



Original Article

Investigating Cost, Quality, and Time Comparisons in Multi-Utility Tunnel Construction at Indonesia's New Capital City

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Citations: Liani, A.E. (2025). Investigating Cost, Quality, and Time Comparisons in Multi-Utility Tunnel Construction at Indonesia's New Capital City. *Global Journal of Emerging Science, Engineering & Technology*, 3(1), 18-29.

Academic Editor: Assoc. Professor Dr. Agus Sukoco

Received: 5 March 2025

Revised: 17 April 2025

Accepted: 8 May 2025

Published: 31 May 2025

Abstract: The Multi-Utility Tunnel (MUT) constitutes a critical infrastructure component in the development of Indonesia's New Capital City (Ibu Kota Nusantara, IKN), serving as the backbone of integrated underground utility networks. Accelerating MUT construction is essential to ensure timely support for subsequent infrastructure development phases. This study investigates and compares the phenolic hollow formwork and sliding formwork methods in terms of cost, quality, and time performance. The analysis is based on actual project implementation data obtained from the Pembangunan Jalan Lingkar Sepaku Tahap 2 project. Cost evaluation is presented as percentage deviations relative to the Owner's Estimated Cost (RBP). The findings indicate that the sliding formwork method achieves higher productivity, improving work efficiency by approximately 30–50% compared with the conventional phenolic-hollow formwork system. However, sliding formwork results in a cost increase of approximately 5–6% per meter relative to the RBP, whereas phenolic-hollow formwork yields cost savings of 1–6%. In terms of quality, sliding formwork produces more uniform and precise concrete surfaces, thereby reducing the need for additional finishing work. Although the initial cost of sliding formwork is higher, its advantages in time efficiency and construction quality make it more suitable for long and repetitive MUT structures. These findings provide practical insights for selecting appropriate formwork methods in large-scale infrastructure projects, particularly in high-priority national development areas.

Keywords: Multi-Utility Tunnel (MUT); Formwork Methods; Construction Productivity; Cost-Time-Quality Analysis.



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1. Introduction

The development of Indonesia's New Capital City, officially known as Ibu Kota Nusantara (IKN), represents one of the most ambitious national infrastructure transformation programs in Southeast Asia. Conceived as a smart, sustainable, and resilient city, IKN is designed to integrate environmental considerations with advanced urban infrastructure systems. The concept of smart and sustainable urban

development emphasizes integrated infrastructure networks, resource efficiency, and long-term resilience (Ahvenniemi et al., 2017; Bibri & Krogstie, 2017). A fundamental element of this integrated infrastructure approach is the Multi-Utility Tunnel (MUT), an underground corridor that consolidates electricity, clean water supply, drainage, fiber-optics, and telecommunications networks within a single protected structure. By relocating utility networks underground, the MUT system enhances urban aesthetics, reduces maintenance disruptions, improves safety, and supports long-term operational efficiency (Zargarian et al., 2018; Wu et al., 2021).

In modern urban development, underground utility integration has become increasingly important due to rapid population growth, spatial constraints, and the demand for sustainable city management. Previous studies indicate that fragmented and above-ground utility systems often create operational inefficiencies, traffic disturbances, and increased lifecycle maintenance costs (Zargarian et al., 2018). In contrast, integrated underground utility tunnels facilitate centralized inspection, systematic asset management, and improved service reliability (Wu et al., 2021). Consequently, the successful implementation of MUT infrastructure in IKN requires careful planning and design, as well as the selection of efficient construction methods that meet strict project timelines, cost constraints, and quality standards. The construction phase of MUT structures presents technical challenges, particularly because tunnels are typically long, linear, and repetitive in configuration. Construction productivity and quality performance are strongly influenced by construction methods and site management strategies (Lin & Huang, 2010; Thomas & Horman, 2006). Achieving dimensional accuracy, structural integrity, and surface uniformity is essential to ensure long-term durability and operational reliability. Therefore, the choice of formwork system plays a critical role in determining construction productivity, cost efficiency, and final structural quality.

