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Original Article

Design of a Portable Freight Ropeway for Transporting Construction Materials on Hillside

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Abstract - *Transporting construction materials in mountainous or sloping terrain poses significant logistical challenges due to limited accessibility. This study proposes the design of a portable freight ropeway for transporting construction materials in hillside areas, addressing the significant challenges posed by mountainous terrain where traditional vehicles struggle, as is the case of the Hill of San Cristobal in Lima, Peru. The results indicate a total weight of 580.61 N for the load-bearing cable, with a Safety Factor (SF) of 3, ensuring the system can withstand up to three times the anticipated loads. The required diameter for the steel cable, which has a tensile strength of 1670 MPa, is calculated to be 12.7 mm, while the cable tension is determined to be 633.68 N. A static simulation of the steel support trestle reveals a maximum stress of 17.52 MPa, well within safe limits, confirming the design's integrity. Additionally, the winch power requirement is approximately 115.2 W, highlighting the efficiency of this low-tonnage design. This innovative solution adheres to the VDI 2221 standard, enhancing the practicality and safety of construction operations in remote and steep terrains, and represents a significant improvement over the traditional method.*

Keywords - *Ropeway, Construction, Portable Design, Hillside, Safety Factor.*

1. Introduction

Transporting materials in mountainous or sloping terrain poses significant challenges for construction projects [1], as land vehicles often struggle with difficult terrain and access limitations, as shown in Figure 1. Consequently, aerial ropeways emerge as the most effective solution for transporting construction materials in such environments, as they provide direct connections between loading and unloading areas, streamlining the process [2].

Fig. 1 Improvised access on the hillsides of Lima [3]

Urban sprawl and growing overpopulation in the city of Lima have increased the demand for housing. As a result, the population is forced to occupy hillside areas for housing, as shown in Figure 2. Aerial cableways are efficient and sustainable solutions for urban transportation, complementing existing public transit systems. They enhance accessibility, reduce congestion, and navigate challenging terrains, making them invaluable for connecting isolated communities while minimizing environmental impact [4].

Fig. 2 Hill of San Cristobal in Lima, Peru [5]

Research by D. Bryja et al. [6] highlights the importance of ropeway inclination on the nonlinear interaction between the carrying cable and the swinging motion of the carriers, emphasizing the operational significance of this inclination.

Albert's invention of steel cable in 1834 significantly accelerated the development of new ropeway systems. Initially designed for transporting goods, ropeways later evolved to accommodate passenger transport. In [7], the authors provide an extensive review of the historical development of rope manufacturing and ropeway systems. The article is structured into two parts: the first part provides an overview of the historical development of rope manufacturing. In contrast, the second part discusses the various stages of ropeway system development from ancient times to the interwar period.

The author Guiju et al. proposed the design of a ropeway with a 12 mm thick circulating traction cable with steel material [2], designed specifically for use in small-scale steep mountain orchards to perform a variety of agricultural tasks, such as transporting fruit and crop protection equipment. On the other hand, the design approach can vary; author R. N. Farahani [8] indicates that an improvement for the ropeway load would be the implementation of an auxiliary winch that allows material transport to be manipulated without the intervention of brute force by the operator. This improvement focuses on freight and passenger ropeways. Research [9] evaluates the impact of cost on the design of the cargo cableway considering design, assembly, deformation and strength constraints.

A mono-cable freight ropeway design with a steel traction-bearing cable has been proposed by Lagerev et al [10]. The design was customized for the mining industry and is optimized to transport heavy loads in mountainous regions far away from development potential, keeping construction costs low. This is achieved by adjusting the distances between intermediate supports and the cable tension force. In addition, Nozadze et al. [11] proposed the design of a self-propelled mobile vehicle driven by ropes with a steel traction cable for load transport in terrain with different inclinations and difficulties up to 100 kg. This rope is optimized for the easy handling, compactness and mobility of the proposed ropeway, allowing quick dismantling and reassembling at new locations.

However, designs proposed by other researchers focused on two-cable ropeways highlight that tonnage significantly influences the choice of multiple cables. Two to four cables can be implemented to improve system stability and reduce wear on individual cables, extending their lifespan [12-14].

