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Research Article

A green bi-objective model for facility location in linear construction projects considering mobile and immobile facilities

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Abstract

Facility location in linear construction projects plays a vital role in optimizing operational efficiency. In real-world conditions, both mobile and immobile concrete batching facilities are typically used to construct viaducts, bridges, and tunnels along a planned route over a specified planning horizon. This study aims to propose a bi-objective model for the green locating of facilities in linear construction projects, considering both mobile and immobile batching. All types of facilities have a given capacity, operational cost, and CO2 emissions. Two objective functions are considered for simultaneous optimization: total expected cost and total CO2 emissions. The performance of the proposed model is confirmed using the data of a real case in linear construction projects in Iran. Moreover, sensitivity analysis represents the effect of variations in four key parameters on two objective functions and the final values of decision variables. The result confirms the accuracy and efficiency of the proposed model and represents the conflict between the two objective functions. In addition, the result indicates that the solution approach could provide proper alternatives for managers in various conditions. The findings underline the importance of green practices in facility management within linear construction, ultimately contributing to the broader discourse on eco-friendly infrastructure development.

Keywords:
Bi-objective;
CO2 emissions;
Facility location;
Linear construction projects

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1. Introduction

Designing a distribution network in the supply chain includes strategic, tactical, and operational decisions. This problem comprises three parts: facility location and allocation, warehouse and distribution management, and finally, vehicle routing (Soltani et al., 2021). The research in the supply chain has increasingly focused on the issues of facility location considering environmental aspects. The reason for this is the pressure exerted by governments and non-governmental organizations that use mechanisms to guide companies in a way that considers environmental and social issues in addition to economic issues.

The main purpose of facility location is to decide how to choose a few points from a certain set of potential supply points and also how to allocate demand points to these facilities (ZahediAnaraki & Esmaeilian, 2021). Locating and allocating centers is an important issue in logistics management, which is a part of the supply chain process that plans the effective implementation and control of the flow of circulation and storage of goods, services and information related to them from the origin to the destination to meet the customer's needs in a favorable way (Güden & Süral, 2014).

Among the various manufacturing and service industries, the construction industry is known as a basic industry in the world. According to Linker's report, the construction industry market will reach 8 trillion dollars in the world by 2030, and China, America, and India will hold the main part of this market. Asia has the largest share of the world's manufacturing industry because the giant markets of India, Japan, and China are located here. In the case of the Middle East, the growth rate was limited to 2% from 2014 to 2018, but it is predicted to reach 5.5% every year until 2025 (ReportLinker.com, accessed in March 2024). Meanwhile, Linear construction projects (e.g., highways, pipelines, railways) face unique logistical challenges due to their elongated, dynamic workspaces. Optimizing facility locations along these corridors is critical for minimizing costs, environmental impacts, and operational delays. This article develops a novel green bi-objective optimization model that addresses the complex interplay between mobile facilities (e.g., cranes, movable batch plants) and immobile facilities (e.g., warehouses, fixed plants) in such projects. The imperative for sustainable development in the construction industry has prompted an evaluation of various operational aspects, including the location of workshops. The concept of "green locating" refers to the selection of site locations for workshops that minimize environmental impact while maximizing operational efficiency (Heidari et al., 2023). This approach entails considering factors such as proximity to materials, accessibility for labor, and the implications of transportation emissions. Furthermore, a green location promotes the use of renewable resources and underscores the importance of reducing waste through efficient logistics (Rajabian et al., 2024). As the construction sector accounts for a significant portion of global carbon emissions, integrating environmentally conscious practices into workshop location decisions is pivotal. The basic role of the construction industry in any society highlights the importance of adopting green locating strategies in construction projects, thereby creating a more sustainable future for the industry. In the construction industry, the location of the facilities is determined at the beginning of the project because changing the layout of the site will be very expensive. Afterwards, placement of facilities in construction projects is done in the "Jobsite mobilization" process (Yilmas et al., 2023). The mobilization of the jobsite is: "operations, actions, and preparations that must be done temporarily for the implementation period to enable starting and carrying out the operations subject to the contract, according to the documents and documents of the contract". From the point of view of jobsite mobilization, two types of topology can be considered for construction industry projects, including: jobsite mobilization in linear projects and Jobsite mobilization in area-based projects (Golpira, 2020). Linear construction projects are generally created according to construction plans in which product parts are placed one after the other and provide the desired result of the customer in the form of a connected line (see Fig. 1). Among the most important examples of linear projects, we can mention the following: railway construction programs, execution of optical fiber lines, intercity highways, power transmission lines and energy carrier transmission pipelines.

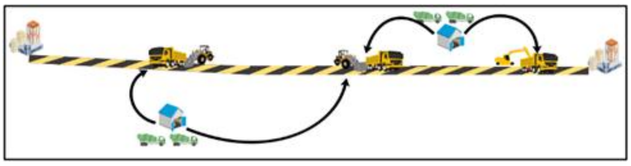

Fig. 1. Jobsite location in a linear construction project

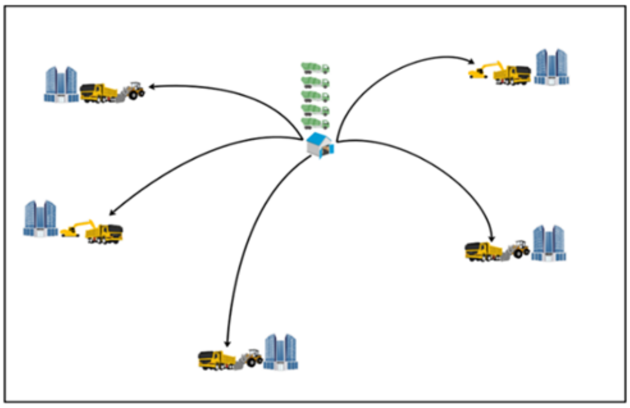

Fig. 2. Jobsite location in an area-based construction project

Due to the lack of dimensional fit in linear projects, all the issues raised in this type of project take a special form because the existing facilities only support a certain range of product manufacturing activities. In these circumstances, the location of the facilities that are responsible for supporting the jobsite is of double importance (Güden & Süral, 2014). This sensitivity is precisely related to the fact that the facilities are not integrated into a linear project. On the other hand, in jobsites where executive operations are carried out on several fronts nearby (such as a dam construction Jobsite, residential settlements, power plants, and factory construction), the jobsite is mobilized in one area (see Fig. 2). The issues of mobilizing area-based jobsites are generally known as "site layout design".