Conventional phenolic-hollow formwork has been widely adopted in infrastructure projects due to its flexibility and relatively low initial investment. Flexible formwork systems allow adaptation to varying geometries and site constraints; however, they often involve repetitive installation and dismantling, which may reduce productivity (Hanna et al., 2002). Variability in manual assembly can also influence concrete surface quality and dimensional precision, potentially increasing rework and indirect costs (Love et al., 2009). Alternatively, the sliding formwork method is a more mechanized system designed for continuous, repetitive concrete structures. Slipform or sliding systems enable simultaneous casting and form movement, thereby shortening cycle times and improving labor productivity (Lin & Huang, 2010). Studies on mechanized formwork systems report improvements in schedule performance and surface consistency compared to conventional systems (Hwang et al., 2013). Sliding formwork is particularly suitable for long and uniform structures such as tunnels, retaining walls, and shafts. Nevertheless, the method typically requires higher initial capital investment, specialized equipment, and skilled supervision, which may affect short-term cost considerations (Hanna et al., 2002).



Figure 1. Location and Map of the Sepaku Ring Road Construction Project (Phase 2)

The implementation of MUT construction within the Pembangunan Jalan Lingkar Sepaku Tahap 2 project further illustrates the strategic importance of efficient construction methodologies. As a key access corridor supporting connectivity within the Core Government Area (Kawasan Inti Pusat Pemerintahan, KIPP) of IKN, the project demands strict adherence to time and quality targets. Delays or inefficiencies in MUT construction may significantly affect subsequent infrastructure phases, reflecting the well-established relationship between method selection and project performance outcomes (Thomas & Horman, 2006). Despite the practical importance of formwork selection in large-scale infrastructure projects, empirical studies comparing phenolic-hollow formwork and sliding formwork specifically in MUT construction remain limited. Existing research tends to examine productivity or cost performance separately, without integrating

cost, quality, and time into a comprehensive evaluation framework (Love et al., 2009; Hwang et al., 2013). As a result, decision-makers may lack holistic evidence when selecting appropriate construction methods for repetitive underground structures.

This study addresses this gap by systematically investigating and comparing the performance of phenolic-hollow formwork and sliding formwork methods in MUT construction at IKN. The comparison is conducted across three primary dimensions of project performance: cost efficiency, construction time, and structural quality. Drawing on actual implementation data from the Sepaku Ring Road Phase 2 project, this research provides quantitative insights into the trade-offs among initial investment, productivity gains, and quality outcomes. Ultimately, this study contributes to the construction management literature by offering an integrated evaluation of formwork systems in large-scale, time-sensitive infrastructure development. The findings are expected to support more informed decision-making in national strategic projects and to serve as a reference for future MUT construction initiatives within Indonesia and other emerging smart city developments.

2. Materials and Methods

This study employs a descriptive-comparative research design, using actual implementation data from the Sepaku Ring Road Construction Project (Phase 2). The object of analysis is the construction of Multi-Utility Tunnel (MUT) Type 1 structures. The comparison focuses on two formwork methods used during project execution: conventional phenolic-hollow formwork and sliding formwork. The evaluation parameters consist of three principal dimensions of project performance: construction cost per meter, execution time and productivity, and concrete surface quality. The Multi-Utility Tunnel (MUT) is an essential component of infrastructure development in Ibu Kota Nusantara (IKN), which is planned as a future-oriented, smart, and sustainable city. Utility systems such as electrical networks, water supply pipelines, drainage, and telecommunications are integrated within an underground corridor to promote an organized, aesthetically clean, and operationally efficient urban environment without visible surface installations.