To determine the required diameter of the supporting cable, it is essential to calculate the forces acting upon it. Based on data from previous studies [12], which often focus on high-capacity ropeway systems employing multiple cables for load distribution, the precise power requirements for such systems are frequently overlooked. This research aims to address this gap by providing a methodology for calculating the necessary power for winch selection. To achieve this, a challenging construction scenario involving rugged terrain, a 50 m length, and a 20 m height difference was considered.

2. Materials and Methods

The design follows the guidelines of the VDI 2221 standard, divided into three stages [15]. The first stage covers specifications and functional structures. The second stage focuses on evaluating the main solutions. Finally, the selected solution is highlighted in the modular structures dedicated to developing the final design.

2.1. Specification

The list of specifications covers all the requirements that the design must meet. The design, material, energy, and control specifications of the proposed machine are shown in Table 1.

Table 1. List of specifications

Category	Specification
Design	A trestle is required to reduce the stress on the supporting points.
Materials	A trestle is required to be composed of rectangular steel tubes.
Energy	A gasoline-powered winch is required to operate the ropeway in remote areas without electricity.
Control	A remote-control system is required to operate the winch and manage the movement of the cargo ropeway.

2.2. Function Structures

Figure 3 shows the function structures of the mechanical processes of the system.

2.3. Principal Solutions

Previous work has focused on low-tonnage ropeways of less than 2 to 5 tons [14]. To overcome the challenges of transporting construction materials in hillside areas, a portable cargo ropeway system has been developed. This study considers a single-cable system sufficient for the load requirements given the cable size and transportation distance. The trestle is constructed from rectangular steel tubes to enhance portability, allowing for easy installation in harsh hillside environments. Low-tonnage electric ropeway winches have maximum weight ratings of 4 tons with a power rating of 1.4 kW [12]. Given the maximum load capacity of less than 1 ton and the need for operation in hillside areas with limited electricity access, an 800W gasoline-powered winch is considered the most suitable option.

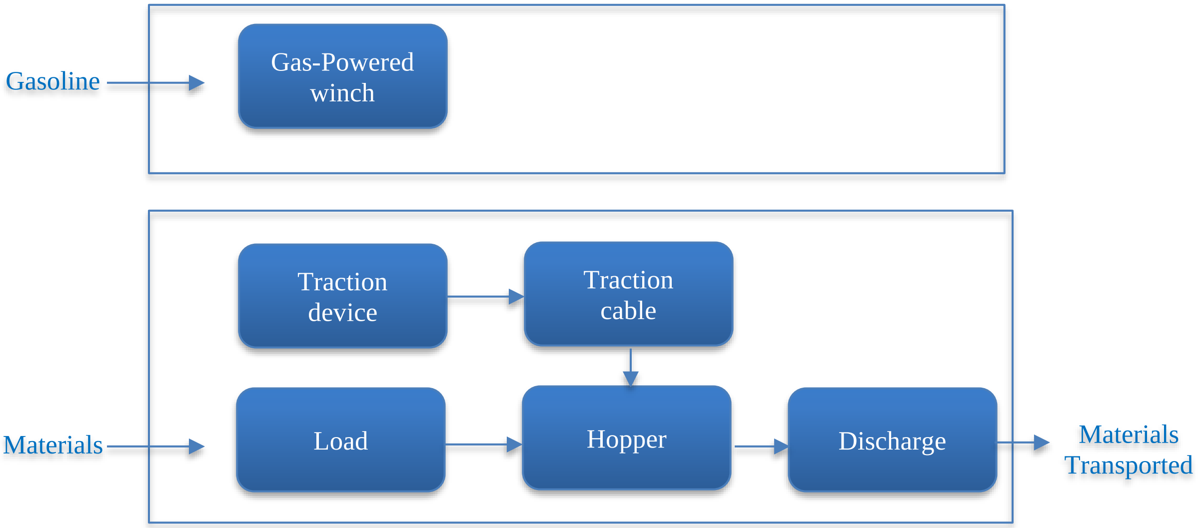

Fig. 3 Function structures

Table 2 shows the selection of the solution carried out through a detailed technical evaluation that considers five key specifications, comparing the technical values obtained from each proposal with the technical value of the ideal solution, which is 13.6. In this analysis, the proposals of Guiju et al. and R. N. Farahani et al. were evaluated as 1st and 2nd, respectively, finding that the design proposed as solution 3, with a technical value of 10.2, is the closest to the ideal solution, which justifies its selection as the most appropriate option. Table 3 shows the cost of solution 3, which is the design proposal.

