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# Environmental and economic optimization of relocation strategies for mobile prefabrication factories in infrastructure projects

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## ABSTRACT

Mobile off-site prefabrication can enhance complex linear infrastructure projects, yet the absence of a general and robust relocation rule limits its practical implementation in the construction industry. This research proposes an integrated model that combines Life Cycle Assessment and Geographic Information Systems to optimize a three-layer mobile supply network. A hyperloop infrastructure case study demonstrates that relocating a pneumatic mobile factory four times reduces carbon emissions by 62 % and costs by 49 % compared to a stationary facility, primarily due to shortened outbound transportation distances. Scenarios-based sensitivity analyses confirm the adaptability of mobile factories to supply diverse projects and recommend relocating the factory every 50–80 km to balance sustainability and practical feasibility. Although direct impacts from factory reconfigurations are modest, they serve as necessary constraints to prevent impractical relocation numbers. The model offers practical guidance for developing sustainable relocation strategies for mobile prefabrication factories used in large-scale infrastructure construction.

## 1. Introduction

### 1.1. Mobile factory concept

The construction industry contributed over 14 % to global GDP in 2022 and is expected to see a long-term rise in global construction value by more than 30 % (Chen and Hammad, 2023). Despite this growth, the industry struggles with low productivity and accounts for about 40 % of global energy use and one-third of worldwide carbon emissions (Pearce and Ahn, 2018). Furthermore, construction-related transportation notably impacts urban logistics. It constitutes at least 30 % of urban goods transport and contributes about 16 % of carbon emissions in linear infrastructure projects (Guerlain et al., 2019; Chang and Kendall, 2011). On-site prefabrication emerges as a promising method to increase productivity and reduce transportation carbon emissions in the construction industry (Dallasega et al., 2023, 2024; Ma et al., 2025; Cao et al., 2024). By shifting the construction process from the site to a controlled

factory environment, prefabrication demonstrates improved project performance compared to conventional on-site construction in terms of cost efficiency, energy performance, and construction quality (Dallasega et al., 2024; Teng et al., 2018; Kong et al., 2018; Barkokebas et al., 2023)

Effective supply chain management (SCM) is a critical yet persistent challenge in prefabricated construction, particularly as supply networks become more decentralized and interdependent (Wang et al., 2019). Numerous studies have emphasized that poor SCM is a key contributor to inefficiencies, delays, and cost overruns in prefabrication projects (Masood et al., 2022; Li et al., 2024). The supply chain of prefabrication is more complex and fragmented due to the high customization of the prefabricated components (PCs) to meet each project's specification (Masood et al., 2022; Hussein et al., 2021; Zhang et al., 2024). The significant weight and bulkiness of these components make the transportation time-consuming, energy intensive, and requires a larger buffer stock to mitigate delivery delays (Wang et al., 2019; Yi et al., 2020; Hsu et al., 2018; Yang et al., 2021). Limited storage capacity at

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prefabrication facilities further complicates buffer management, particularly in linear infrastructure projects characterized by high component demand (Kong et al., 2018).

To tackle these SCM challenges, the on-site mobile factory concept has been introduced into the prefabrication industry. A mobile factory is a relocatable production facility composed of modular and flexible systems, which is designed to adjust both the quantity and type of output based on specific on-site conditions (Dallasega et al., 2023). By deploying the factory close to the construction site, Just-In-Time (JIT) delivery can be facilitated to minimize the buffer and reduce both the economic and environmental impact of construction projects (Kim et al., 2024; Rathnayake and Middleton, 2023; Xiang et al., 2024). Building on this concept, researchers have examined its functional requirements, business models, and network-oriented approaches to enhance the viability of mobile prefabrication factories. Rauch et al. (2015a) analyzed the functional requirements and proposed key design parameters for mobile factories using the Axiomatic Design (AD) method. Subsequently, they proposed a Mobile Factory Network (MFN) as a network-oriented business model to commercialize the mobile prefabrication factory concept from an organizational perspective. By adopting the AD method, Dallasega et al. (2023) presented the requirements and a concept prototype for a mobile concrete prefabrication factory to sustainably and continuously supply PCs to hyperloop construction projects.

Fig. 1 illustrates the concept of employing a mobile concrete prefabrication factory to supply large-scale linear infrastructures, such as a hyperloop line. The dashed box highlights the system boundary, which covers inbound transportation of raw materials, factory reconfiguration, and outbound transportation of PCs. Inbound transportation includes the delivery of materials such as cement, aggregates, and steel from geographically distributed suppliers to the currently deployed factory location. These inbound flows vary with each relocation depending on the spatial configuration of the supply network. The factory reconfiguration process involves four key stages: site preparation, factory assembly, disassembly, and site restoration, enabling the mobile factory to be periodically repositioned along the infrastructure. With its modular and relocatable design (Dallasega et al., 2023, 2024), the mobile factory gains high flexibility to adapting to different site conditions and

following the advancing construction site along the infrastructure. Outbound transportation refers to the delivery of fabricated components from the mobile factory to the active construction site. Together, these three logistics processes form the core of the system evaluated in this study.

### 1.2. Hyperloop infrastructure

Global freight and passenger transport demand is rising with population and industrial growth. In 2022, transport accounted for over one-third of end-use GHG emissions and continues to grow with international air travel (IEA, 2023a; IEA, 2023b). The decarbonization of aviation is slow, as Sustainable Aviation Fuels (SAFs) face barriers such as high electricity demand and limited production scalability (Odenweller et al., 2022; Ueckerdt et al., 2021) while electric aircraft require battery energy densities that are currently infeasible (Miller et al., 2023). Recent studies highlighted hyperloop, an innovative vacuum-based maglev transportation system, as a promising alternative to short-haul aviation. Capable of achieving speeds exceeding 1000 km/h with end-to-end travel times comparable to flights, hyperloop requires only half the battery density needed by electric aircraft, making it a more practical and feasible solution (Beckert et al., 2024; Pareschi et al., 2023; Scholz et al., 2022).

A hyperloop system primarily comprises a sealed tube that maintains low pressure and a pod using maglev technology to carry passengers or cargo. Fig. 2 provides a schematic overview of hyperloop infrastructure proposed by EuroTube (EuroTube Foundation, 2024), a Swiss non-profit research organization for the development of vacuum transport infrastructure. Hyperloop infrastructure mainly comprises three component types: structural components, electrical components, and vacuum components. The main structural components consist of sealed tubes supported by pillars, connection joints between the tubes, and rails for pod movement. The electrical components are responsible for power transfer and signal transmission. They ensure the continuous operation of the levitation, propulsion, and vacuum systems throughout the hyperloop infrastructure. Vacuum components, such as the liner, airlock, valve, and pumps, maintain low-pressure conditions essential for efficient operation. The airlock serves as a terminal section that allows

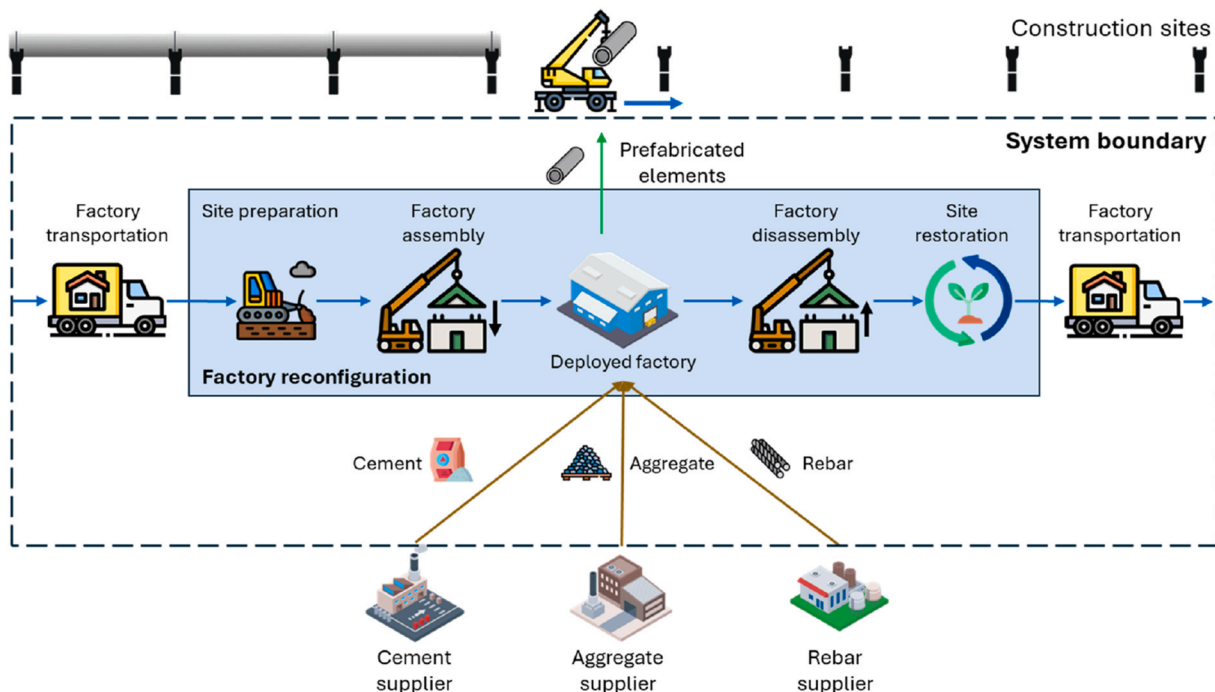


Fig. 1. Illustration of use the mobile factory to supply the construction of large linear infrastructures such as hyperloop.