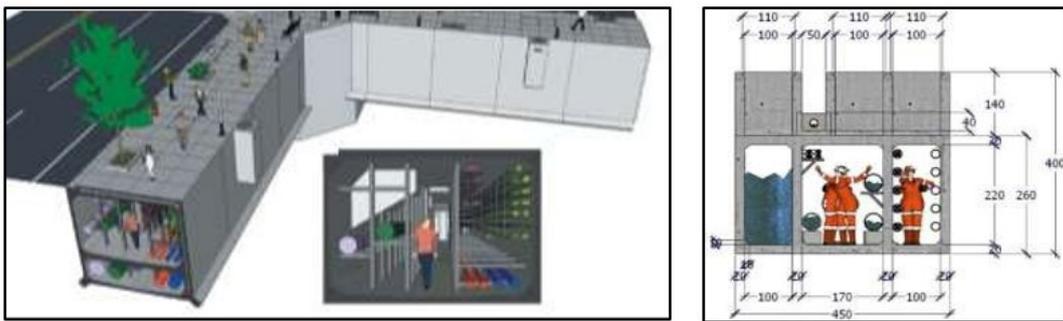


Figure 2. Cross Section of the Multi-Utility Tunnel (a); Type 1 Multi-Utility Tunnel (b).

The MUT construction process comprises three primary work components: reinforcement installation, formwork installation, and concrete casting. Among these components, formwork operations significantly influence project duration and productivity due to their repetitive and cycle-based nature. In the observed project, the conventional formwork method using phenolic plywood supported by hollow steel frames was partially replaced by a mechanized sliding formwork system comprising movable steel plate assemblies. This modification aimed to accelerate construction progress and improve surface consistency in repetitive tunnel segments. Cost analysis was conducted by comparing actual contract unit prices for each method with the Owner's Estimated Cost (RBP). The differences were calculated and presented as percentages to determine relative cost efficiency. Time performance analysis was based on measured productivity rates, expressed in meters of completed MUT structure per unit time, achieved under each formwork system. Quality assessment was carried out through systematic visual inspection of concrete surface uniformity, dimensional precision, and the extent of additional finishing work required after formwork removal. Through this comparative framework, the study evaluates the relative advantages and trade-offs of each formwork method in terms of cost implications, schedule performance, and construction quality.



Figure 3. Phenolic-Hollow Formwork System (a); Sliding Formwork System (b).

3. Results

The Owner’s Estimated Cost (RBP) is first presented as a baseline reference prior to comparing the costs associated with different construction methods. The cost structure of MUT Type 1 construction based on the Owner’s Estimated Cost (RBP) is summarized as follows:

Table 1. Basic Unit Price Analysis Based on the Owner’s Estimated Cost (RBP)

No.	Description	Unit	Volume	Unit Price (IDR)	Total Cost (IDR)
A	Labor				
1	Formwork Work	m ²	25.8	183,000.00	4,721,400.00
2	Concrete Casting Work	m ³	3.62	50,000.00	181,000.00
3	Scaffolding Installation	m ²	25.8	6,000.00	154,800.00
4	Reinforcement Installation	kg	872.93	1,800.00	1,571,274.00
5	Lean Concrete (LC) Work	m ²	4.7	16,000.00	75,200.00
	Total Labor Cost (per m')				6,703,674.00
B	Equipment				
1	Auxiliary Equipment	-	3.62	1,200.00	4,344.00
2	Concrete Pump	day	0.58	737,500.00	427,160.00
3	Generator Set	day	0.58	127,100.00	73,605.00
	Total Equipment Cost (per m')				505,109.00
C	Materials				
1	Concrete, fc' 10 MPa	m ³	0.47	1,654,800.00	777,756.00
2	Structural Concrete, fc' 30 MPa	m ³	3.62	2,126,334.26	7,697,330.03
3	Deformed Reinforcing Steel (BjTS 420B)	kg	872.93	10,403.00	9,081,090.79
	Total Material Cost (per m')				17,556,176.82
	Total Cost (per m')				24,764,959.82