3. Module Structures

3.1. Mechanical Structure

The general design of the Portable Freight Ropeway for Transporting Construction Materials in Hillside Areas is shown in Figure 4. The hopper used to load and unload materials is positioned in the center of the transport system. At both ends are the trestles at different levels, providing the necessary support and elevation for the ropeway to function efficiently. The ropeway is used to transport construction materials in the hills.

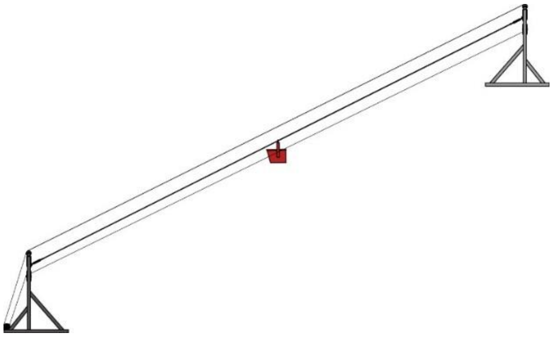

Fig. 4 The overall design of the Portable Freight Ropeway

Figure 5 shows an isometric view of the construction materials transport ropeway. In the middle part is the transport hopper, which is supported by cables and designed to carry materials efficiently. For mechanical transmission, rollers and steel cables are connected to the traction device and a gas-powered winch, ensuring smooth and reliable operation. This setup allows for the effective movement of materials across varying elevations and distances.

Table 2. Technical value analysis

Solution		**1st**		**2nd**		**3rd**		**Ideal**	
Specification	g	p	gp	p	gp	p	gp	p	gp
Design	0.5	2	1	2	1	3	1.5	4	2
Function	0.9	3	2.7	3	2.7	3	2.7	4	3.2
Material	0.4	2	0.8	2	0.8	3	1.2	4	1.6
Energy	0.9	2	1.8	3	1.8	3	2.7	4	3.2
Data	0.7	1	0.7	2	1.4	3	2.1	4	2.1
Total Score		10	7	13	7.7	18	10.2	20	12.1
Technical value		7		8.6		10.2		13.6	

Table 3. List of cost

No.	Part	Cost
1	Compression	$ 7.87
2	Turn	$ 5.20
3	Traction	$ 89.99
4	Hopper	$ 50.36
5	Traction	$ 28.8
6	Load	$ 16.00
7	Roller	$ 7.84
8	Trestle	$ 201.0
9	Connecting	$ 18.00
10	Screws	$ 6.80
TOTAL		**$ 431.86**

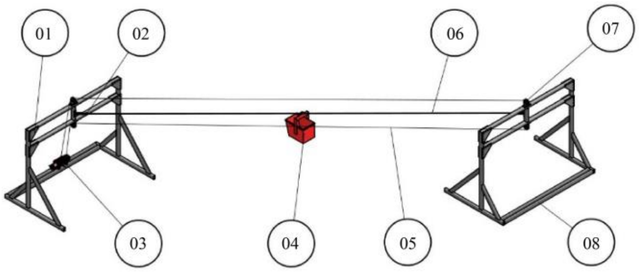

Fig. 5 Isometric view of the overall design of the portable freight ropeway

Figure 6 shows the cable system consists of two rollers; the upper one keeps the traction cable moving along the top of the system and then returns it via the lower roller. In the central part of the trestle, there is a slack link that adjusts the tension of the load-bearing cable, keeping the hopper in its moving position.