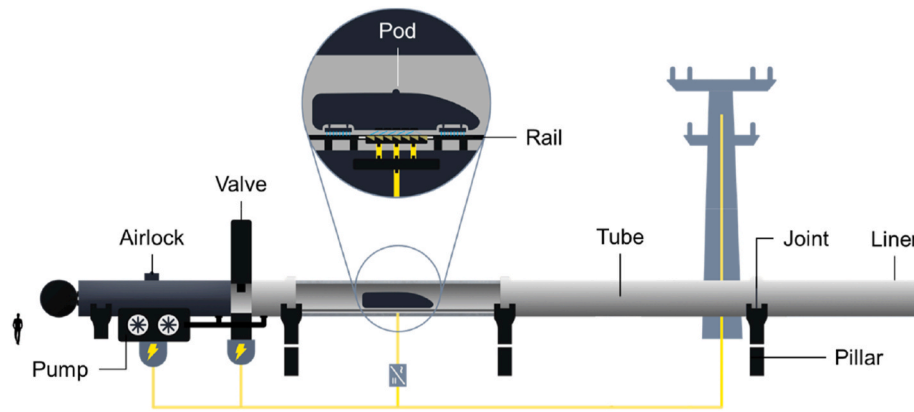


Fig. 2. Schematic illustration of hyperloop transportation system from EuroTube (EuroTube Foundation, 2024).

pod entry and exit while preventing atmospheric air from entering, ensuring both efficiency and safety. Vacuum pumps reduce air pressure in the airlock to operational levels for each departure and compensate for vacuum losses caused by infrastructure leakage.

Maintaining the vacuum environment inside the structure poses a high requirement for prefabrication quality of those large and heavy concrete components. This can be very challenging if the components are produced in-situ without a well-controlled environment. In this context, the mobile prefabrication concept can be one fit for the construction of hyperloop infrastructure. According to EuroTube's current plan, the PC tube sections will be cast, assembled, sealed and quality checked inside the mobile factory then transported to installation sites. The mobile factory will be relocated several times as the project progresses to reduce the carbon footprint of the transportation of those PCs. The objective of this study is to develop low-carbon and cost-effective relocation strategies in conceptual stage for mobile prefabrication factories that can be transferable to various linear concrete infrastructure projects.

## 2. Literature review

The development of sustainable relocation strategies for mobile factories involves two critical aspects: (1) the mathematical modeling of the relocation of mobile factories and (2) the environmental and economic assessment of the mobile supply chain. Relocating mobile factories is traditionally classified as a Mobile Facilities Locations Problem (MFLP) which focuses on the strategic movements of facilities to different sites and the reallocation of customer demand to these new locations. The primary goal is to minimize total weighted distances traveled by both factories and clients (Alarcon-Gerbier and Buscher, 2022; Halper et al., 2015; Patil et al., 2020).

In the construction industry, existing publications on MFLP are still scarce (Alarcon-et al., 2022). Gden and Sral (2014) introduced a Mixed Integer Linear Programming (MILP) model to determine the number of mobile concrete mixers, stationed concrete plants, relocation sequence, and production-allocation to minimize total costs for a railway construction project. They later advanced this work with a multi-period MILP model that considers the service period and coverage distance of facilities (Gden and Sral, 2019). This model aims to minimize total costs by optimizing facility locations, operation times, routes for mobile facilities, and demand allocations. These models focused on cost optimization within a single project case and did not account for environmental impacts. Recently, Kaushal et al. (2025) optimized the outbound transportation using mobile prefabrication to supply a hyperloop construction and compared its carbon emissions and costs to using a centralized factory (Kaushal et al., 2025). Ma et al. (2025) developed a two-stage model that first selects factory locations to minimize outbound transportation and then identifies the nearest

suppliers to those locations. They found that four to six relocations effectively reduce emissions from transportation of materials and PCs in a case study of constructing a hyperloop infrastructure from Zurich to Geneva. While these studies demonstrate that mobile factories can reduce carbon emissions and transport costs, their results are limited to projects where the locations are fixed and do not provide transferable relocation strategies for taking advantage of different supplier networks and logistical constraints.

Mobile factory concepts have also been explored in other industries, such as recycling, bioenergy production, and agricultural equipment servicing. For example, Alarcon-Gerbier et al. (2023) developed a Mixed Integer Programming (MIP) model for relocating mobile recycling units, demonstrating substantial reductions in total costs and carbon emissions. Mirkouei et al. (2016) analyzed a bio-oil network consisting of fixed and mobile oil refineries, concluding that mobile units are more suitable when transportation distances and costs increased. Sadeghi and Haapala (2019) used carbon taxes to represent carbon emissions in their MILP model, showing increased mobile refinery capacity significantly reduces total supply costs and carbon emissions. ten Kate et al. (2017) also studied the use of mobile process units (MPUs) for bio-diesel production, finding that operating relatively expensive MPUs at maximum capacity is still cost-effective. Han et al. (2021) presented a MILP model to optimize the planning of a temporary maintenance station to repair agricultural machinery. This work indicates that the strategic relocation of the mobile maintenance stations can improve overall productivity. Additional studies extended the MFLP by including the scheduling, routing, and inventory decisions (Alarcon-Gerbier and Buscher, 2019; Zimmer et al., 2018; Shahmoradi-Moghadam and Schnberger, 2021).

Although these works highlight the logistical benefits of mobile supply systems, they are not directly transferable to the prefabrication sector. Unlike truck-mounted units in bioenergy and recycling, mobile prefabrication factories are non-containerized, heavy, and require site-specific reassembly, which introduces additional emissions and logistical complexity. Moreover, the construction supply chain involves heterogeneous, material-specific inbound flows (e.g., cement, aggregate, rebar) that are rarely modeled separately in prior models from other sectors. Failing to address these differences overlooks practical constraints that critically affect proving general feasibility of using mobile prefabrication factories in the construction industry.

In summary, existing studies are limited by their focus on single case projects, cost-only objectives, and fixed project locations, while neglecting environmental impacts and the unique supply-chain characteristics of prefabrication industry. These limitations make it difficult to move beyond isolated case studies and establish mobile factories as a feasible and scalable method for carbon- and cost-efficient infrastructure delivery, thereby limiting their practical deployment in real-world infrastructure projects. To address this, we developed an integrated optimization model that combines Life Cycle Assessment (LCA) and

Geographic Information Systems (GIS), explicitly modeling the spatial structure of inbound and outbound supply chains and the environmental burden of factory reconfiguration. We evaluated the proposed model through a hyperloop infrastructure case study and developed diverse supply network scenarios to identify key parameters that affect the sustainability of relocation strategies. By analyzing these scenarios, we derive transferable relocation rules that support practical decision-making across different large-scale linear infrastructure projects.

### 3. Methodology and data

#### 3.1. Problem description

Fig. 3 provides a general example of this three-layer supply network problem for using a mobile prefabrication factory in a linear infrastructure project. The diagram illustrates the key elements, including construction sites set  $K$ , candidate factory deployment locations set  $J$ , and material suppliers set  $I$ . Both sets  $J$  and  $K$  are indexed in ascending order along the linear infrastructure.  $I_A$  and  $I_B$  denote the sets of suppliers' locations for materials A and B, respectively. The grey dashed lines in the figure represent potential supply links  $(i, j, k)$ , while the blue dashed lines indicate the potential factory movement link  $(j, j')$ , highlighting the flexibility and mobility of the factory within the supply network.

In the depicted mobile supply network, the mobile prefabrication factory is assumed to be initially assembled and deployed at location  $j_2$ , where it produces PCs for construction site  $k_1$  using materials supplied by  $i_{a1}$  and  $i_{b2}$ . After completing the production task at  $j_2$ , the factory is disassembled and transported to location  $j_3$ , where it supplies construction sites  $k_2$  and  $k_3$  with materials from suppliers  $i_{a2}$  and  $i_{b2}$ . At the end, the factory moves to its last position  $j_j$  to supply the final construction site  $k_k$ .

Based on the characteristics of the example shown, we can formulate this factory relocation problem by identifying supply chain links that minimize carbon emissions or costs across different relocation strategies. Given the long duration of infrastructure projects, we can model this problem as an uncapacitated problem, assuming that (1) each construction site  $k$  receives PCs from only one factory location  $j$ , and (2) the mobile prefabrication factory is supplied by only one supplier for each material at one deployment location  $j$ .