Table 1 presents the detailed cost breakdown of MUT Type 1 construction per linear meter based on the Owner’s Estimated Cost (RBP). The total construction cost per meter amounts to IDR 24,764,959.82, composed of three primary components: labor, equipment, and materials. The labor component totals IDR 6,703,674.00 per meter, representing approximately 27.07% of the overall construction cost. Among labor items, formwork work accounts for the largest share at IDR 4,721,400.00, representing about 70.43% of total labor costs and approximately 19.06% of the total project cost. Reinforcement installation follows at

IDR 1,571,274.00, contributing 23.44% of labor costs. Other labor elements, including concrete casting, scaffolding installation, and lean concrete work, contribute relatively minor proportions. These findings indicate that formwork and reinforcement activities are the most labor-intensive components in MUT construction. The equipment cost amounts to IDR 505,109.00 per meter, equivalent to only 2.04% of the total construction cost.

Within this category, the concrete pump accounts for the largest share of equipment expenses at IDR 427,160.00, or approximately 84.60% of total equipment costs. The generator set and auxiliary equipment represent marginal contributions. This result suggests that equipment utilization, while essential, does not significantly influence the overall cost structure compared to labor and materials. Materials account for the largest cost component, totaling IDR 17,556,176.82 per meter, or approximately 70.89% of the total construction cost. The most significant contributor is deformed reinforcing steel (BjTS 420B), amounting to IDR 9,081,090.79 (51.73% of material costs and 36.67% of total cost). Structural concrete with compressive strength $f_c' 30$ MPa accounts for IDR 7,697,330.03 (43.85% of material costs), while lean concrete ($f_c' 10$ MPa) contributes a comparatively small share. The findings demonstrate that MUT Type 1 construction is highly material-intensive, with reinforcing steel and structural concrete constituting the dominant cost drivers. Labor costs, particularly formwork work, also play a substantial role, whereas equipment costs have a relatively minor financial impact. These results highlight that any effort to improve cost efficiency should primarily focus on optimizing material usage and enhancing formwork productivity, as these components exert the greatest influence on total construction expenditure per linear meter.

3.1. Cost Analysis of the Subcontractor for MUT Type 1

3.1.1. MKS

Table 2. Unit Price Analysis of MKS

No.	Description	Unit	Volume	Unit Price (IDR)	Total Cost (IDR)
A	Labor				
1	Formwork Work (including materials)	m ²	25.8	162,500.00	4,192,500.00
2	Concrete Casting Work	m ³	3.62	105,000.00	380,100.00
3	Wall Footing Work (including materials)	m'	1	90,000.00	90,000.00
4	Lean Concrete (LC) Casting	m ²	4.7	13,000.00	61,100.00
5	Reinforcement Installation	kg	872.93	1,650.00	1,440,334.50
	Total Labor Cost (per m')				6,164,034.50
B	Equipment				
1	Auxiliary Equipment	-	3.62	1,200.00	4,344.00
2	Concrete Pump	day	0.77	737,500.00	569,546.67
3	Generator Set	day	0.58	127,100.00	73,605.00
	Total Equipment Cost (per m')				647,495.67
C	Materials				
1	Concrete, $f_c' 10$ MPa	m ³	0.47	1,654,800.00	777,756.00
2	Structural Concrete, $f_c' 30$ MPa	m ³	3.62	2,126,334.26	7,697,330.03
3	Deformed Reinforcing Steel (BjTS 420B)	kg	872.93	10,403.00	9,081,090.79
	Total Material Cost (per m')				17,556,176.82
	Total Cost (per m')				24,367,706.99

Table 2 presents the unit price analysis of MKS for MUT Type 1 construction per linear meter using the phenolic-hollow formwork method. The total unit cost is IDR 24,367,706.99 per meter, including labor, equipment, and materials. The labor cost totals IDR 6,164,034.50 per meter, representing approximately 25.30% of the total construction cost. The largest labor contribution comes from formwork work (including materials), totaling IDR 4,192,500.00, accounting for 68.02% of total labor cost and about 17.21% of the overall unit cost. Reinforcement installation follows at IDR 1,440,334.50, accounting for 23.37% of the labor cost. Other labor items, including concrete casting, wall footing work, and lean concrete casting, make relatively minor contributions. These figures indicate that formwork activities remain the most labor-dominant operation in the phenolic-hollow system.