Both in linear and area-based structure of construction projects, in case of inappropriate facility allocation, with the passage of time and the distance between the work faces, the costs related to the logistics of materials and machinery increase dramatically. Therefore, establishing a detailed plan that predicts the conditions of the project operation until completion will be of special importance. This model should be able to place the mobilization in a way that provides the best support for the executive operations throughout the project. Considering that the main goal of most construction projects is to make a profit, the most important goal in locating and allocating support mobilization is to reduce the cost of deploying and operating this mobilization during the project. Besides the operational cost, the increasing importance of environmental issues creates restrictions for contractors and even executives in the employer sector. Compliance with environmental requirements creates several restrictions for project implementation that may overshadow the contractor's profit. This issue is more effective in projects that are very long in terms of dimensions, so that these types of projects, which generally include the construction of various highways and railway lines, are affected by the project activities by passing through different environmental areas with different conditions. These two objectives (i.e., operational cost and environmental issues) should be investigated simultaneously to provide ideal results. Using the scientific approach, it is possible to consider the above two necessities in the form of a two-objective model that can provide both concerns to an acceptable extent. Given the above explanation, the current research aims to develop a two-stage optimization model for facility location allocation in a linear construction project to minimize the total expected costs as well as $CO2$ emissions. That is as realistic as possible and close to the operational conditions of a linear construction project (Khural et al., 2024). In the problem at hand, providing the required concrete in different parts of the project is investigated, which can be supplied both through fixed batching and by using mobile batching. The pollution caused by the multiple relocations of these facilities is considered an environmental aspect. However, the amount of pollution caused by concrete production by fixed and mobile batching is also included in the model to have a more comprehensive approach to the pollution resulting from executive operations and its reduction. Therefore, the proposed model seeks to minimize the total pollution throughout the project as well as total expected costs. In summary, the model aims to integrate three concepts below:

- Facility Location Theory (FLT): Extends classical FLT to linear, dynamic contexts, accounting for spatial constraints and sequential task dependencies.
- Bi-Objective Optimization: Simultaneously minimizes economic costs (transportation and operation) and environmental impact (carbon emissions) using Pareto-efficient solutions.
- Sustainable Construction Principles: Embeds "green" criteria via lifecycle assessment (LCA) frameworks, aligning with circular economy goals.

The rest of the paper is outlined as follows. Section 2 provides a comprehensive literature review of this work and seeks to identify a research gap in the field of locating facilities in the linear project. Section 3 presents the problem definition and the proposed mathematical formulations of the problem. The solution approach is described in Section 4. Section 5 introduces the case study and explains how the data were collected and the classes determined. Section 6 discusses the results and implications of the findings, along with a sensitivity analysis. Finally, Section 7 presents the study's conclusions, limitations, and suggestions for future research.

2. Literature Review

Locating facilities within construction projects is a critical determinant of operational efficiency, cost management, and overall project success. Numerous studies have contributed to the understanding of facility location in the field of construction, addressing various methodologies and factors influencing these decisions.

One prominent approach emphasized in the literature is the application of optimization techniques. Daskin (1997) highlights the significance of location-allocation models in effectively determining the placement of facilities by considering demand distribution and transportation costs. These models employ mathematical algorithms to identify optimal solutions, thus minimizing operational costs while maximizing service delivery. Furthermore, recent advancements in computational methods, as illustrated by Galindo & Batta., (2013), have enhanced the complexity and applicability of these models, allowing for real-time data integration.

Facility location models in construction projects are receiving increasing attention in the field of academic research and manufacturing enterprises due to their great impact in reducing the total expected costs. Extensive research is still being conducted in all subjects and applications of various sciences around this axis.

Among construction industry projects, linear projects have special layout and location issues that generally bring them close to logistics issues, because some equipment must serve several small workshops along the way. Meanwhile, locating and allocating with demand dependent costs (Drezner and Zelewski, 1996) and locating and allocating capacity (Falcao et al., 2016) are two important topics investigated in the existing literature in the field of linear construction projects. For instance, we can refer to Liu et al. (2018) and Mansour et al. (2019), who investigated the facility location in the linear construction projects to minimize the total operational costs. Furthermore, Falcao et al. (2016) presented the applications of optimization techniques for facility location in earthworks and highway construction in a comprehensive literature review.

Another important aspect discussed in the literature is the impact of environmental and regulatory considerations on facility location. Chan et al. (2020) stress the importance of assessing ecological impacts and compliance with local building codes and zoning laws. The integration of sustainability into facility location decisions is increasingly becoming a focal point of research, given the global shift towards eco-friendly construction practices. This perspective aligns with the findings of Zhang et al. (2016), who advocate for the incorporation of life-cycle assessments to ensure that facility placements contribute positively to environmental outcomes. In this way, Yoo et

al. (2025) investigated the long-term impact of railway infrastructure on air pollution by examining Japan's railway network. They used some methods to identify a causal link between railway development and improved air quality. The result demonstrated that increased ridership and a shift towards railways followed these expansions.
Additionally, the role of technology in enhancing decision-making processes related to facility locations is gaining prominence. The use of Geographic Information Systems (GIS) and Building Information Modeling (BIM) has been explored by
demonstrating how these tools facilitate spatial analysis and enable stakeholders to visualize the implications of various location scenarios. Such technological innovations not only improve accuracy but also promote collaborative planning among project teams, thereby fostering a comprehensive understanding of logistical challenges.
The complexity inherent in facility location problems has led researchers and practitioners to adopt multi-objective optimization approaches, which facilitate the simultaneous consideration of multiple, often conflicting objectives. Multi-objective optimization (MOO) entails the simultaneous optimization of two or more objective functions that may conflict with one another. Common objectives in facility location problems include minimizing construction and operational costs, maximizing accessibility, and minimizing environmental impact. The literature demonstrates a robust evolution of methodologies used to address these multifaceted challenges. One prominent approach in the literature is the application of mathematical programming techniques. Linear programming (LP) and mixed-integer linear programming (MILP) are frequently employed to formulate location problems with multiple objectives. For instance, a study by Ghorbani et al. (2019) introduced a MILP model that optimizes facility locations by balancing cost and service level, demonstrating the effectiveness of traditional optimization methods in practical scenarios. Similarly, Hong Son and Soulisa (2023) proposed a Hybrid Ant Lion Optimizer (ALO) algorithm combining optimization techniques and heuristic methods for optimizing the Construction Site Layout problem. The proposed method provides very competitive results in terms of improved exploration, local optima avoidance, exploitation, and convergence compared to existing algorithms. Other researchers such as Wang et al. (2020) demonstrated the advantages of combining geographic information systems (GIS) with multi-objective optimization to optimize the locations of construction facilities based on accessibility and environmental aspects.
Given the existing literature, the core research streams and foundational concepts related to location in construction projects can be summarized as below:

- Facility Location Problems (FLPs) In this field, the classic models, including p-median, p-center, and uncapacitated/capacitated, are applied to optimize locations to minimize cost, distance, or maximize coverage (ReVelle & Eiselt, 2005). These models provide the fundamental mathematical framework for siting facilities incorporating mobility.
- Construction Site Layout Planning (SLP)In this area, researchers focus on locating temporary facilities (offices, warehouses, batch plants, laydown areas) within a construction site boundary to minimize travel time/cost, improve safety, and reduce congestion (Pham & Pham, 2025). Traditionally considers static (immobile) facilities. This concept directly addresses the "facility location in construction projects" aspect but often lacks explicit consideration of linearity, mobility, and formalized environmental objectives.
- Linear Construction Projects (LCPs)The linear construction projects refer to projects like roads, railways, pipelines, tunnels, where the "site" is a narrow, elongated corridor. In these projects, the work front progresses along the alignment. This spatial constraint fundamentally changes logistics (Almahameed & Bisharah, 2024). This concept distinguishes the problem from typical square/rectangular site layouts. Location decisions must account for dynamic work front movement along the line.
- Mobile Facilities & Relocatable FacilitieRelated efforts in this field highlight the concept that some facilities (e.g., batch plants, site offices, fuel depots) can be relocated during the project lifecycle to follow the progressing work front, reducing travel distances for resources/materials (Al Hawarneh et al., 2019).