#### 3.2. Carbon emissions and cost estimation of transportation

Currently, there are two approaches for calculating the carbon emissions and costs of transportation: the fuel-based method and the distance-based method. In the fuel-based approach, emissions are determined by multiplying fuel consumption by the emission indicator, while the distance-based method calculates emissions by multiplying the distance traveled by the freight mass and the emission indicator. Generally, the fuel-based approach requires more data and is more

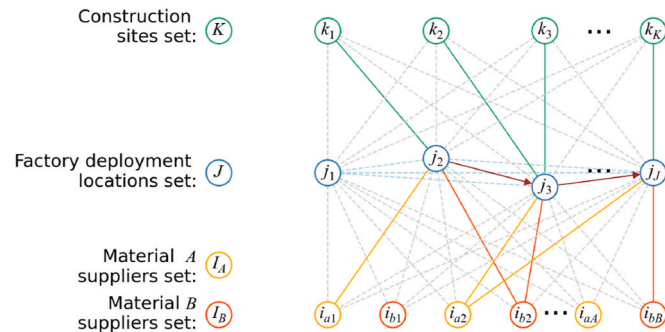


Fig. 3. Illustrative example for the mobile supply network composed of materials suppliers, mobile prefabrication factory, and construction sites.

accurate, while the distance-based method requires fewer details and is more scalable (Davison et al., 2020). The choice between these two approaches is typically determined by data availability (Ziaei and Jabbarzadeh, 2021). Since most of the available data are distance-based in an LCA database such as Ecoinvent (ecoinvent, 2024) in Switzerland, we used the distance-based approach in this study.

#### 3.3. Carbon emissions estimation of factory reconfiguration

We adopted the process-based approach to estimate the carbon emissions  $e_j$  from the factory reconfiguration at candidate location  $j$  using Equation (1). Here,  $e_e$  represents the carbon emissions indicator for electricity,  $p_i$  denotes the power of the electric machine  $i$ ,  $t_i$  is the total operation time for electric machine  $i$ ,  $e_k^d$  refers to the emissions indicator for using diesel machine  $k$ , and  $t_k$  is the total operation time for diesel machine  $k$ .

$$e_j = e_e \cdot \sum_i p_i \cdot t_i + \sum_k e_k^d \cdot t_k \quad (1)$$

#### 3.4. Mathematical model

The carbon emissions and costs in the factory relocation problem arise from three main activities: (1) inbound transportation (from  $I$  to  $J$ ) of raw materials and outbound transportation (from  $J$  to  $K$ ) of PCs, (2) the reconfiguration processes of the mobile prefabrication factory, and (3) the transportation of the disassembled mobile factory. To quantify the carbon emissions and costs from these activities, we introduce three binary decision variables:

- $x_{i_n j k}$  denotes the selection of the supply link  $(i_n, j, k)$  and equals one if the factory is deployed at location  $j$  and supplies construction site  $k$  with material  $n$  from supplier  $i_n$ .
- $y_j$  represents the selection of the factory deployment location and equals one if location  $j$  provides PCs to at least one construction site.
- $z_{j j'}$  describes the selection of transportation route  $(j, j')$  of the mobile prefabrication factory and equals one if the factory travels from candidate deployment location  $j$  to  $j'$ .

##### 3.4.1. Objective function for the carbon emissions minimization

Using the introduced decision variables  $x_{i_n j k}$ ,  $y_j$ , and  $z_{j j'}$ , we formulate the objective function in Equation (2), which aims to minimize the overall carbon emissions.

$$\text{Min } E(x_{i_n j k}, y_j, z_{j j'}) = E_{\text{inbound}}(x_{i_n j k}) + E_{\text{outbound}}(x_{i_n j k}) + E_{\text{relocation}}(y_j, z_{j j'}) \quad (2)$$

The first component,  $E_{\text{inbound}}$ , denotes the carbon emissions from inbound transportation and is calculated with Equation (3):

$$E_{\text{inbound}}(x_{i_n j k}) = \sum_{n \in N} \sum_{i_n \in I_n} \sum_{j \in J} \sum_{k \in K} e_{i_n j} m_{nk} d_{i_n j} x_{i_n j k} \quad (3)$$

where  $N$  is the set of main materials required for PCs production,  $d_{i_n j}$  represents the transportation distance between supplier  $i_n$  and factory location  $j$ ,  $m_{nk}$  is the mass of material  $n$  for construction site  $k$ ,  $e_{i_n j}$  refers to the carbon emissions indicator for transportation link  $(i_n, j)$  for material  $n$ .

Equation (4) calculates the carbon emissions from the outbound transportation of PCs from the factory to the construction sites.

$$E_{\text{outbound}}(x_{i_n j k}) = \sum_{i_n \in I_n} \sum_{j \in J} \sum_{k \in K} e_{j k} m_{pk} d_{j k} x_{i_n j k} \quad (4)$$

Here,  $d_{j k}$  is the transportation distance between factory location  $j$  and construction site  $k$ .  $m_{pk}$  denotes the mass of PCs required at construction

site  $k$  and  $e_{jk}$  represents the carbon emissions indicator for the outbound transportation link  $(j, k)$ .

$$E_{\text{relocation}}(y_j, z_{jj}) = \sum_{j \in J} e_j y_j + \sum_{j \in J} \sum_{j' \in J} e_{jj'} m_f d_{jj'} z_{jj'} \quad (5)$$

Equation (5) estimates the carbon emissions from the factory relocation processes, which includes the reconfiguration process and transportation of the mobile prefabrication factory. The first term represents the carbon emissions from the reconfiguration process at potential deployment location  $j$ , where  $e_j$  is the carbon emissions from the associated reconfiguration process. The second term calculates the carbon emissions from transporting the factory from factory deployment location  $j$  and  $j'$ , where  $d_{jj'}$  is the distance in-between.  $m_f$  is the total mobile prefabrication factory mass and  $e_{jj'}$  refers to the carbon emission indicator for transportation link  $(j, j')$ .

### 3.4.2. Objective function for the cost minimization

By substituting the carbon emissions indicators in Equations (2)–(5) with distance-based cost indicators, we can derive the objective function aimed at minimizing the overall costs, as shown in Equation (6).

$$\begin{aligned} \text{Min } C(x_{i_n j k}, y_j, z_{jj'}) = & \sum_{n \in N} \sum_{i_n \in I_n} \sum_{j \in J} \sum_{k \in K} c_{i_n j} m_{n k} d_{i_n j} x_{i_n j k} + \sum_{i_n \in I_n} \sum_{j \in J} \sum_{k \in K} c_{j k} m_{p k} d_{j k} x_{i_n j k} \\ & + \sum_{j \in J} c_j y_j + \sum_{j \in J} \sum_{j' \in J} c_{j j'} m_f d_{j j'} z_{j j'} \end{aligned} \quad (6)$$

Here,  $c_{i_n j}$ ,  $c_{j k}$ , and  $c_{j j'}$  are the cost indicators for transportation links  $(i_n, j)$ ,  $(j, k)$ , and  $(j, j')$ , respectively.  $c_j$  is the cost indicator for the reconfiguration processes at factory deployment location  $j$ .

### 3.4.3. Model constraints

The presented model is subject to the following constraints.

$$x_{i_n j k} \in \{0, 1\}, \forall n \in N, \forall i_n \in I_n, \forall j \in J, \forall k \in K \quad (7)$$

$$y_j \in \{0, 1\}, \forall j \in J \quad (8)$$

$$z_{j j'} \in \{0, 1\}, \forall j \in J, \forall j' \in J \quad (9)$$

$$\sum_{i_n \in I_n} \sum_{j \in J} x_{i_n j k} = 1, \forall n \in N, \forall k \in K \quad (10)$$

$$\sum_{i_n \in I_n} x_{i_n j k} = \sum_{i_n' \in I_n'} x_{i_n' j k}, \forall n \in N, \forall n' \in N, \forall j \in J, \forall k \in K \quad (11)$$

$$y_j \leq \sum_{i_n \in I_n} \sum_{k \in K} x_{i_n j k}, \forall j \in J \quad (12)$$

$$y_j \geq x_{i_n j k}, \forall n \in N, \forall i_n \in I_n, \forall j \in J, \forall k \in K \quad (13)$$

$$\sum_{j \in J} y_j = l + 1, l \in \{0, 1, 2, 3, \dots, J - 1\} \quad (14)$$

$$z_{j j'} \leq y_j, \forall j \in J, \forall j' \in J \quad (15)$$

$$z_{j j'} \leq y_{j'}, \forall j \in J, \forall j' \in J \quad (16)$$

$$z_{j j'} = 0, \forall j' \geq j, \forall j \in J, \forall j' \in J \quad (17)$$

$$\sum_{j' \neq j} z_{j j'} \leq y_j, \forall j \in J, \forall j' \in J \quad (18)$$

$$\sum_{j' \neq j} z_{j j'} = l, \forall j \in J, \forall j' \in J, l \in \{0, 1, 2, 3, \dots, J - 1\} \quad (19)$$

Here, constraints (7)–(9) are the binary constraints for the binary decision variables. Equality (10) ensures that all material demand

required at construction site  $k$  for producing the PCs is satisfied. Constraint (11) ensures that the mobile prefabrication factory receives the correct quantities of different materials required for producing precast components at deployment location  $j$ . Inequalities (12) and (13) state that the mobile prefabrication factory should only be deployed at the locations that supply at least one construction site. Constraint (14) mandates that the mobile prefabrication factory must be relocated  $l$  times during the project. Without constraint (14), the model still works but only outputs the optimal relocation plan. Constraints (15) and (16) state the factory only moves between the selected factory locations. Constraints (17)–(19) regulate the sequence of factory relocations across the selected deployment locations.