Equipment costs amount to IDR 647,495.67 per meter, equivalent to approximately 2.66% of the total unit cost. The concrete pump accounts for the largest equipment expense at IDR 569,546.67 (87.96% of total equipment cost), while the generator set and auxiliary equipment contribute only marginal amounts. This demonstrates that equipment costs have a limited influence on the overall cost structure compared to labor and materials. Material costs constitute the largest component, totaling IDR 17,556,176.82 per meter or approximately 72.04% of the total cost. The dominant material cost is deformed reinforcing steel (BjTS 420B), amounting to IDR 9,081,090.79 (51.73% of material cost and 37.26% of total cost). Structural concrete with compressive strength f_c' 30 MPa contributes IDR 7,697,330.03 (43.85% of material cost), while lean concrete (f_c' 10 MPa) accounts for a relatively small proportion. The findings reveal that MUT Type 1 construction under MKS is highly material-intensive, with reinforcing steel and structural concrete serving as the primary cost drivers. Labor costs, particularly for formwork, also account for a significant share, whereas equipment costs have a minimal impact on total expenditure. These results suggest that cost optimization strategies should primarily focus on improving material efficiency and enhancing formwork productivity to achieve greater cost competitiveness per linear meter.

3.1.2. Metalindo

Table 3. Unit Price Analysis of Metalindo

No.	Description	Unit	Volume	Unit Price (IDR)	Total Cost (IDR)
A	Labor				
1	Concrete Casting and Formwork Work (including materials)	m ²	1	3,400,000.00	3,400,000.00
2	Lean Concrete (LC) Work	m ²	4.7	12,000.00	56,400.00
3	Reinforcement Installation	kg	872.93	1,700.00	1,483,981.00
	Total Labor Cost (per m')				4,940,381.00
B	Equipment				
1	Auxiliary Equipment	-	3.62	1,200.00	4,344.00
2	Concrete Pump	day	0.77	737,500.00	569,546.67
3	Generator Set	day	0.58	127,100.00	73,605.00
	Total Equipment Cost (per m')				647,495.67
C	Materials				
1	Concrete, f_c' 10 MPa	m ³	0.47	1,654,800.00	777,756.00
2	Structural Concrete, f_c' 30 MPa	m ³	3.62	2,126,334.26	7,697,330.03
3	Deformed Reinforcing Steel (BjTS 420B)	kg	872.93	10,403.00	9,081,090.79
	Total Material Cost (per m')				17,556,176.82
	Total Cost (per m')				23,144,053.49

Table 3 presents the unit price analysis for Metalindo's MUT Type 1 construction per linear meter using the sliding formwork method. The total unit cost is IDR 23,144,053.49 per meter, including labor, equipment, and materials. The labor cost totals IDR 4,940,381.00 per meter, representing approximately 21.35% of the overall construction cost. The largest contribution within this category comes from the combined concrete casting and formwork work (including materials), amounting to IDR 3,400,000.00, which accounts for 68.83% of the total labor cost and about 14.69% of the total unit cost. Reinforcement installation contributes IDR 1,483,981.00 (30.04% of labor cost), while lean concrete work accounts for a relatively minor proportion. Compared to the phenolic-hollow method, the labor cost structure under the sliding form system is more consolidated, reflecting operational efficiency and reduced manual handling.