The existing literature on facility location in construction projects reveals a multifaceted landscape where optimization models, environmental considerations, and operational costs converge via technological advancements and proper facilities management. However, the existing literature shows that no attempt has presented a multi-objective optimization model for facility location in linear projects considering immobile and mobile concrete production facilities, and there is an important research gap in this field. Moreover, CO2 emission caused by mobile batching, which is an important environmental concern, is considered as a new objective function to be minimized.

3. Problem Statement

In this part, the problem and its features are explained. afterwards, the notations of the problem are presented, and finally, the problem at hand is formulated in the form of a mixed integer programming model (MIP).
This study addresses a facility location problem in a linear road construction project, including the implementation of earthworks is infrastructure, construction of bridges and tunnels. In places where there is a need to build artificial structures, metal and concrete materials are needed, and in this study, the production of concrete and sending them to the demand points is considered. The demand for concrete is issued by sites that are located next to bridges or tunnels. This concrete is produced with batching that is intended for the project. These batchings can be used in two immobile and mobile forms. These facilities have limited production capacities, initial start-up costs, and periodic operating costs. In addition to the costs of supplying and transporting stone materials, cement, water, and concrete, there are also the costs of moving mobile batchings from one jobsite to another.
The first goal of the problem is to minimize the sum of all costs related to the supply of concrete. The reduction of concreting costs depends to a large extent on moving

mobile batchings to produce concrete in the closest location to the place of consumption.

Given the environmental concerns and the need for a special truck to move mobile batchings, the problem of pollution caused by the multiple movements of these facilities is considered as another objective function. Therefore, the proposed model seeks to minimize the pollution caused by moving batching machines in the project and reducing the traffic of these facilities in the project in addition to the total expected cost. However, the amount of pollution caused by concrete production by fixed and mobile batching is also included in the model in order to have a more comprehensive approach to the pollution resulting from executive operations and its reduction.

The assumptions of the considered problem and the complete notation for the proposed model are given below.

Assumptions:

- There are several demand points, including tunnels (viaducts) and bridges to receive concrete, and many of these points are in the critical path of the project schedule.
- After batching, concrete spoils for a certain period, according to the speed of the truck mixer, there is a limited time available to bring the concrete to the demand point.
- The total concrete demand of each jobsite is known.
- The concrete demand of each jobsite in each period is known. According to the schedule, each of the work faces must receive a certain amount of concrete in each period.
- The concrete production capacity of each batching is considered limited.
- In addition to the operational costs, the purchase of materials is also considered.
- There are no obstacles to the movement of mobile batching along the entire route that will make the movement time longer than the assumed time.
- The time of emptying and loading concrete at the loading and demand points is considered very low.
- There is a difference between terminating and closing a facility. A terminated facility cannot be reopened until the end of the period, but a facility can be closed and reopened several times in a period.
- It takes a week to unpack mobile batchings, move them to a new location, and assemble them.
- All mobile batchings are of the same type and therefore produce the same amount of pollution when moving.
- All immobile and mobile batchings produce the same amount of pollution during concrete production.

Indices:

i,j Indices of sites (jobsites); ($i, j = 1, 2, \dots, D$)
t Index of schedule periods (in terms of months); ($t = 1, 2, \dots, T$)

Parameters:

D_{it} The concrete demand of jobsite i in the period t
dD_{ij} Jobsite distance i to j.
CS Fixed cost of establishing a mobile facility.
CF Fixed cost of establishing an immobile facility.
TCS Fixed cost of moving a mobile facility (including costs of disassembly, moving to a new location, and reassembly).
ρ The percentage of the period length to relocate a mobile facility.
KS Concrete production capacity of mobile facilities in one period.
KF Concrete production capacity of immobile facilities in one period.
OC Fixed operating cost of the facilities during the schedule (including labor costs, loader rental, and maintenance)
α The maximum distance that a loaded mixer-truck can cover in two hours.
G_{ij} Total cost of input materials needed to produce one ton of concrete at i and transporting the concrete produced at i to j.
FCP Fixed cost of a facility when producing concrete.
RC Fixed cost of reopening the facility.
PbU Emissions released due to the movement of mobile batching in g/km.

V Variables:

S_{it} Binary variable taking value 1 if a mobile facility is opened at i in t, and 0 otherwise.
F_{it} Binary variable taking value 1 if an immobile facility is opened at i in t, and 0 otherwise.
SV_{it} Binary variable taking value 1 if a mobile facility is available at i in t, and 0 otherwise.
FV_{it} Binary variable taking value 1 if an immobile facility is available at i in t, and 0 otherwise.
SC_{it} Binary variable taking value 1 if an available mobile facility produces concrete at i in t, and 0 otherwise.
FC_{it} Binary variable taking value 1 if an available immobile facility produces concrete at i in t, and 0 otherwise.
SR_{it} Binary variable taking value 1 if a mobile facility is reopened at i in t, and 0 otherwise.
FR_{it} Binary variable taking value 1 if an immobile facility is reopened at i in t, and 0 otherwise.
SA_{it} Binary variable taking value 1 if an available mobile facility at i is abolished in t, and 0 otherwise.
FA_{it} Binary variable taking value 1 if an available immobile facility at i is abolished in t, and 0 otherwise.
SK_{ijt} Binary variable taking value 1 if an available mobile facility moves from i to j in t, and 0 otherwise.
r_{ij} Binary variable taking value 1 if the distance between sites i and j is equal to or less than α, and 0 otherwise.
SA_t The number of the abolished mobile facilities in t.
x_{ijt} The amount of concrete transported from i to j in t (tons).

Mathematical model

The proposed mathematical model is presented inspired by the Güden and Süral (2014), which focused on linear road construction projects involving both mobile and immobile concrete production facilities. The basic model is a single-objective MIP model that minimizes the total concrete supply cost subject to demand satisfaction, capacity, and relocation constraints. This model is developed into a bi-objective framework by incorporating environmental concerns, specifically, the pollution caused by relocating mobile batching plants and operating concrete production facilities. Additionally, some modifications are performed based on Dias et al. (2007).

$$Min\ Z_1 = \sum_{i\epsilon D}\sum_{t=1}(CS\ S_{it} + CF\ F_{it} + OC(SV_{it} + FV_{it})) + \sum_{i\epsilon D}\sum_{j\epsilon D. j\neq i}\sum_{t=1}^{T} TCS\ SK_{ijt} + \sum_{i\epsilon D}\sum_{j\epsilon D. j\neq i}\sum_{t=1}^{T} G_{ij}X_{ijt} + \sum_{i\epsilon D}\sum_{i=1}^{T} FPC(FC_{it} + SC_{it}) + \sum_{i\epsilon D}\sum_{i=1}^{T} RC(FR_{it} + SR_{it})$$

$$Min\ Z_2 = \sum_{i\epsilon D}\sum_{j\epsilon D. j\neq i}\sum_{t=1}^{T} PbU\ SK_{ijt}dD_{ij} \quad (2)$$