### 3.5. Scenario-based sensitivity analyses

Relying solely on solutions from the optimization analysis without justifying the input data involves significant risk (Du and Bormann, 2014). Therefore, we included a sensitivity analysis to identify key parameters impacting relocation strategies.

Sensitivity analysis techniques are classified into local sensitivity analysis (LSA) and global sensitivity analysis (GSA) (Hamby, 1994). LSA varies one parameter at a time, while keeping others at their nominal values. In contrast, GSA relies on probabilistic frameworks to explore the effects of variations in randomly sampled input parameters to identify how these variations influence model outputs (Yi and Lu, 2019). Given the complexity and computational intensity of GSA for optimization problems, and the similarity in insights for linear models between LSA and GSA (Razavi et al., 2021), we opted for LSA, using multiple scenarios created by altering only one input parameter for each scenario.

Table 1 presents the parameters used for sensitivity analysis scenarios, classified into geospatial, physical, environmental, and economic categories. The "Factor Range" shows the scaling applied to parameters relative to their baseline values, while "Step" refers to the increment used within each range. These parameters are selected based on key

**Table 1**

Parameters for creating sensitivity analysis scenarios (abbreviations in parentheses).

Parameter	Category	Factor Range	Step
Aggregate supplier location distance to infrastructure (Aggregate Dist.)	Geospatial	(2, 10)	1
Aggregate supplier distribution (Aggregate Dsb.)	Geospatial	–	–
Cement supplier location distance to infrastructure (Cement Dist.)	Geospatial	(2, 10)	1
Cement supplier distribution (Cement Dsb.)	Geospatial	–	–
Rebar supplier location distance to infrastructure (Rebar Dist.)	Geospatial	(2, 10)	1
Rebar supplier distribution (Rebar Dsb.)	Geospatial	–	–
Candidate factory location distance to infrastructure (Factory Dist.)	Geospatial	(2, 10)	1
Candidate factory location distribution (Factory Dsb.)	Geospatial	–	–
Number of candidate factory locations (Factory Number)	Geospatial	(10/19, 50/19)	5/19
Total factory mass $m_f$ (Factory Mass)	Physical	(2, 10)	1
Total infrastructure length (Infra. Length)	Physical	(0.2, 4)	0.2
Average PC mass per length $m_p$ (Avg. PC Mass)	Physical	(0.5, 1.5)	0.1
Carbon emissions from factory reconfiguration $e_j$ (Carbon Reconfig.)	Environmental	(2, 10)	1
Carbon emissions indicators for transportation $e_{i_n j}$ , $e_{j k}$ , $e_{j j'}$ (Carbon Indicator)	Environmental	(0.1, 0.9)	0.1
Cost from factory reconfiguration $c_j$ (Cost Reconfig.)	Economic	(2, 10)	1
Cost indicators for transportation $c_{i_n j}$ , $c_{j k}$ , $c_{j j'}$ (Cost Indicator)	Economic	(0.3, 0.9)	0.1

performance indicators (KPIs) and critical factors (CFs) identified as influential in the performance of prefabrication supply chains in previous study. The geospatial, physical, and economic parameters are based on (Masood et al., 2021), where geographical proximity to market is emphasized under the Logistics component, high design variability is listed as CF 12, and intensive capital investment as CF 18. These factors significantly influence the design and operational feasibility of mobile prefabrication strategies. The environmental parameters reflect the Social Responsiveness KPI under the Strategic Management component in (Masood et al., 2024), capturing sustainability considerations.

### 3.5.1. Geospatial parameters

Geospatial parameters refer to the locations of existing material suppliers and the candidate factory deployment sites. Given the compact geography of Switzerland's central plateau, these locations are near the infrastructure in the base case, as shown in Fig. 4. Therefore, in the sensitivity analyses, we shifted these locations perpendicularly from the infrastructure line by a factor of 2–10 times their original distance.

Moreover, in order to generalize the sensitivity analysis and develop a more general and transferable mobile factory relocation strategy, we generated a set of synthetic spatial distributions of material supplier and candidate factory locations using a consistent, data-driven approach. We first buffered the infrastructure line and divided the buffer zone into a regular grid of square cells. Existing facility locations were then spatially joined to this grid to extract three reference parameters: the total number of observed locations  $N^*$ , the ratio of non-empty grid cells, and the maximum number of locations observed in any single cell. While keeping  $N^*$  fixed, we treated the non-empty cell ratio and the per-cell maximum count as user-defined parameters rather than replicating their empirical values. Based on this, we randomly sampled the prescribed fraction of grid cells. We then distributed exactly  $N^*$  locations across the sampled grid cells. Finally, each assigned location was placed by uniform random sampling within its respective grid cell. This method preserves the total number of locations fixed while enabling controlled variation in spatial coverage and clustering.

We use this approach to generate the locations for scenarios developed to study the impact of geospatial parameters including the

aggregate supplier distribution, the cement supplier distribution, the rebar supplier distribution, the candidate factory location distribution, the number of candidate factory locations, and both supplier locations and candidate factory locations for different infrastructure length scenarios. We generated nine different distributions for each of the supplier distribution parameters with diverse setup to validate the identified relocation rule. Fig. 5 shows the generated aggregate plants in one scenario developed for the sensitivity analysis of the geospatial distribution of aggregate suppliers. The non-empty ratio of cells is 8/26 and the maximum number of aggregate plants within one cell is 15. We can notice that, compared to the existing aggregate suppliers, the aggregate suppliers generated are more geographically uneven distributed.

### 3.5.2. Physical parameters

Physical parameters include the total infrastructure length, the average mass of PCs per unit length, and the total mass of the mobile prefabrication factory. For the hyperloop infrastructure, the infrastructure length was scaled by a factor ranging from 0.2 to 4 in increments of 0.2 so that the tested length was within the practical range of 50–1000 km (Hyde et al., 2016). We also use the location generation approach described in the previous section to generate the supplier and candidate factory locations for different infrastructure length scenarios. The average mass of PCs in construction practice ranges from 70 tons to 150 tons (Transportation Components, 2024), scaling by a factor from 0.5 to 1.5 in steps of 0.1. Considering the lightweight pneumatic framework of the current design, the factory's total mass was scaled from 2 to 10 times in steps of 1 to accommodate diverse designs of the mobile prefabrication factory.

### 3.5.3. Environmental and economic parameters

Environmental parameters include carbon emissions from the factory reconfiguration per relocation and carbon emissions indicators for transportation. We adjusted the former parameter by scaling it with factors ranging from 2 to 10 in steps of 1, corresponding to the factory's total mass. Recent studies (Jahangir Samet et al., 2023; Fufa and Venås, 2023) indicate adopting electric trucks can reduce carbon emissions by approximately 90 %. Consequently, we adjusted the carbon emissions

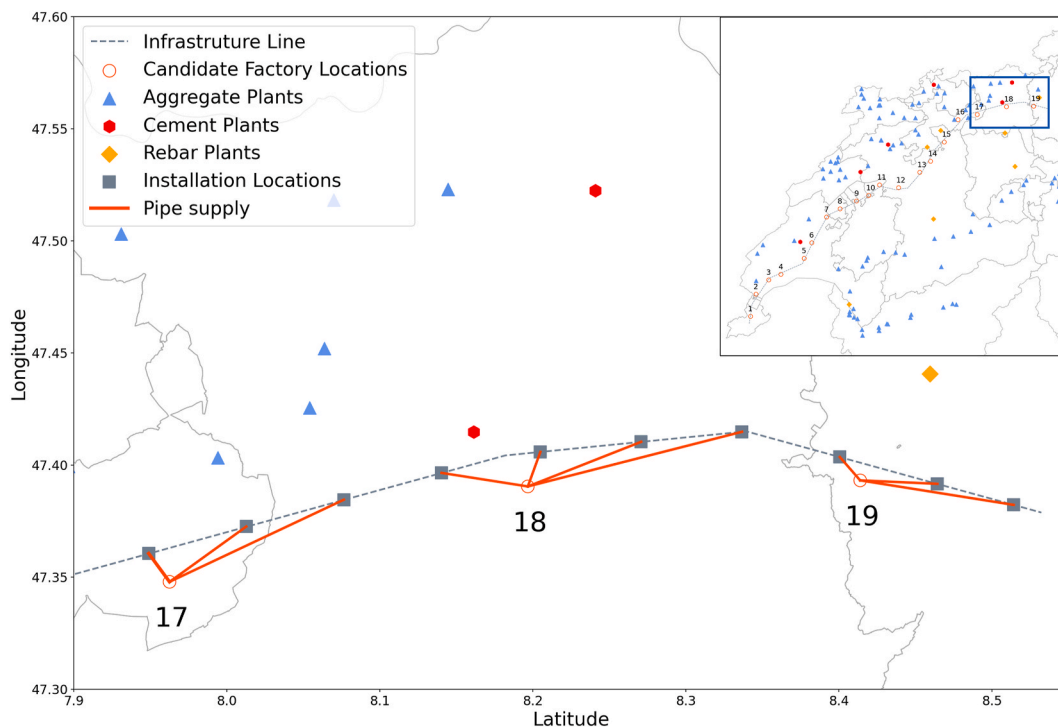


Fig. 4. Case study of hyperloop construction near candidate factory locations 17 to 19.