Equipment costs amount to IDR 647,495.67 per meter, equivalent to approximately 2.80% of the total cost. The concrete pump constitutes the dominant equipment expense at IDR 569,546.67 (87.96% of total equipment cost), whereas the generator set and auxiliary equipment contribute only marginal shares. This indicates that equipment expenses remain relatively stable and have a limited impact on total construction costs. Material costs represent the largest component at IDR 17,556,176.82 per meter, accounting for approximately 75.85% of the total unit cost. The primary cost driver is deformed reinforcing steel (BjTS 420B), amounting to IDR 9,081,090.79 (51.73% of material cost and 39.24% of total cost). Structural concrete with a compressive strength of f_c' 30 MPa contributes IDR 7,697,330.03 (43.85% of material cost), while lean concrete (f_c' 10 MPa) forms a comparatively small portion. The findings indicate that the

sliding formwork method used by Metalindo yields a lower total unit cost than the phenolic-hollow method. The most significant reduction is observed in the labor component, suggesting improved productivity and streamlined execution processes. Although material costs remain dominant and relatively fixed due to structural design requirements, labor efficiency gains contribute substantially to the overall cost competitiveness of the sliding formwork system per linear meter.

3.1.3. Mandor Ahmad

Table 4. Unit Price Analysis of Mandor Ahmad

No.	Description	Unit	Volume	Unit Price (IDR)	Total Cost (IDR)
A	Labor				
1	Concrete Casting and Formwork Work (including materials)	m ³	1	4,650,000.00	4,650,000.00
	Total Labor Cost (per m')				4,650,000.00
B	Equipment				
1	Formwork System	m ²	25.8	119,379.84	3,080,000.00
2	Auxiliary Equipment	-	3.62	1,200.00	4,344.00
3	Concrete Pump	day	0.77	737,500.00	569,546.67
4	Generator Set	day	0.58	127,100.00	73,605.00
5	Mobile Crane	day	0.32	825,000.00	264,000.00
	Total Equipment Cost (per m')				3,991,495.67
C	Materials				
1	Concrete, fc' 10 MPa	m ³	0.47	1,654,800.00	777,756.00
2	Structural Concrete, fc' 30 MPa	m ³	3.62	2,126,334.26	7,697,330.03
3	Deformed Reinforcing Steel (BjTS 420B)	kg	872.93	10,403.00	9,081,090.79
	Total Material Cost (per m')				17,556,176.82
	Total Cost (per m')				26,197,672.49

Table 4 presents the unit price analysis of Mandor Ahmad for MUT Type 1 construction per linear meter. The total unit cost is IDR 26,197,672.49 per meter, including labor, equipment, and materials. The labor cost totals IDR 4,650,000.00 per meter, representing approximately 17.76% of the total construction cost. Unlike other vendors, the labor component is consolidated into a single item that covers concrete casting and formwork (including materials). This integrated pricing structure indicates a bundled execution approach, in which labor and certain operational inputs are combined into a single contractual unit. Although the labor proportion is relatively lower than other cost components, it provides a simplified but less detailed cost breakdown. The equipment cost amounts to IDR 3,991,495.67 per meter, accounting for approximately 15.24% of the total unit cost. The largest equipment expense is the formwork system, valued at IDR 3,080,000.00, which constitutes 77.19% of the total equipment cost and about 11.76% of the total project cost. Additional equipment, such as the concrete pump, generator set, and mobile crane, accounts for a moderate share, while auxiliary equipment has a minimal financial impact. Compared to other vendors, this cost structure indicates a significantly higher allocation to equipment, particularly for the formwork system, suggesting the use of capital-intensive resources.

Material costs remain the dominant component at IDR 17,556,176.82 per meter, representing approximately 67.00% of the total unit cost. As observed in previous analyses, deformed reinforcing steel (BjTS 420B) is the primary cost driver at IDR 9,081,090.79 (51.73% of material cost and 34.68% of total cost), followed by structural concrete (fc' 30 MPa) at IDR 7,697,330.03. Lean concrete (fc' 10 MPa) contributes a relatively small portion. The findings indicate that Mandor Ahmad's cost structure is characterized by a substantial equipment component, particularly for the formwork system, which increases the total unit cost compared to other vendors. Although labor costs appear lower proportionally, the higher equipment expenditure results in the highest total cost per linear meter among the compared alternatives. These results suggest that while mechanized or equipment-intensive approaches may enhance operational capacity, they must be carefully managed to ensure overall cost efficiency in MUT construction.