Subject to:

$$S_{i1} = SV_{i1} \quad \forall\ i\epsilon D \quad (3)$$

$$F_{i1} = FV_{i1} \quad \forall\ i\epsilon D \quad (4)$$

$$F_{it} + FV_{i.t-1} = FV_{i1} + FA_{it} \quad \forall\ i\epsilon D\ , t = 2, 3. \dots . T \quad (5)$$

$$\sum_{i\epsilon D} r_{ij}\ \ x_{ijt} \geq D_{jt} \quad \forall\ j\epsilon D\ , t = 2, 3. \dots . T \quad (6)$$

$$FV_{it} + SV_{i.t} \leq 1 \quad \forall\ i\epsilon D\ , t = 1, 2, 3. \dots . T \quad (7)$$

$$x_{ijt} \geq 0 \quad \forall\ i, j\epsilon D\ , t = 1, 2, 3. \dots . T \quad (8)$$

$$x_{ijt} \leq D_{jt}(FC_{it} + SC_{it}) \quad \forall\ i, j\epsilon D\ , t = 1, 2, 3. \dots . T \quad (9)$$

$$FC_{it} \leq FV_{it} \quad \forall\ i, j\epsilon D\ , t = 1, 2, 3. \dots . T \quad (10)$$

$$SC_{it} \leq SV_{it} \quad \forall\ i, j\epsilon D\ , t = 1, 2, 3. \dots . T \quad (11)$$

$$FV_{it} + FV_{i.t-1} + FC_{it} - FC_{i.t-1} \leq 2 + FR_{it} \quad \forall\ i\epsilon D\ , t = 2, 3. \dots . T \quad (12)$$

$$SV_{it} + SV_{i.t-1} + SC_{it} - SC_{i.t-1} \leq 2 + SR_{it} \quad \forall\ i\epsilon D\ , t = 2, 3. \dots . T \quad (13)$$

$$S_{it} + SV_{i.t-1} + \sum_{j\epsilon D} SK_{ijt.i\neq j} = SV_{it} + \sum_{j\epsilon D} SK_{ijt.i\neq j} + SA_{i.t} \quad \forall\ i\epsilon D\ , t = 2, 3. \dots . T \quad (14)$$

$$\sum_{j\epsilon D} x_{ijt} = KS\ SV_{it} + KF\ FV_{it} - \rho\ KS \sum_{j\epsilon D} SK_{ijt.i\neq j} \quad \forall\ i\epsilon D\ , t = 1, 2, 3. \dots . T \quad (15)$$

$$x_{ijt} \geq 0 \quad \forall i, j\epsilon D, t = 1.2\ \dots . T \quad (16)$$

$$S_{it}, F_{it}, SV_{it}, FV_{it}\epsilon\{0,1\} \quad \forall i, j\epsilon D, t = 1.2\ \dots . T \quad (17)$$

$$SA_{it}, FA_{it}\epsilon\{0,1\} \quad \forall i, j\epsilon D, t = 2.3. \dots . T \quad (18)$$

$$SK_{ijt}\epsilon\{0,1\} \quad \forall i, j\epsilon D | i \neq j, t = 1.2. \dots . T \quad (19)$$

Given (1) and (2), the first and second objective function minimizes the total expected cost and total CO_2 emissions, respectively. Constraint (3) ensures that the initialization status of mobile batching facilities at time period 1 matches the assignment decision. That is, a mobile batching facility is considered to be initially deployed at site i if and only if it is active there in the first period. This constraint supports the correct modeling of the initial setup of mobile resources. Constraint (4) links the installation decision of immobile batching facilities to their operation in the first period. It guarantees that if an immobile facility is installed at site i, it must be active from period 1, and vice versa. This constraint helps maintain consistency in representing fixed facilities throughout the planning horizon. So, constraints (3) and (4) determine whether there is a mobile facility at site i in period t or not. Similarly, Constraints set (5) indicate whether there is an immobile facility at site i in period t or not. Constraints set (6) enforce that demand points should be satisfied by only the facilities not farther than α distance units away. Constraints set (7) prevent more than one facilitation in a site in period t. The amount of concrete transported from i to j in t according to (8). Constraints set (9) force to have a facility at i in t if any demand is satisfied from i in t. Constraints (10) and (11) guarantee that if facility i produced concrete in period t, it must have been available. Constraints (12) and (13) enforce that mobile or immobile facilities, if they have been abolished before, must be reopened for concrete production. Constraints set (14) determine whether there is a mobile facility at i in t or not. According to (15) there must be a facility at i in t if there is any demand satisfied from i in t without exceeding the total available capacity.

It is worth mentioning that the capacity in the new location should be reduced in the moving period for a mobile facility. Constraints (16) to (19) represent restrictions of variables.

4. Solving approach

The problem at hand is a bi-objective optimization problem, and so, the proposed mathematical model is solved using the augmented $\varepsilon -$constraint method and run in GAMS. The CPLEX solver was used to find the exact Pareto front. The augmented $\varepsilon -$ constraint method, which is among the classical methods of solving multi-objective optimization problems, optimizes problems based on one of the objective functions using the remaining objective functions as constraints, varying their right-hand side (Vardan & Hosseini, 2024). As such, other objective functions are constrained by the allowable limits as constraints of the model. To generate more solutions, the limit would be modified one by one. The non-dominated solutions are selected accordingly from the initial solutions and the solutions generated by modifying the barriers. The generated optimal solutions proved to be efficient solutions of the multi-objective problem under certain conditions (Hasani & Hosseini, 2020).
The general form of the $\varepsilon -$ constraint method for a bi-objective optimization problem is as below:

$$Min\ f_1(x)$$

s.t

$$g(x) \le 0$$

$$f_2(x) \le \varepsilon_2$$

$$x \in X$$

Where g(x) represents all constraints of the main problem and ε_2 demonstrates the upper limit of the second objective function.
Although the classical ε-constraint method solves the bi objective optimization problem, the provided solutions are not efficient enough, and so, a new improved version of this method, the so-called augmented $\varepsilon -$constraint method (AUGMECON), was proposed in 2009 (Mavrotas, 2009). In the new approach, the non-equality constraints related to the objective functions that have been added as constraints to the model are converted into equality constraints by the deficit or surplus variables, and the problem is defined by improving the objective function or adding the weighted sum of these variables (Hasani & Hosseini, 2022). The main idea of this method is to present an improvement over the epsilon constraint method, which is suitable for dealing with multi-objective integer programming problems. This method has the ability to accurately produce the Pareto set by adjusting its parameters. In the augmented ε-constraint method, converting the constraints into equality by combining the missing or additional variables overcomes the inefficient solutions, and at the same time, these variables are used as the second term in the objective function and force the model to generate only effective solutions.