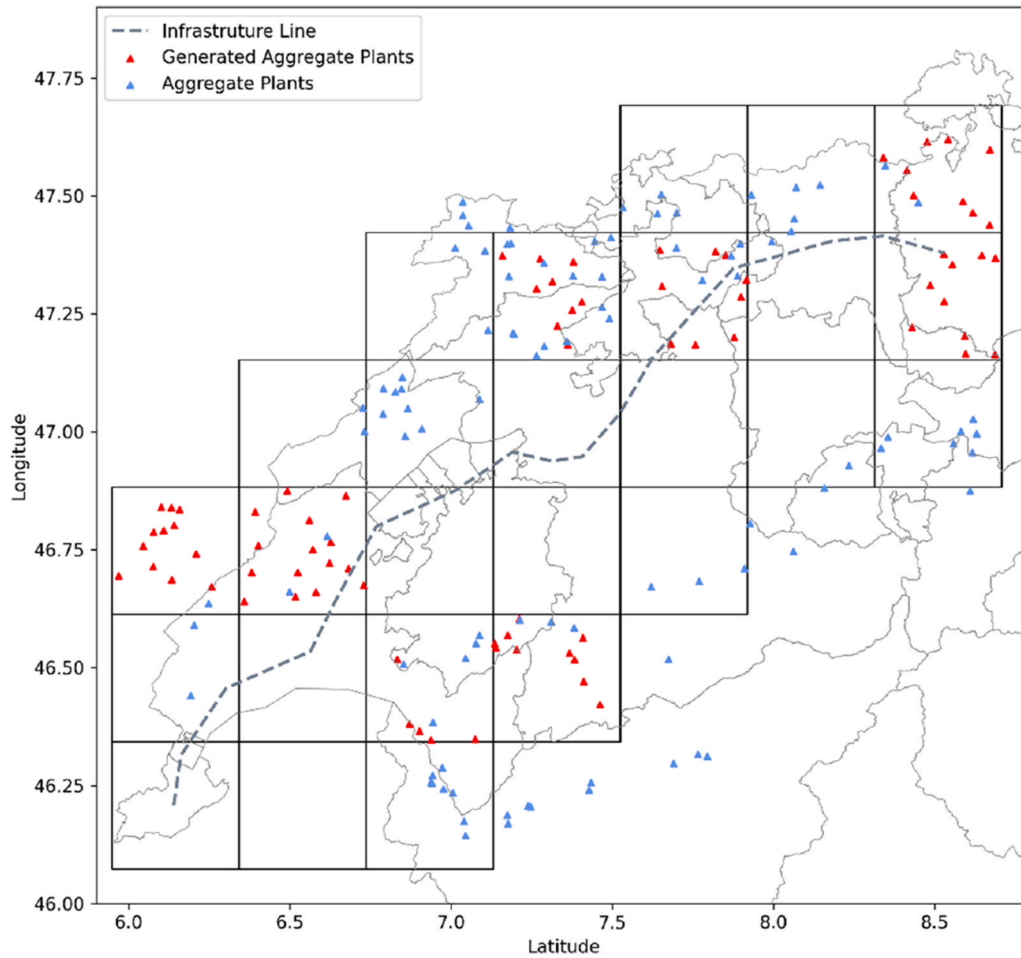


Fig. 5. Generated aggregate supplier locations vs. existing aggregate locations. The grid size is 30 km·30 km with the buffer zone radius of 35 km.

indicator for transportation by applying reduction factors ranging from 0.1 to 0.9 in steps of 0.1.

Economic parameters encompass the cost of factory reconfiguration per relocation and the cost indicator for transportation. Using electric trucks can reduce transportation costs by around 70 % (T. Earl and T. and Environmen t, 2018). Thus, we scaled this parameter by applying a reduction factor ranging from 0.3 to 0.9 in steps of 0.1.

### 3.6. Model implementation

The proposed model was implemented using Pyomo 6.7.1 (Bynum et al., 2021) and solved by IBM CPLEX (Cplex, 2009). The carbon emissions associated with the reconfiguration processes were estimated using Brightway 2.5 (Mutel, 2017) with the IPCC 2021 GWP100 method (IPCC et al., 2023). The transportation distances were calculated using GeoPandas 1.0.1 (Jordahl et al., 2020), with EPSG 3035 (ETRS89-extended, 2024) as the projected coordinate system. The result visualization is created with Matplotlib 3.10 (Hunter, 2007).

### 3.7. Case study description

In this paper, we constructed the base case scenarios by applying the mobile prefabrication factory to a hyperloop infrastructure project. The hyperloop concept consists of a passenger pod traveling through a tube under a light vacuum, propelled and levitated by a combination of permanent magnets and electromagnets (Decker et al., 2017). EuroTube Foundation (ETF) (EuroTube, 2024), a Swiss non-profit research organization, is dedicated to the development of hyperloop technology.

Their hyperloop infrastructure solution utilizes concrete tubes to lower production costs and facilitate easier maintenance and management throughout the infrastructure’s life cycle (Dallasega et al., 2023). In this case study, the prefabricated components (PCs) are the concrete tubes produced in the mobile prefabrication factory. The candidate factory locations were selected using the Multi-Criteria Decision Making (MCDM) method in collaboration with the factory design team from the Free University of Bozen-Bolzano and ETF (EuroTube, 2024). The main criteria included proximity to the infrastructure line, sufficient space for deploying the mobile prefabrication factory, and good accessibility to major roads.

Fig. 4 depicts the geographic information near the candidate factory locations 17 to 19 in this case study. The numbers below the red circles are the indices of the candidate factory locations. The infrastructure (dashed line) from Geneva to Zurich was defined in collaboration with ETF (EuroTube, 2024). The locations of materials suppliers were obtained from Google Maps (Google Maps, 2024). The green line demonstrates the transportation routes for concrete tubes from the candidate factory locations to the construction sites. The hyperloop infrastructure studied is approximately 250 km in length. Each PC measures 20 m in length. Since the MFLP is NP-hard, we partitioned the infrastructure into 250 pieces of 1-km segments instead of modeling the exact installation sites for 12,500 PCs. We assumed that each segment’s midpoint (represented by a grey square) serves as the construction site for every concrete 1 within that segment. Based on this segmentation, we reformulated Equation (3) and Equation (4) as Equation (20) and Equation (21) to calculate  $E_{inbound}$  and  $E_{outbound}$ , respectively. Here,  $l_k$  is the length of infrastructure segment  $k$  and  $l_p$  is the length of one piece of PC.  $m_n$

denotes the mass of material  $n$  required for producing one piece of PC while  $m_p$  represents the mass of one piece of PC.

$$E_{\text{inbound}}(x_{i,j,k}) = \sum_{n \in N} \sum_{i_n \in I_n} \sum_{j \in J} \sum_{k \in K} e_{i_n,j} \frac{l_k}{l_p} m_n d_{i_n,j} x_{i,j,k} \quad (20)$$

$$E_{\text{outbound}}(x_{i,j,k}) = \sum_{i_n \in I_n} \sum_{j \in J} \sum_{k \in K} e_{j,k} \frac{l_k}{l_p} m_p l_k d_{j,k} x_{i,j,k} \quad (21)$$

### 3.8. Input data for case study

Table 2 summarizes the key input data for the base case study. The bill of materials for the concrete tubes was provided by ETF (EuroTube, 2024). On average, each PC has a mass of 123.4 tons, consisting of 94.8 tons of aggregate, 24.2 tons of cement, and 4.4 tons of rebar. Due to the 20-m length of each PC, transportation is handled by a Longer Heavy Vehicle (LHV), whereas the raw materials are transported by standard trucks. Carbon emissions indicators were obtained from Ecoinvent 3.9.1 database (ecoinvent, 2024), and the cost indicators for transportation were sourced from a report published by the Netherlands Institute for Transport Policy Analysis (Van der Meulen et al., 2024).

The mobile prefabrication factory employs a lightweight pneumatic tent solution to reduce carbon emissions and relocation costs, as detailed in (Dallasega et al., 2023) and (Alix et al., 2019). The mobile prefabrication factory weighs approximately 770 tons, including the factory's structure and machinery. Table 3 presents the energy type, total operation time, carbon emissions indicators, and hourly costs for the machinery used in the factory reconfiguration process. Based on this data, each factory relocation results in emissions of approximately 3865 kg CO<sub>2</sub>-eq and incurs costs of about 13,000 euros.