3.1.4. Cost Comparison as a Percentage Relative to the RBP

Table 5. Summary of Cost Analysis for MUT Type 1

Vendor	MUT Length (m')	RBP Unit Cost (IDR/m')	Vendor Unit Cost (IDR/m')	Total RBP (IDR)
MKS	700	24,764,959.82	24,367,706.99	17,335,471,877.36
Metalindo	300	24,764,959.82	23,144,053.49	7,429,487,947.44
Mandor Ahmad	250	24,764,959.82	26,197,672.49	6,191,239,956.20
Total	1,250.00	—	—	30,956,199,781.01

Table 5. Summary of Cost Analysis for MUT Type 1 (Cont'd)

Vendor	MUT Length (m')	Total Vendor Cost (IDR)	Deviation (IDR)	Deviation (%)
MKS	700	17,057,394,894.03	278,076,983.33	1.60%
Metalindo	300	6,943,216,047.44	486,271,900.00	6.55%
Mandor Ahmad	250	6,549,418,122.87	-358,178,166.67	-5.79%
Total	1,250.00	30,550,029,064.34	406,170,716.67	—

Table 5 presents a comprehensive comparison between the Owner's Estimated Cost (RBP) and the actual vendor contract costs for MUT Type 1 construction across three subcontractors: MKS, Metalindo, and Mandor Ahmad. The total MUT length constructed by all vendors is 1,250 meters. Using the RBP unit cost of IDR 24,764,959.82 per meter as a benchmark, the total estimated budget for the entire scope amounts to IDR 30,956,199,781.01. In comparison, the aggregated vendor contract value is IDR 30,550,029,064.34, resulting in an overall cost saving of IDR 406,170,716.67 relative to the RBP baseline. MKS executed the largest portion of the work, covering 700 meters. With a vendor unit cost of IDR 24,367,706.99 per meter, which is 1.60% lower than the RBP, MKS generated a total cost saving of IDR 278,076,983.33. Although the percentage deviation is modest, the large contract length amplifies the financial impact, making MKS a stable and cost-efficient contributor to overall savings.

Metalindo constructed 300 meters and demonstrated the highest cost efficiency among the vendors. Its unit cost of IDR 23,144,053.49 per meter is 6.55% lower than the RBP, producing a total saving of IDR 486,271,900.00. Despite handling a shorter contract length than MKS, Metalindo achieved the greatest proportional and absolute cost reduction, indicating superior cost performance, likely influenced by improved productivity and method efficiency. In contrast, Mandor Ahmad executed 250 meters at a unit cost of IDR 26,197,672.49 per meter, which exceeds the RBP by 5.79%. This resulted in a cost overrun of IDR 358,178,166.67 compared to the reference budget. The negative deviation indicates that this vendor's construction approach was less cost-efficient relative to the established benchmark. This study reveals that two vendors delivered cost savings below the RBP, while one vendor exceeded the benchmark. The aggregated outcome remains favorable, as total vendor costs are lower than the RBP projection. These results highlight the importance of selecting appropriate methods and implementing cost-control strategies to achieve financial efficiency in large-scale MUT construction projects.

3.2. Time Analysis Based on Vendor Productivity for MUT Type 1

The productivity analysis of Multi-Utility Tunnel (MUT) Type 1 construction was conducted by quantifying daily production rates based on a standardized work segment length of 12 meters per section. For each section analyzed, the daily productivity of individual construction activities, namely reinforcement installation, formwork operations, and concrete casting was assessed. In addition, the effectiveness of inter-team coordination was considered a contributing factor influencing overall productivity performance.