5. Case Study and Data

A real case study is presented and solved with the proposed mathematical model in this section. The considered case study is a 500-kilometer high-speed railway construction project from Tehran to Isfahan in Iran. The Tehran–Isfahan high-speed railway project was selected as the case study due to its strategic importance, large-scale construction activities, and diverse geographical conditions, which provide a comprehensive environment for testing the proposed model. This project, being one of the first high-speed railway developments in Iran, involves various engineering challenges such as mountainous terrain, long distances, and the need for efficient resource allocation. Furthermore, detailed and reliable project data were available through official reports and studies conducted by Rahsaz Tarh Engineering Company, making it a suitable and practical candidate for validating the model. Additionally, the diversity of construction elements and logistical requirements in this project make it a representative example of large-scale infrastructure projects in developing countries, thereby increasing the generalizability of the proposed model. Considering these aspects, the Tehran–Isfahan project serves as a practical ground for implementing and evaluating the proposed mathematical model, as described below. The path of this project is shown in figure (3) with a yellow line.

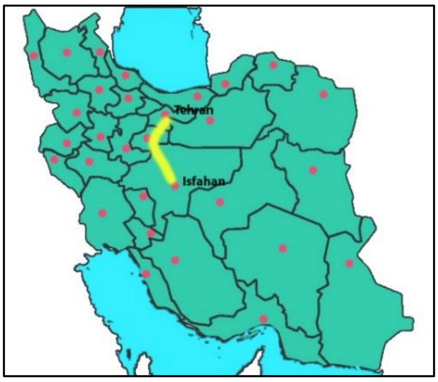

Fig. 3. The location of the considered case study on the map of Iran (RahsazTarh Eng. Co, comprehensive route study and design report for the Tehran-Isfahan high-speed railway.)

The construction activities of this project include the implementation of underground earthworks, the construction of bridges, and tunnels. Wherever there is a need to build artificial structures, metal and concrete materials are needed, and in this study, the production of concrete materials and sending them to the demand points is considered. Demand for concrete is issued by sites that are located next to bridges or tunnels. This concrete is covered with batching that is intended for the project. The batching can be used in two mobile and immobile forms. These facilities have limited production capacities, initial start-up costs, and periodic operating costs. Also, in addition to the costs of supplying and transporting stone materials, cement, water, and concrete, there are also the costs of moving mobile batching from one site to another. The first objective of the problem is to minimize the total expected costs related to concrete supply. In this way, the reduction of concreting costs depends to a large extent on moving mobile batchers to produce concrete in the closest location to the place of consumption. In addition, the pollution caused by the multiple relocation of these facilities is considered as the second objective function to address environmental concerns. The amount of pollution caused by concrete production by immobile and mobile batching is considered in the model in order to have a more comprehensive approach to the pollution resulting from executive operations and its reduction.

In this project, 75 positions with concrete demand have been identified, which are dotted in Figure (4). Since these structures are generally required in mountainous areas, the concentration of points along the route is not the same.

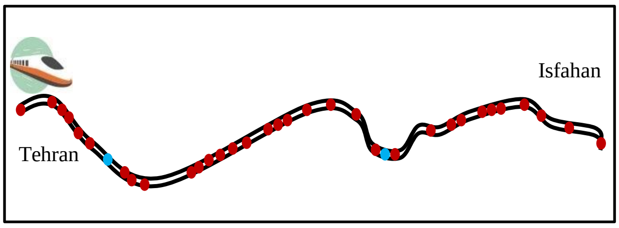

Fig. 4. Concrete demand situations during the project (RahsazTarh Eng. Co, comprehensive route study and design report for the Tehran-Isfahan high-speed railway.)

Table 1
Jobsite demand for concrete during the schedule

Demand Points	Monthly Periods																													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
1											130	160	230	250	270	330	390	470	511	630	720	120	40							
2																						40	280	550	2200	1200				
3						60	90	101	130	160	190	210	240	310	330	380	350	140	50											
4																						70	270	790	3100					
5																								86	850	1150	1180	520	330	120
6														40	70	140	220	290	340	462	561	707	800	450	130					
7						62	80	60	70	70	120	100	100																	
8																						60	290	1370	2560					
9														50	90	160	230	300	360	440	540	720	810	350	120					
10																							40	650	3400	210				
11												80	170	220	240	330	430	460	500	630	760	400	70							
12																						90	360	1690	1700	400				
13																							40	440	2300	1040	430			
14															30	70	120	190	260	400	560	800	730	590	330	140				
15	6	11	35	50	45	20	20	10	10																					
16											50	80	120	190	230	287	320	380	420	440	570	740	390	40						
17																								50	1490	1890	500	330		
18																						50	240	1290	2720					
19						30	70	90	120	150	190	200	230	290	330	230	130	20												
20																							60	450	1190	1590	1530	220	180	38
21																						70	320	1450	1690	400	220	120		
22													40	90	110	180	230	320	440	510	620	820	540	290						
23																							30	440	2210	1090	360	120	330	20
24								50	80	120	160	190	220	280	200	140	60													
25																							90	620	2370	1140	80			
26																							80	560	2090	1050	300	110	440	30
27																20	70	160	210	340	460	680	1210	800	320					
28													30	70	130	190	230	310	430	560	670	770	670	130						
29																						50	370	1260	2590					
30					60	80	100	120	80	60	60	40	30																	
31																							30	450	2790	1020				
32												50	90	120	130	170	230	280	350	420	530	650	610	380	90					
33																						40	380	120	1980	1190	340	200	340	

Demand Points	Monthly Periods																													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
34							20	60	90	130	140	180	210	240	290	180	90													
35																						50	200	1180	2800					
36																							30	490	2190	1060	1140	220	490	
37													50	70	110	170	230	350	420	570	670	820	490	200						
38																							40	390	2430	990	310	130	100	30
39																						70	279	1160	2570	210				
40												40	60	90	130	190	260	330	410	630	790	670	540	150						
41																							40	550	2290	400	300	1793		
42																50	80	130	190	300	390	590	850	760	650	230				
43																							30	430	2300	40	1490	1690		
44										40	70	90	130	160	190	260	300	350	420	590	680	570	250	90						
45																							40	580	2160	1090	300	1450		
46						50	80	90	110	150	170	220	200	170	130	220	310	390	220	50										
47																							40	530	1980	1220	330	130	40	30
48																40	70	120	190	270	390	530	840	1200	530	120				
49																								40	1690	1370	680	420	190	110
50										40	70	130	170	220	270	290	330	380	450	550	660	450	220	30						
51																							60	420	2150	1490	130	100	20	
52													28	68	142	170	210	280	350	480	590	770	780	310	120					
53																						40	290	890	3070					
54				62	70	80	90	80	70	50	30																			
55												84	110	160	210	240	280	350	420	570	470	800	450	90						
56																							30	550	2650	980	90			
57															60	90	150	210	310	420	540	730	940	660	130					
58																							40	570	3430	220				
59																30	100	130	170	220	340	660	960	1320	350					
60									70	90	100	120	150	190	270	290	350	420	510	200	50									
61																						20	70	400	2190	1300	220	90	10	
62																60	110	140	220	330	410	770	1080	850	290					
63									60	90	110	140	170	210	290	350	370	430	500	320	70									
64																							70	330	1890	1670	330			
65																						30	110	990	2450	500	210			
66																							30	560	2550	1100				
67					70	90	100	130	150	160	190	140	80																	
68																							50	630	2190	1420				
69															60	90	130	160	220	310	430	660	990	1200						
70																							40	570	2290	1150	210	40		
71																							60	560	2190	1020	410	40		
72						60	100	140	160	180	190	230	250	190	150	100	60													
73							40	60	80	80	90	140	180	230	270	300	360	390	240	60										
74																						90	230	1350	2620					
75														40	80	110	190	221	300	420	550	770	1070	490						