## 4. Results

### 4.1. Base case results

Fig. 6 illustrates the optimized results for varying numbers of factory relocations in the base case for both carbon emissions and cost. Zero relocations represent the scenario where the mobile prefabrication factory is deployed at a single optimal location to minimize overall carbon emissions. Factory reconfiguration accounts for site preparation, factory assembly, disassembly, and site restoration at each relocation. In contrast, factory transportation refers solely to the movement of factory components between locations. Fig. 6(a) and (b) demonstrate that using a mobile prefabrication factory significantly reduces transportation carbon emissions and costs. This reduction is primarily due to shorter outbound transportation distances achieved through factory relocation, as shown in Fig. 6(c) and (d). In contrast, emissions and costs from inbound transportation remain relatively constant across all scenarios, averaging approximately 11.5 tons CO<sub>2</sub>-eq and 27.5 kEuro per kilometer of construction, respectively.

**Table 2**  
Main input data for the optimization model.

	Mass [ton]	Commodity group	Vehicle type	Carbon emissions indicator [kgCO <sub>2</sub> -eq/tkm]	Cost [euro/tkm]
Aggregate per PC	94.8	Dry bulk	Truck	0.1478	0.395
Cement per PC	24.2	Break bulk	Truck	0.1478	0.375
Rebar per PC	4.4	Break bulk	Truck	0.1478	0.375
PCs	123.4	Break bulk	LHV	0.1002	0.122
Factory	770	Break bulk	Truck	0.1478	0.375

Fig. 6(a) highlights aggregate transportation as the largest contributor to carbon emissions due to its high material mass despite having shorter transport distances than cement and rebar. Rebar transportation has the longest distance, followed by cement. In contrast, factory relocation distances vary minimally, resulting in stable emissions and costs associated with relocations. Fig. 6(e) and (f) show that factory relocations have a slightly greater impact on costs than on carbon emissions. Consequently, the optimal number of relocations for minimizing costs is 10, whereas 12 relocations minimize carbon emissions. However, incremental carbon emission reductions are less than 5 % after five relocations. Considering the complexity and duration of relocation processes, we recommend three to five relocations as an efficient strategy to balance environmental benefits and economic feasibility in this case study.

### 4.2. Sensitivity analyses results

#### 4.2.1. Sensitivity analysis for carbon emissions optimization

Fig. 7 presents the results of the sensitivity analysis on carbon emissions across diverse sensitivity analysis scenarios, showing consistent reductions when using mobile prefabrication factories. Except the infrastructure length (shown in light grey), a clear trend across all parameter variations, is that total carbon emissions decline sharply in the first few relocations and begin to stabilize after approximately three to five relocations. Given a total infrastructure length of 250 km, this corresponds to a relocation interval of roughly 50–80 km. This reinforces it as a robust and generalizable factory relocation planning rule for balancing carbon efficiency and operational feasibility.

Among all parameters analyzed, the aggregate suppliers' distance to the infrastructure line, average PC mass per unit length, and the carbon emissions indicator for transportation are the most influential factors driving carbon emissions. The dominance of the geospatial locations of the aggregate is due to the large quantities required for PCs production. Although cement is needed in smaller amounts, its relatively longer transportation distances give it a noticeable carbon impact as well. In contrast, the distance and distribution of rebar suppliers has a minor effect. The geospatial distribution of candidate factory locations also influences emissions, but to a lesser extent. Variations in factory distance to the infrastructure line, number of candidates, and their distribution have a limited effect once the carbon emissions stabilize after five relocations.

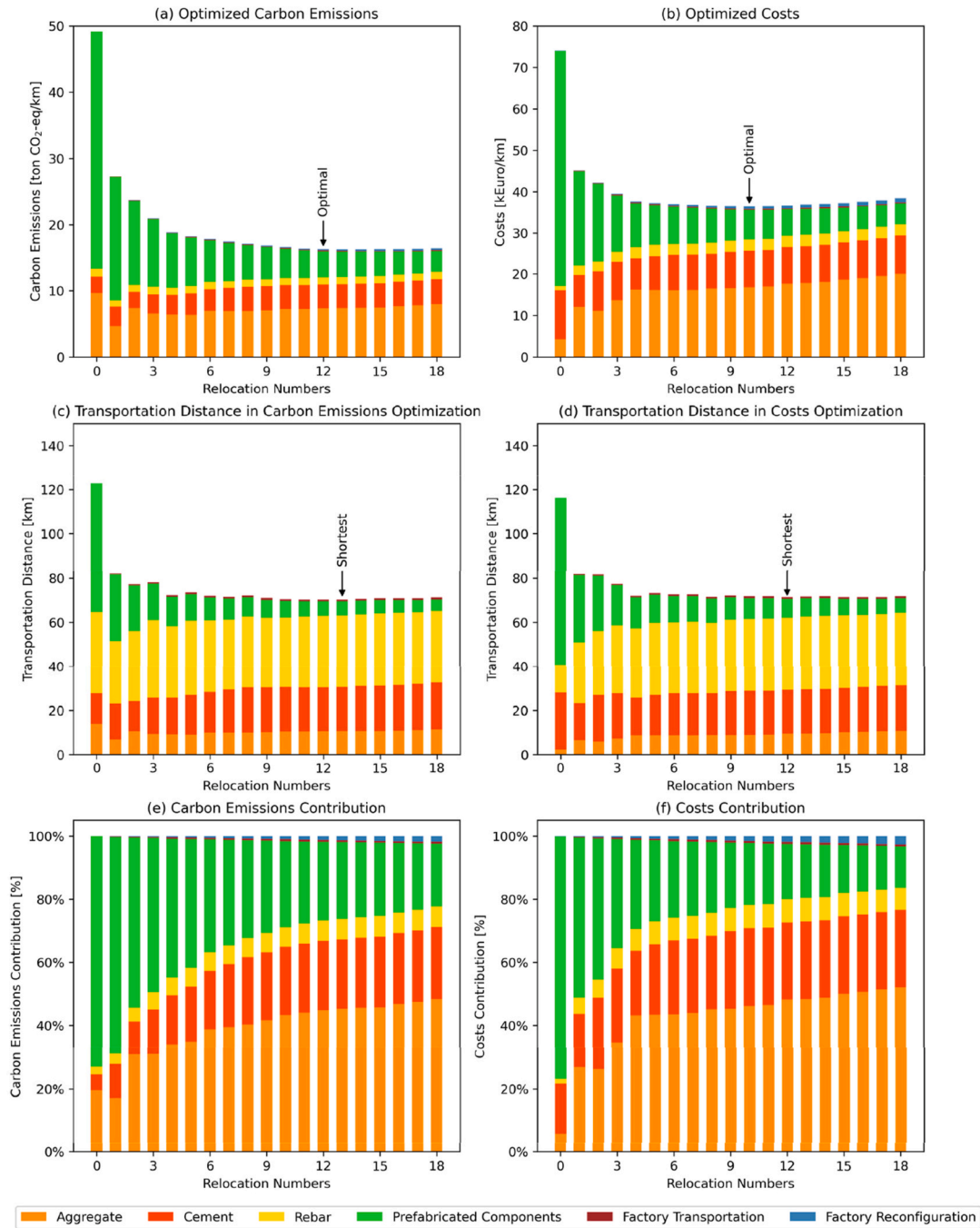
For physical parameters, while the total mobile factory mass has marginal impact, both the infrastructure length and PC mass per unit length are critical. Longer infrastructures inherently lead to higher transportation emissions due to greater outbound distances. Heavier infrastructures benefit more from mobile factory relocations, as the lightweight design of the mobile factory helps offset transportation emissions, leading to greater overall carbon reductions.

Environmental parameters, such as the carbon emissions indicator and factory reconfiguration emissions, influence the optimal relocation strategy. Compared to the total mass of the factory, emissions from factory reconfiguration play a more significant role in the trade-off between relocating the factory and transporting PCs. However, this impact is relatively minor, as the optimal number of relocations stabilizes at 13 even when reconfiguration emissions increase tenfold. The reduction in the carbon emissions indicator represents the future scenario where electric trucks replace diesel vehicles. While this shift significantly lowers the overall carbon emissions at each relocation number, it also reduces the incremental emission benefits of relocating the mobile factory, slightly shifting the optimal number of relocations from 12 to 11.