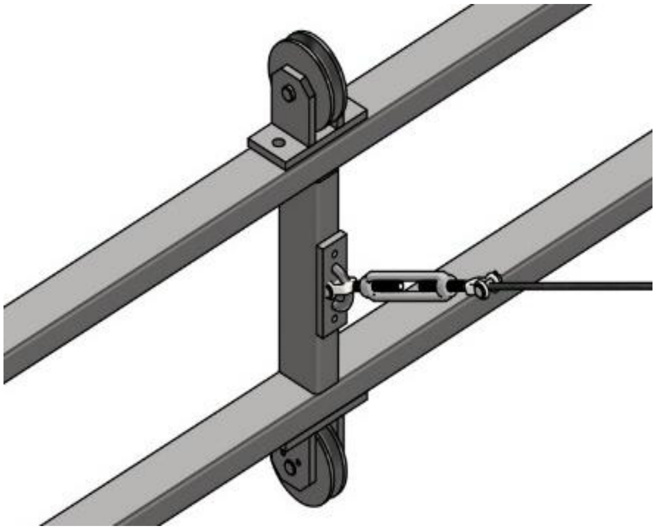

Fig. 6 View of the cable system

The exploded view in Figure 7 illustrates the modular design of the portable trestle assembly, facilitating easy transportation and on-site assembly. The pieces to join the frame structure are connecting plates secured by screws for assembly.

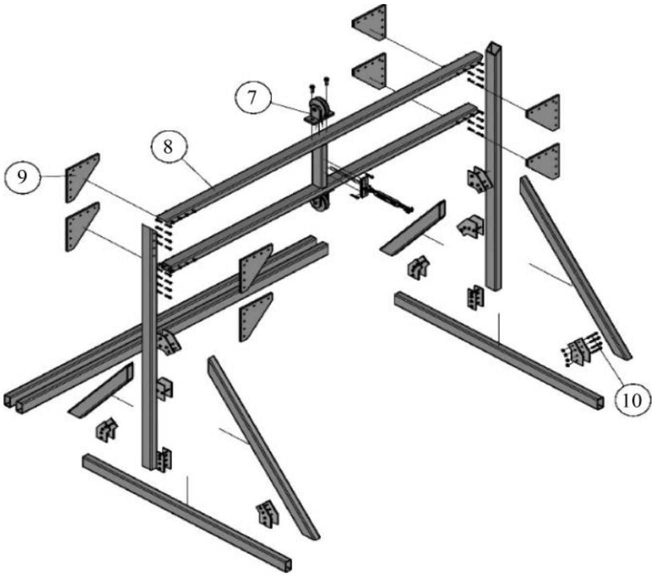

Fig. 7 Isometric view of the portable trestle assembly

Table 4 shows all parts of the portable freight lane according to the numbers assigned to the components.

Table 4. List of parts

No.	Part	No.	Part
1	Compression	6	Load
2	Turn	7	Roller
3	Traction	8	Trestle
4	Hopper	9	Connecting
5	Traction	10	Screws

To determine the total load of the concrete hopper, several factors must be taken into account, including the volume of the hopper, which is $0.0015\, m^3$, the density of the concrete, which is $2400\, kg/m^3$ and the structural capacity, where the volume that the concrete will cover is considered to be $0.019\, kg/m^3$.

Equation 1 calculates the mass of the concrete contained in the hopper, where $\mathrm{m_{hopper}}$ is the mass, $\mathrm{V_{hopper}}$ is the volume of the hopper and ρ_{steel} is the density of the steel.

$$m_{hopper} = V_{hopper} \times \rho_{steel} \tag{1}$$

Equation 2 calculates the mass of the concrete contained in the hopper, where the mass of the concrete is $\mathrm{m_{concrete}}$, the volume of the hopper capacity is V, and the density of the concrete is ρ_{concrete}

$$m_{concrete} = V \times \rho_{concrete} \tag{2}$$

The mass of the hopper is determined to be 13.126 kg from the above calculations and data. This value is obtained from the volume of the hopper and the density of the material it is made of. Similarly, the mass of the concrete is determined to be 46.085 kg. This calculation takes into account the volume of the concrete and its density. These values are crucial to ensure the structural integrity and stability of the design.

To ensure the safety and efficient operation of the system, previous research used an SF of 4; since the weight suspended from the cable was between 2 and 5 tons, using this data as a reference [14], it was decided to choose an SF greater than 2 as the design proposed by Nozadze et al. [11] because the design is of low tonnage; therefore it was decided to select an SF of 3 to guarantee the reliability and robustness of the system under operational conditions taking into account that the proposed design is intended for the transport of construction materials. This factor implies that the system must withstand up to three times the anticipated loads before it is considered at risk of failure.

Equation 3 calculates the total weight that the Load-Bearing Cable must support. The suspended load is the sum of the masses of the hopper and the concrete multiplied by the acceleration of gravity, which is taken to be $9.81 m/s^2$.

$$F_{total} = \left(m_{hopper} + m_{concrete}\right) \times g \tag{3}$$

Replacing the previously obtained values, we obtain 580.61N, which represents the total weight that the load-bearing cable must support.