The duration of the project is 30 months. Therefore, each of these 75 demand points may require concrete for several months to carry out their executive operations. These values are extracted according to the schedule and are listed in Table 1. Taking into account the demand sites, which can be bridges, tunnels, or technical buildings for concrete, a number of mixer trucks carrying concrete are sent from the nearest batching to meet the needs of the site. For example, in Figure 5, at T=t1, the concrete demand of the bridge and two tunnel devices on the left side is supplied with fixed batching, and the tunnel and two bridge devices on the right side are supplied with mobile batching. After the completion of concrete pouring at any point of the track, the mixers return to their batching place and are ready for the next service. In the necessary period, according to the existing restrictions and the environmental issues (CO2 emission caused by the movement of equipment and concrete production), the moving of mobile batching is done. At T=t2, the mobile batching is moved to a new position. In this situation, the distance of the mobile batching to the left tunnel is closer than the immobile batching, and for this reason, in this period, the concrete required by this site is supplied by the mobile batching.

As a result, despite the fact that moving the mobile batching and opening and reinstalling it has associated costs, the total cost is reduced due to the reduction of the distance of transporting concrete with truck mixers to the new demand points. After selecting the demand point according to the distance, the delivery of concrete to the site with demand resumes. This process continues until the end of the 30 time periods of the project.

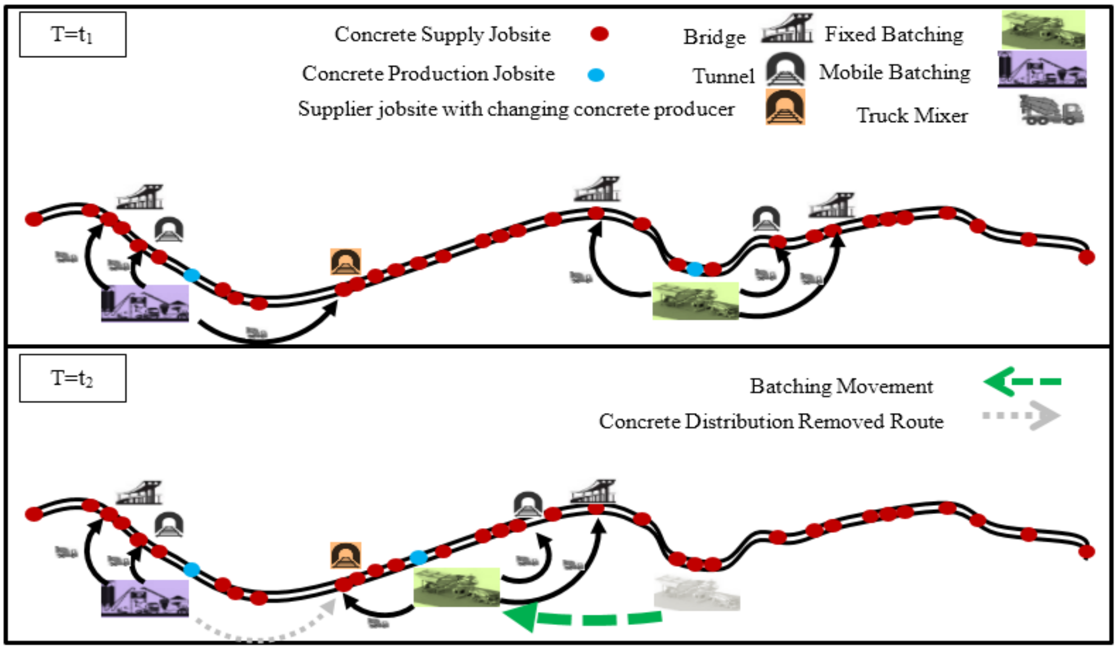

Figure 5: Supplying the concrete demand of sites with mobile and immobile batching (RahsazTarh Eng. Co, comprehensive route study and design report for the Tehran-Isfahan high-speed railway.)

Stances between the demand points and material supply points from each other have been calculated using the Euclidean method, which is an acceptable assumption due to the existing current roads and the simplicity of moving from one site to another on a straight line. Other parameters, which are largely derived from the real conditions of the problem, are given in Table 2.

Table 2
Data of the case study

Parameter	Symbol	Value
Fixed cost of establishing a mobile facility	CF	210000
Fixed cost of establishing an immobile facility	CS	190000
Fixed cost of moving a mobile facility	TCS	15000
The percentage of the period length to relocate a mobile facility	ρ	0.25
Fixed operating cost of the facilities during the schedule	OC	15000
Emissions released due to the movement of mobile batching in g/km	PbU	45

6. Result analysis

In this section, the proposed mathematical model is applied based on the augmented $\varepsilon -$ constraint procedure to solve the considered case study as a real instance of the problem at hand. To this end, the model is coded in GAMS, and the CPLEX solver is used to find the exact Pareto front. All experiments are executed on a Pc with a 2.0GHz Intel Core i5 processor and 8GB of RAM. The optimality gap in this study is zero due to the The model is linear, and GAMS can solve it exactly. Nonetheless, the test case was solved with a computational time of 3600 seconds.

Figure 6 shows the Pareto front of the final solutions related to each of the two objective functions. For ease of visualization, the horizontal axis is adjusted. According to the figure, it is clear that improving of the value of each objective function leads to the worsening of the value of the other objective function. In short, two objective functions are in conflict with each other

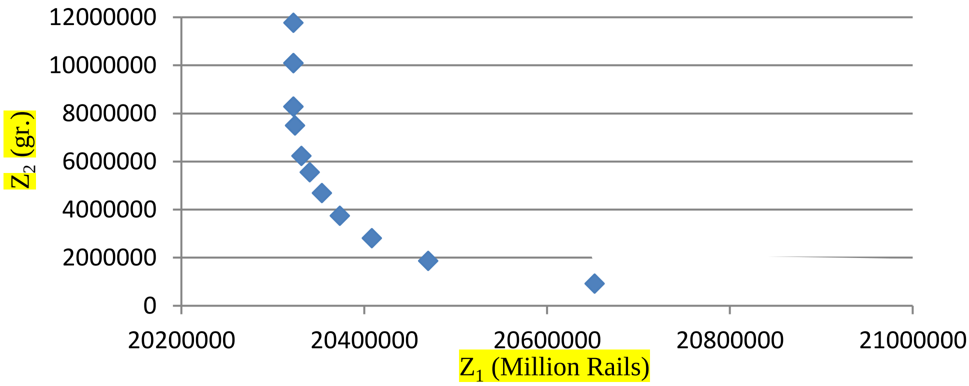

Fig. 6. Pareto front solutions for the case study

In this figure, the first objective function indicated on the vertical axis shows the amount of total cost in million Iranian Rials, and the second objective function indicated on the horizontal axis indicates the amount of total pollution caused by the movement of mobile batching and concrete production by fixed and mobile batching in grams. It can be seen that as the value of the first objective function decreases, the value of the second objective function increases, which indicates the conflict between the above two objectives in this particular problem, which somehow confirms the validity of the two-objective model. Moreover, each point represents an option for management to decide, which means the proposed number of mobile batching used in the project and the cost and emissions resulting from each chosen option. This issue has been investigated in Table 3 by providing the different values of decision variables resulting from solving the problem.

