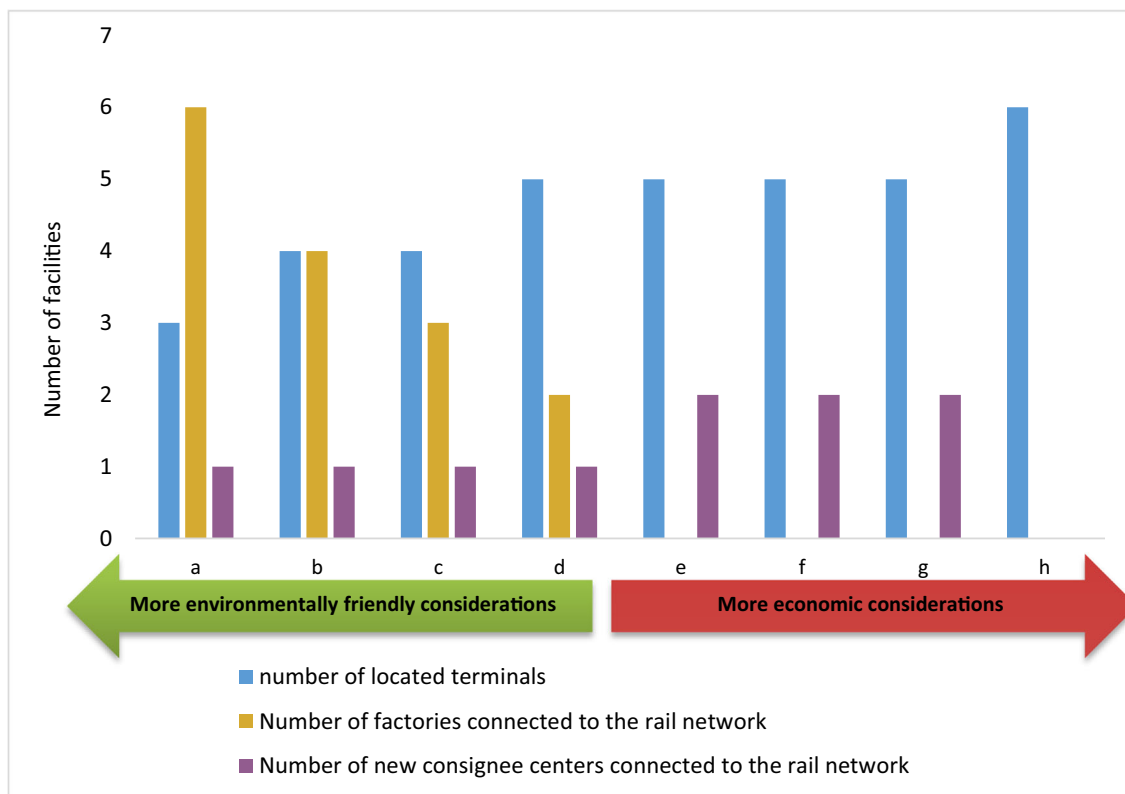


**Fig. 5** Number of facilities in the multimodal transportation network

transportation. Other applications of the model can also be developed, such as the analysis of new policy to increase the use of environmentally friendly transportation modes. The developed mathematical model is complex. Therefore, providing efficient solution methods and algorithms can be very effective in solving large-scale problems.

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**Data availability** The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

## Declarations

**Human and animal rights** This article does not contain any studies with human participants or animals performed by any of the authors.

**Ethics approval and consent to participate** Not applicable.

**Consent for publication** Not applicable.

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