Equation 4 calculates the cable tension generated by the diagonal inclination where the angle θ is determined by the ratio of Height and Length.

$$\sin\theta = \frac{H}{L} \tag{4}$$

With this formula, we obtain the angle of inclination of the hillside concerning the data mentioned above for calculating the tension, which is 23.58°.

Equation 5 calculates the tension in the cable where the hopper and concrete are suspended, where T is the cable tension.

$$T = \frac{F}{\cos\theta} \tag{5}$$

The data obtained from the total weight and the inclination angle are obtained from the formula 633.68 N.

Equation 6 calculates the maximum allowable stress in the cable, where an SF of 3 is considered, where S_t is the material strength limit. The cable material is steel with a fiber core and a tensile strength of 1670 MPa [16].

$$\sigma_{max} = \frac{S_t}{SF} \tag{6}$$

The maximum tension that the Load-Bearing Cable can withstand is 556.67 Mpa.

Equation 7 calculates the diameter of the Load-Bearing Cable for the design requirements.

$$d = \sqrt{\frac{4T}{\pi\sigma_{max}}} \tag{7}$$

Substituting the values gives a diameter of 11.52 mm for the supporting cable required by the design. The manual Dogo Tuls [16] shows 1/2' steel wire ropes, equivalent to 12.7 mm. Since flexibility and weight are factors in the ropeway design, choosing a 12.7 mm diameter steel wire rope with a fiber core is the most suitable for the proposed design.

To determine the required winch power for transporting materials, the parallel force that the winch must overcome is first calculated using Equation (8), where $F_{parallel}$ is the load weight, and θ is 23.58°. The power required is then determined by Equation (9), where v is the lifting speed. Frictional and wind forces, as well as the elongation of the steel wire rope, are not considered in the calculation.

$$F_{parallel} = F \times \sin\theta \tag{8}$$

$$P = F_{parallel} \times v \tag{9}$$

Substituting the values obtained from the previous equations, the winch lifts a load of 580.61 N at a 23.58° incline at a lifting speed of 0.5 m/s, resulting in a required power of approximately 115.2 W.

4. Results

The simulation that was carried out was the stress analysis using Finite Element Analysis (FEA) of the 3D modeling software Autodesk Inventor, where the analysis of the structural behavior of the trestle under the various loading conditions presented by the design as the support with the specified dimensions of 2 1/2 x 1 1/2 x 1/8 in AISC mild steel tubes was simulated to determine the maximum stress caused by the cable tension supporting the hopper and concrete. Figure 8 shows a maximum stress obtained of 17.52 MPa at the midpoint of the rollers. Given the steel's tensile strength of 345 MPa, the stress is within allowable limits, indicating a safe design. The image shows a beam subjected to a combined loading of a 580.61 N horizontal force from the steel cable and a vertical gravitational force. The resulting deformation highlights the significance of the maximum stress, which represents the highest stress experienced by the beam. This parameter is crucial for ensuring the beam's structural integrity and preventing failure.