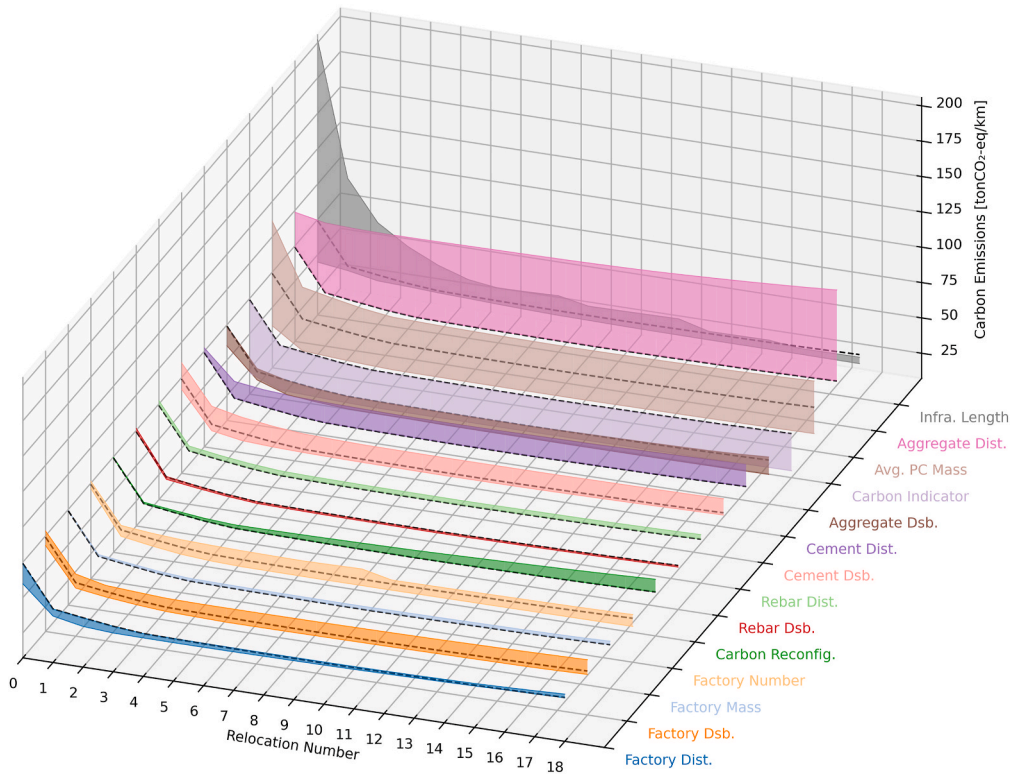
Fig. 8(a) illustrates carbon emissions per kilometer for infrastructure lengths ranging from 50 km to 1000 km across different relocation numbers, with the color gradient representing infrastructure length. Carbon emissions decrease significantly with initial relocations, stabilizing at higher relocation frequencies. Longer infrastructures consistently yield higher emissions at a fixed number of relocations. The

**Table 3**  
Data for factory reconfiguration processes.

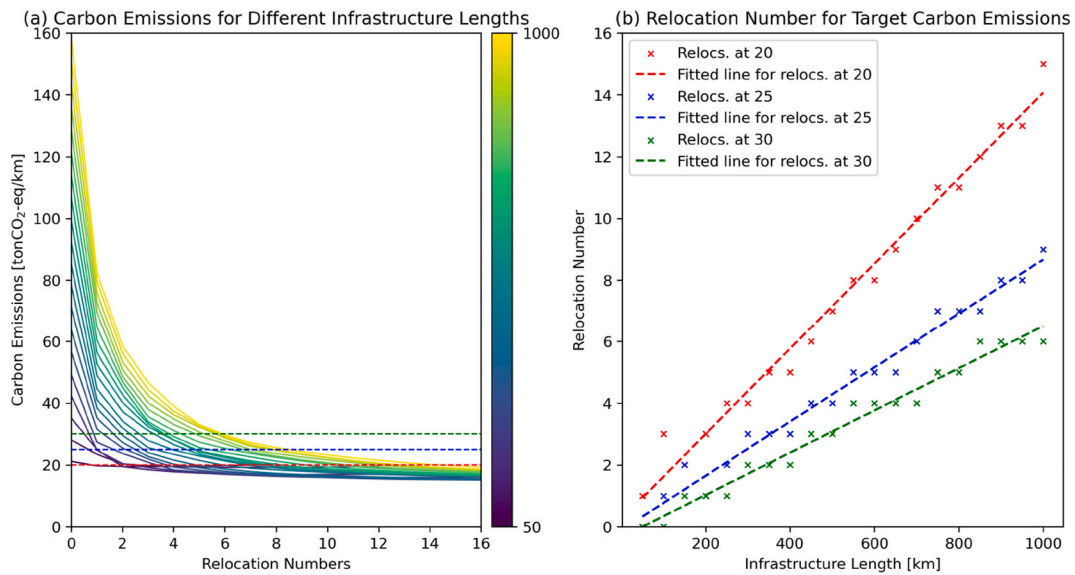
Machine	Energy Type	Total operation time [h/reconfiguration]	Carbon emissions indicator [kg CO <sub>2</sub> -eq/h]	Cost [euro/h]
Bulldozer	diesel	8	25.5	300
Truck	diesel	4	161.2	200
Roller	diesel	4	161.2	200
Truck crane	diesel	20	87.9	300
Drilling rig	diesel	4	21.6	600
Mobile compressor	diesel	6	87.9	100



**Fig. 6.** Optimized results for different factory relocation numbers in the base case: (a) Optimized carbon emissions, (b) Optimized costs, (c) Transportation distance in carbon emissions optimization, (d) Transportation distance in costs optimization, (e) Carbon emissions contribution, (f) Costs contribution.



**Fig. 7.** Sensitivity analyses results for carbon emissions. The shaded areas, matching the colors of the tick labels, show the variation in carbon emissions per kilometer caused by changes in individual parameters, while the dashed line represents the base-case cost.



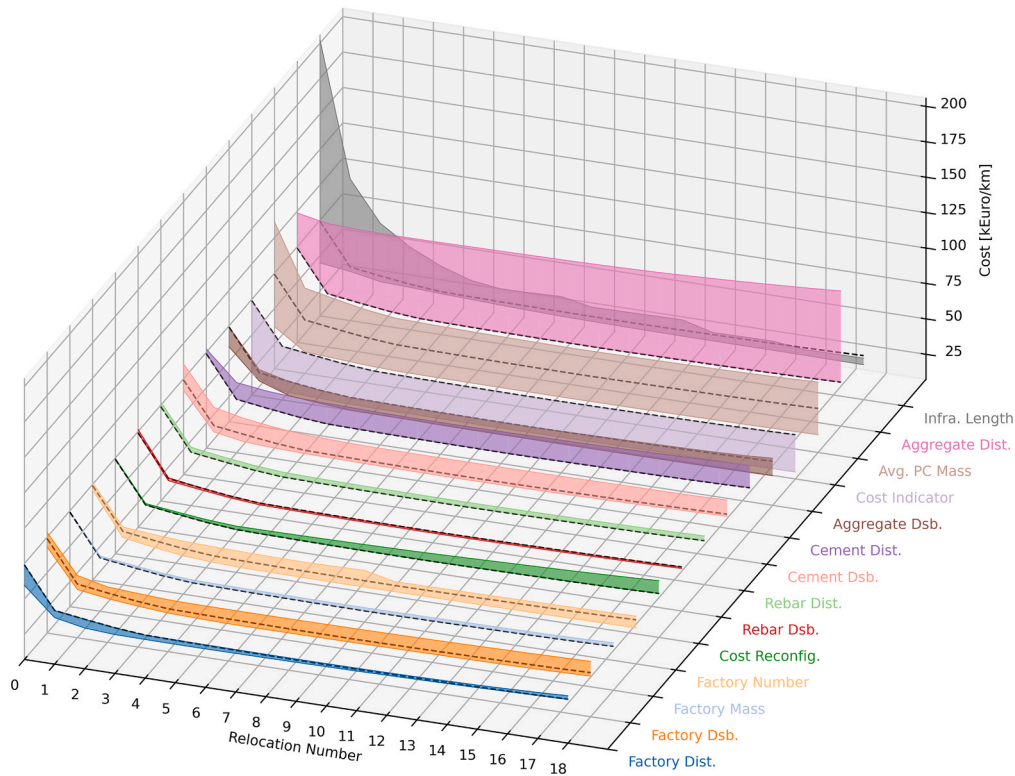
**Fig. 8.** (a) Carbon emissions for different relocation numbers and different infrastructure length with the color gradient representing total infrastructure length. (b) Required minimal relocation numbers to achieve target carbon emissions for varying infrastructure lengths. Red, blue, and green crosses indicate the relocation numbers needed to reach 20, 25, and 30 tons CO<sub>2</sub>-eq/km, respectively, with dashed lines representing fitted trends.

horizontal dashed lines represent emission targets of 20 (red), 25 (blue), and 30 (green) tons CO<sub>2</sub>-eq/km. Fig. 8(b) shows the relationship between infrastructure lengths and the minimal number of relocations needed to achieve lower emissions than these emission targets. The dashed lines indicate linear regression fits, confirming a strong linear correlation: longer infrastructures necessitate more frequent relocations to meet stricter emission targets. This analysis provides practical guidance for defining relocation strategies based on environmental targets

across varying infrastructure lengths. For example, to achieve a carbon emissions around 20 ton CO<sub>2</sub>-eq/km, the results indicate that the factory should be relocated approximately every 50–80 km, regardless of the total project length. This consistency across scenarios reinforces the robustness and general applicability of the proposed relocation rule.