Table 3
value of decision variables according to each solution

Solution number	Z_1 (Million Rails)	Z_2 (gr.)	Number of immobile batching	Number of mobile batching	The number of moves of mobile batches
1	20322792	10102500	3	5	8
2	20322792	8289000	3	5	8
3	20322792	8289000	3	5	8
4	20324332	7506000	4	4	7
5	20331608	6237000	4	4	7
6	20340428	5557500	4	4	6
7	20353854	4698000	4	4	6
8	20373460	3753000	4	4	6
9	20408539	2817000	4	4	5
10	20469944	1872000	4	4	5
11	20652299	931500	5	3	4

For more clarity, the procedure of moving a mobile batching in solution number 11 is represented schematically in Figure 7, for instance. The dynamic nature of the problem at hand determines in what period each mobile batching is moved to produce and ship a larger volume of concrete. This issue is also worth noting to confirm the correctness of the model's performance. Considering the multitude of non-dominant answers, now we can make a trade-off and choose the best according to the decision maker's preferences.

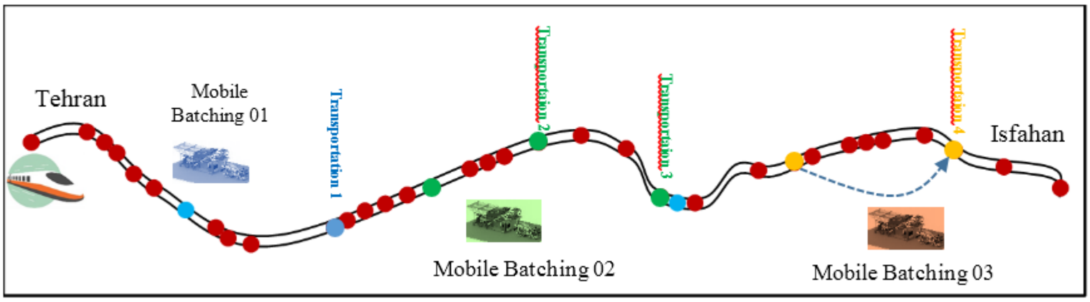

Fig. 7. Moving of a mobile batching in solution 11

The real conditions of the projects in the construction industry present other significant requirements and aspects to the managers, based on which he can make a decision regarding the selection of non-superior options available. For example, in a situation where no other factor affects the project manager, if the environmental aspects are very strict, he will move towards option 11 (the last solution), and if cost issues are very restrictive, he will move towards option 1 (the first solution). But if other preferences are effective in choosing between these options and the analyst has not been able to quantify them and include them as an objective in the model, the project manager will consider them implicitly. For example, if due to the process limitations of the company, there is a ceiling for the purchase of new machinery for this project, the project manager will be inclined towards option 11.

In the following, some sensitivity analyses are performed considering the key parameters to explore the changes in the values of the two objective functions. To investigate the sensitivity of the model parameters, in addition to the possibility of making fundamental changes in the results, the possibility of changing it in the reality of the project is also considered. Therefore, considering the stability of many of these factors during the project implementation, the parameters CS (fixed cost of establishing a mobile facility), CF (fixed cost of establishing an immobile facility) and TCS (fixed cost of moving a mobile facility) from the first objective function and the parameter Pbu (emitted released due to the movement of mobile batching in g/km) are analyzed from the second objective function. We considered the range of changes between -15% and +15% and investigated its effect on two objective functions. However, we changed PbU between -60% and +60% for more clarity. Figure 8 highlights change in the two objective functions according to changes in fixed cost of establishing a mobile facility. In this figure, the right and left vertical axis shows the values of the first and second objective function respectively. As the figure indicates, the total cost (Z_1) changes is completely upward, which is a completely correct trend because the more the cost of installing mobile batching production equipment increases, the overall cost will increase anyway. But the graph of the amount of pollution (Z_2) is generally decreasing, which seems to be a correct trend. In the part of the graph where the pollution has increased, the number of moving batching in the model has decreased, which has led to more batching being moved to cover more parts of the route, and finally, the pollution has increased.

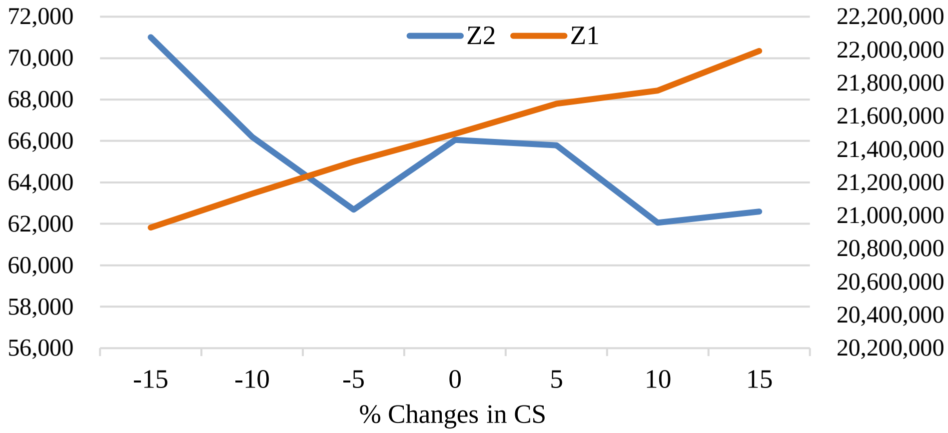

Fig. 8. Changes of two objective functions for different values of CS

Similarly, Figure 9 demonstrates change in the two objective functions according to changes in fixed cost of establishing an immobile facility. As is evident, the changes in the first objective function is incremental except for one point.

The trend of changes in the first objective function is expected because the more the cost of installing immobile batching production equipment increases, the total expected cost will increase anyway. However, trend of the amount of pollution as the second objective function does not shows a noticeable change, which seems to be a correct trend because the pollution is not under the effect of fixed batching.