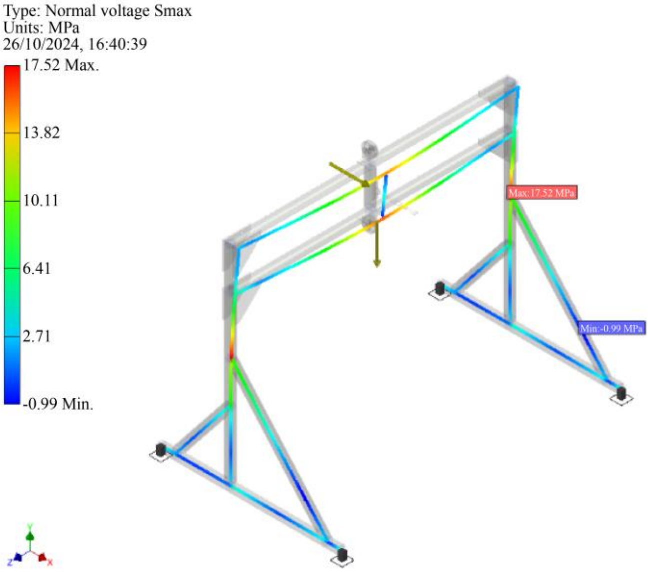

Fig. 8 Static simulation of the trestle

5. Discussion

The design of a portable ropeway for transporting materials in mountainous areas presents significant challenges that must be addressed by carefully analysing several critical factors, including rope diameter, suspended weight, motor power, and structural integrity. In densely populated urban areas such as Lima, Peru, ropeways are used to transport construction materials to difficult-to-access hillsides. Furthermore, their implementation in reforestation projects in mountainous urban areas facilitates the transport of the necessary plants and equipment. These case studies validate the ropeway design and highlight its versatility and efficiency in diverse contexts, demonstrating its potential to solve logistical problems in challenging environments.

The results obtained from the calculation of the rope diameter of 12.7 mm indicate that the rope diameter is critical to ensure the safety and efficiency of the system. System components, such as hydraulic cylinders and motors, were essential for the operation of the ropeway in the study of Y. Huang [12]. In contrast, the study of J. Qin specifies load ropes with a diameter of 30 mm and traction ropes of 22 mm [13], while C. Liu emphasizes using a load rope of 26 mm but the same diameter as the traction rope of 22 mm, as in the research of J. Qin [14]. These diameters are selected to withstand significant stresses, highlighting the need for a robust design capable of safely handling heavy loads. The diameters mentioned in previous research are larger than the diameters obtained by the calculations because low tonnage is considered in the system load, which influences the cable size even on a steep slope to carry a load.

This design does not account for frictional losses within the system, such as those occurring between the cable and rollers. Additionally, wind forces can adversely affect the stability and safety of the ropeway, potentially causing oscillations and increasing the risk of system failure. Addressing these factors in future studies is crucial for optimizing the design and ensuring reliable and safe operation. The load capacity is a critical design parameter. Ropeways are typically designed to support loads ranging from 2 to 5 tons, as demonstrated in previous studies [12][13][14]. However, research by Y Huang [12] specifically addresses motor design calculations for lower load capacities, which is more closely aligned with the requirements of this project. Given the maximum load limit of less than 1 ton, a lower-capacity design with reduced motor power is recommended.

The power of the winch is essential for efficient ropeway operation. The gasoline-powered winch has less power than an electric winch but is suitable for transport in rural areas where there is no access to electricity. A winch with a nominal power of 1.5 kW, designed to provide sufficient traction to move the trolleys, is the safest choice, according to Y. Huang [12]. Although other studies do not directly mention winch power, they emphasize the importance of power for specific terrain conditions and expected loads. However, this research determined that a power requirement of 115.2 W is sufficient for the proposed design, significantly lower than that reported by other researchers. This highlights the reduced power needs of low-tonnage designs.

In this study, the supporting trestle made of 2 1/2 x 1 1/2 x 1/8 in AISC mild steel pipes was simulated to evaluate the maximum stress caused by the tension exerted by the cable. The simulation revealed a maximum stress of 11.52 MPa at the midpoint of the rollers due to the applied force of 580.61 N. This finding is crucial to assess the structural integrity of the beam as the peak stress indicates the highest stress experienced, which is essential to ensure that the design can withstand operational loads without failing. They were compared with experimental data available in the literature to validate the results, and mesh convergence analysis was performed to ensure their accuracy.

6. Conclusion

Initially, a total weight of 580.61 N was determined for the load-bearing cable, with an SF of 3 considered to ensure system safety. The load-bearing cable is made of steel, with a tensile strength of 1670 MPa. While a diameter of 11.52 mm was calculated, a diameter of 12.7 mm (1/2') is preferred due to commercial availability.

This highly adaptable portable ropeway design offers a flexible solution for transporting construction materials on various terrains. The design adheres to the VDI 2221 standard, ensuring a structured specification, evaluation, and implementation approach. Key features, including the arched trestle, gas-powered winch, and multi-cable system, contribute to the system's robustness and adaptability. The calculated total weight of 580.61 N and the required cable diameter of 12.7 mm validate the design's capability to manage anticipated loads effectively. This innovative solution enhances the practicality and safety of construction operations in remote and steep terrains, significantly improving over traditional methods. Future work could explore further optimizations and adaptations to accommodate a wider range of construction scenarios.

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