4.2.2. Sensitivity analysis for cost optimization

Fig. 9 illustrates the results of the sensitivity analysis for costs,

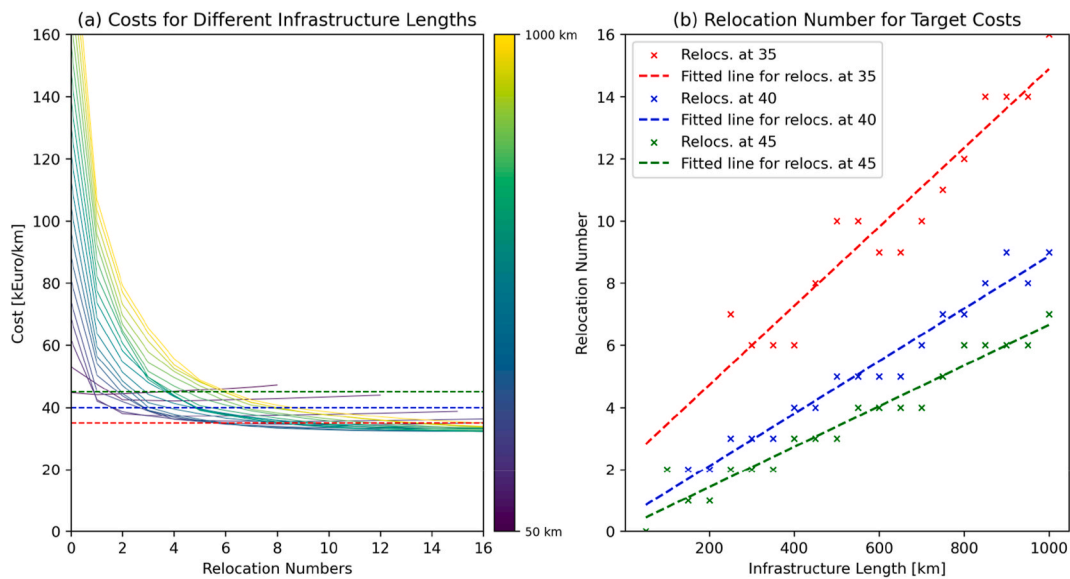


**Fig. 9.** Sensitivity analyses result for costs. The shaded areas, matching the colors of the tick labels, show the variation in costs per kilometer caused by changes in individual parameters, while the dashed line represents the base-case cost.

revealing patterns similar to those observed in the carbon emissions analysis. The results confirm the effectiveness of mobile prefabrication factories in reducing overall transportation costs, with the total cost stabilizing after approximately three to five relocations in all scenarios, except for infrastructure length (light grey). However, optimal relocation numbers for minimizing cost are consistently lower than those required for minimizing emissions. This is due to the higher relative impact of factory reconfiguration processes on the overall costs.

Notably, the factory reconfiguration costs per relocation notably

outweigh total factory mass in influencing the trade-off between relocating the factory and transporting PCs. As reconfiguration costs increase, the optimal number of relocations decreases from ten to four. Meanwhile, improving transportation cost indicators by replacing diesel trucks with electric ones lowers the baseline cost across all relocation numbers. This trend closely mirrors the pattern observed in carbon emissions reductions in Fig. 7. However, the cost reduction is slightly less substantial than the carbon emissions reduction, as the cost per ton-kilometer can be reduced by only up to 70 % (T. Earl and T. and



**Fig. 10.** (a) Costs for different relocation numbers and different infrastructure length with the color gradient representing total infrastructure length. (b) Required minimal relocation numbers to reach target cost for different infrastructure length. Red, blue, and green crosses indicate the relocation numbers needed to reach 35, 40, and 45 kEuro/km, respectively, with dashed lines representing fitted trends.

Environment, 2018).

Fig. 10 depicts the cost trends across varying numbers of relocations and infrastructure lengths, which follows a similar pattern to carbon emissions in Fig. 8. Fig. 10(a) illustrates that costs decrease significantly during the initial relocations and then stabilize. Fig. 10(b) highlights that longer infrastructure lengths necessitate more relocations to achieve cost targets, following linear trends similar to Fig. 8(b). Compared to carbon emissions, costs optimization requires slightly fewer relocations due to the greater influence of factory reconfiguration expenses. However, relocating the factory every 50–80 km of construction remains effective for cost optimization.

## 5. Discussion

In this paper, we presented a comprehensive optimization model that integrates inbound and outbound transportation as well as factory reconfiguration processes, offering a holistic view of mobile prefabrication factory operations. Our findings demonstrate substantial potential for reducing carbon emissions and costs by strategically relocating mobile prefabrication factories. By explicitly quantifying carbon emissions via LCA, the model moves beyond traditional cost-based analyses and highlights the high potential of both carbon and cost reduction offered by the adoption of mobile prefabrication factories in linear infrastructure projects.

The extensive sensitivity analyses base diverse scenarios confirm that mobile prefabrication factories can substantially reduce both carbon emissions and costs across diverse scenarios. Specifically, aggregate supplier locations have the largest impact among geospatial parameters, due to the large volumes required for PC production. Despite variations in candidate factory locations, both emissions and costs stabilize after approximately five relocations when constructing a 250-km hyperloop infrastructure. Longer infrastructures and heavier prefabricated components per unit length inherently increase emissions and costs, but also amplify overall benefits derived from relocations. Factory reconfiguration activities have a stronger influence than total factory mass on the trade-off between relocation frequency and outbound transportation for both environmental and economic impacts. While adopting electric trucks significantly lowers emissions and costs, it also reduces incremental benefits from frequent relocations. Overall, relocating the factory approximately every 50–80 km offers a practical balance between sustainability gains and logistical feasibility.

While providing general insights into the carbon reduction potential of using mobile factory for infrastructure, this study has certain limitations. The model does not consider the influence of traffic conditions on emissions. However, according to (Kellner, 2016), the average increase in carbon emissions due to traffic congestion remains below 5 % with a small linear coefficient of 0.025. The sensitivity analysis results indicate this marginal impact is negligible compared to the significant carbon reduction achieved through relocating the mobile factory to shorten outbound transportation distances.

Additionally, our economic model excludes the potential costs incurred by the temporary disruption of production during the factory relocation. While such disruption could theoretically incur financial penalties, the work of Rauch and Dallasega (Dallasega et al., 2023; Rauch et al., 2015a, 2015b, 2017) underscores the feasibility of mitigating such disruptions through advanced synchronization strategies. For example, parallelizing factory relocation with on-site prefabricated components installation can avoid disruptions to the overall project timeline. Furthermore, the pneumatic design of the mobile prefabrication factory further enhances operational flexibility, reducing relocation-induced disruptions by facilitating rapid reconfiguration (Dallasega et al., 2023). Although our model assumes unlimited supplier capacity for prefabricated concrete materials, this constraint can be addressed by securing material commitments in advance through strategic procurement planning, ensuring suppliers align with project demands (Howell and Ballard, 1996).

Collectively, these limitations do not undermine the study's core findings but instead highlight opportunities for refinement. Future studies could extend this work through multi-objective optimization frameworks that balance carbon emissions, economic costs, and scheduling constraints to enable more holistic decision-making support for operating mobile prefabrication factories in diverse linear infrastructure projects such as roads and railways.

## 6. Conclusions

This paper presents a holistic strategy for optimizing mobile prefabrication factories in large-scale linear infrastructure projects by integrating material specific supply-chain modeling with Life Cycle Assessment (LCA) and Geospatial Information System (GIS).

The Geneva–Zurich hyperloop case study demonstrates that strategically relocating a lightweight pneumatic mobile factory four times lowers carbon emissions by 62 % and costs by 49 % compared to a stationary scenario. Such reductions are mainly due to the shortened outbound transportation of prefabricated components. Although the direct environmental and economic impacts of factory reconfigurations are relatively small, they function as a critical optimization constraint that enables the identification of practical solutions rather than mathematically infinite relocations. Through the sensitivity analysis based on diverse scenarios, we found that relocating the factory approximately every 50–80 km of construction achieved a robust balance between cost efficiency and carbon reduction across diverse scenarios. While specific inputs such as carbon emissions indicators, supplier distributions, and reconfiguration-related emissions may vary across region, the core benefit of reducing outbound transportation by moving the lightweight mobile factory rather than hauling heavy precast components remains consistent. This makes the proposed relocation strategy broadly applicable to the planning of large-scale linear infrastructure projects across diverse geographic and logistical contexts.

This research extends existing studies on containerized factories from sectors such as oil, chemicals, and manufacturing to mobile factories requiring on-site assembly and disassembly in the construction domain. The proposed decision-support framework provides practical guidance for simultaneously achieving cost-effectiveness and carbon reductions in large-scale infrastructure construction projects.

## CRedit authorship contribution statement

**Jianxiang Ma:** Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jianpeng Cao:** Writing – review & editing, Visualization, Project administration, Methodology. **Lorenzo Benedetti:** Writing – review & editing, Resources, Data curation. **Andrea Revolti:** Resources, Data curation. **Edwin Zea Escamilla:** Writing – review & editing, Visualization, Supervision, Methodology. **Guillaume Habert:** Writing – review & editing, Visualization, Supervision, Methodology, Funding acquisition.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Data availability

Data will be made available on request.

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