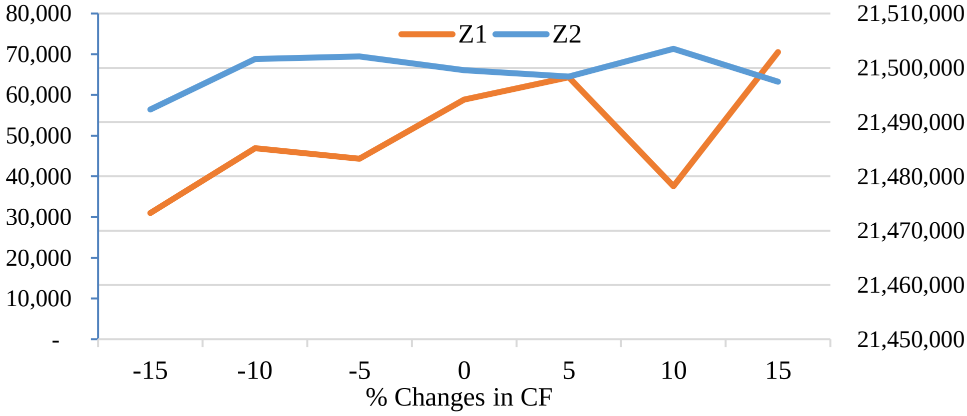

Fig. 9. Changes of two objective functions for different values of CF

Figure 10 represents effect of change in fixed cost of moving a mobile facility on two objective functions. As shown in the figure, the cost changes have been upward, which is a correct trend because the more the moving cost of mobile batching production equipment increases, the overall cost will increase anyway. But the pollution rate function shows almost a decreasing trend, which is a correct trend. By increasing the fixed cost of moving batching, the model is under pressure and the number of movements is reduced, and as a result, the pollution caused by movement is also reduced.

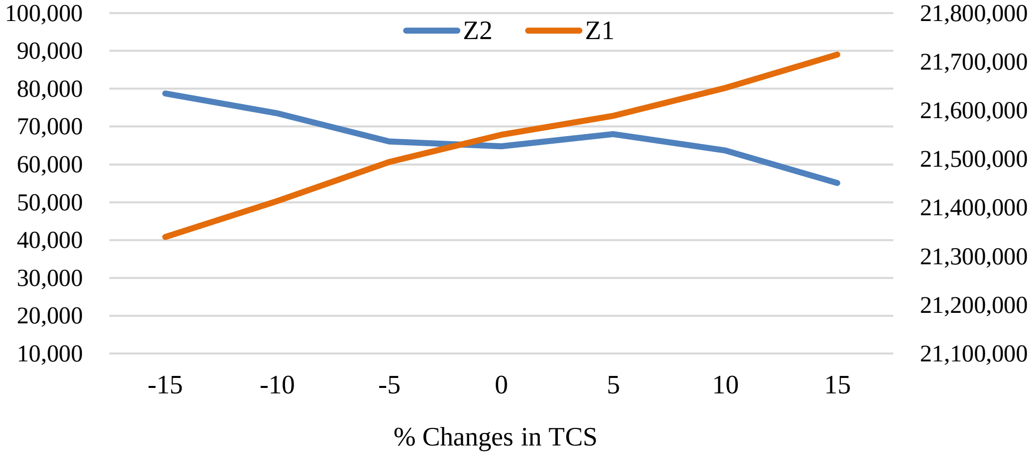

Fig. 10. Changes of two objective functions for different values of TCS

Finally, the effect of changes in the emission rate due to moving batch motion (g/km) on the objective functions is presented in Figure 11. To better highlight effects, we considered a range changes of -60% and +60% for this parameter. According to the figure, the total expected cost is completely constant, which is a correct trend because the more the amount of pollution per unit of distance increases, there is no effect on cost elements. It is worth mentioned that this means that the ransportation fleet is more worn out or of poorer quality, and theoretically it means more cost, but since the above items are not predicted in the model, they have no effect on the first objective function (cost). However, the graph of the amount of pollution (the second objective function) is completely increasing, which is a correct trend. By increasing the emission rate of machinery, more pollution is produced per the same route.

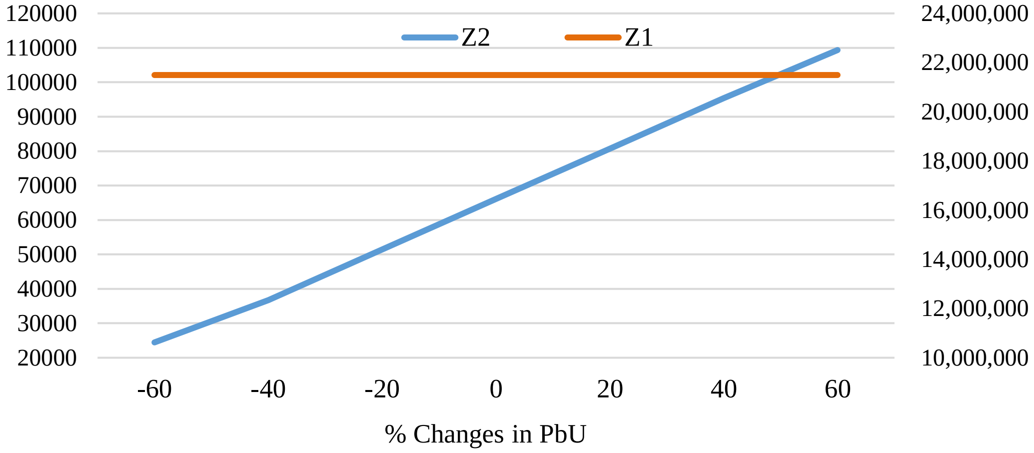

Fig. 11. Changes of two objective functions for different values of PbU

7. Conclusion

This study developed a novel bi-objective optimization model for the strategic placement of both mobile and immobile concrete batching facilities in linear construction projects, addressing the critical trade-off between economic efficiency and environmental sustainability. By simultaneously minimizing total expected costs (encompassing establishment, operation, relocation, and material transport) and total CO_2 emissions (from facility operations and mobile batch relocations), the model provides a comprehensive decision-making framework aligned with green facility location principles.

The proposed mathematical model was applied to solve a real-world case study involving a 500-kilometer high-speed railway project in Iran using the augmented $\varepsilon-$constraint method. The result validated the efficiency of the proposed model and demonstrated a clear trade-off between minimizing total expected costs and environmental impact, as evidenced by the Pareto front analysis. This analysis provided decision-makers with a range of viable solutions, allowing them to select options that best align with their specific priorities and constraints. Sensitivity analyses further illuminated the impacts of key parameters (e.g., facility setup and relocation costs, emission rates per distance) on both objectives, empowering managers to anticipate outcomes under varying operational constraints. These insights are invaluable for project managers, enabling them to navigate the complexities of facility location decisions while balancing economic and environmental objectives.

This research underscores the viability of multi-objective optimization for eco-efficient infrastructure planning. By embedding environmental metrics into facility location decisions, the construction sector can significantly reduce its carbon footprint while maintaining economic viability—a crucial step toward sustainable urbanization and climate-resilient development.

As with any research, this study suffers from limitations. This work is limited to the linear construction projects. Furthermore, the considered facilities (distinguished between mobile and immobile) have the same level of technology and require the same skills and equipment. Future research could expand on this work by exploring the model's applicability to other types of construction projects and incorporating additional environmental factors. Considering different levels of technology for facilities in terms of operational cost, capacity, speed, and CO_2 emissions could bring the problem closer to real-world conditions. As another exciting research, it is worthwhile to model and solve the problem considering practical assumptions such as machine breakdown and under uncertainty, especially in transportation times.

Compliance with Ethical Standards

Ethical approval: We confirm that all the research meets the ethical guidelines, including adherence to the legal requirements of the study country.

Funding: No funding is received by this study.

Conflict of Interest: The authors declare that they do not have any conflict of interest of other works.

Data Availability Statement: The authors confirm that the data supporting the findings of this study are available within the article.

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