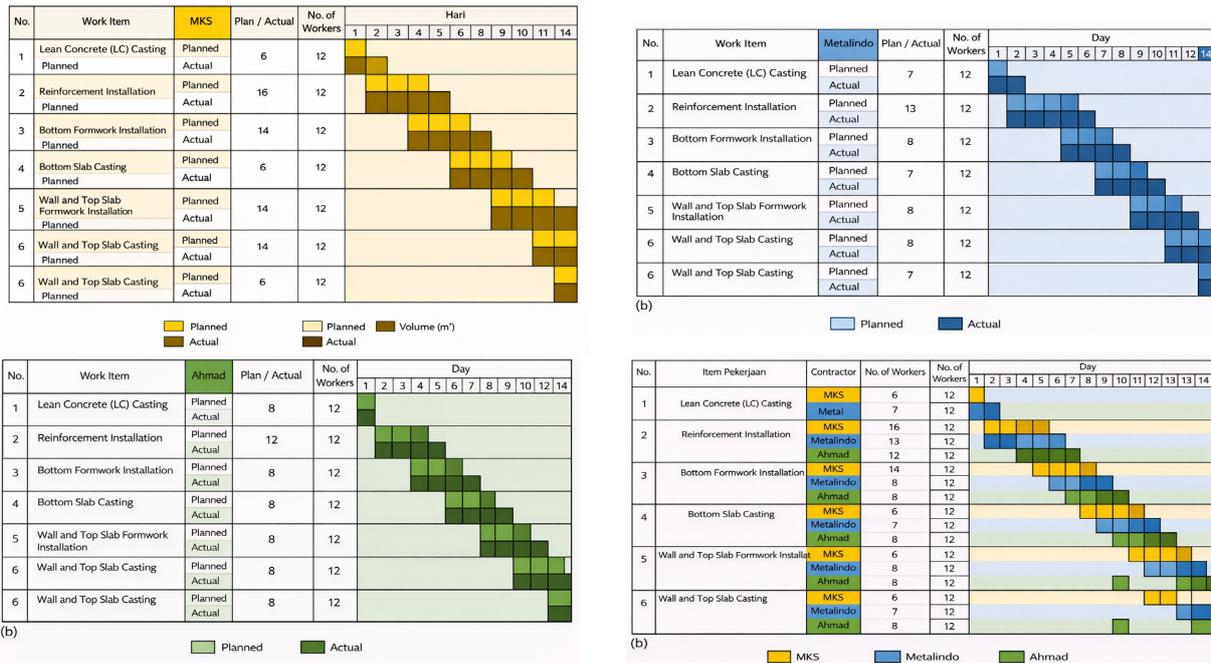


Figure 4. Time Analysis Based on the Productivity of Each Vendor: (a) MKS; (b) Metalindo; (c) Mandor Ahmad; (d) Overall Performance.

The results indicate that the sliding formwork method significantly enhances productivity, reducing overall construction time and minimizing idle intervals between successive work stages.

Table 6. Summary of Time and Productivity

Vendor	Formwork Method	Manpower	Planned Productivity (m/day)	Actual Productivity (m/day)
MKS	Phenolic-Hollow	36	9	11
Metalindo	Phenolic-Hollow	28	11	13
Mandor Ahmad	Sliding Form	28	7	7

Table 6 summarizes the comparative time performance and productivity levels achieved by each vendor in the construction of MUT Type 1, measured in meters per day for a 12-meter work segment. The table presents manpower allocation, planned productivity targets, and actual productivity outcomes for each formwork method. MKS employed 36 workers using the phenolic-hollow formwork system. The planned productivity was 9 m/day, while the actual productivity reached 11 m/day. This reflects a performance improvement of approximately 22.22% above the planned target. The result indicates effective field coordination and labor utilization, enabling the team to exceed its scheduled productivity expectations despite using a conventional formwork system. Metalindo utilized 28 workers under the same phenolic-hollow formwork method. The planned productivity was 11 m/day, and the realized productivity increased to 13 m/day, representing an 18.18% improvement over the planned rate. Notably, Metalindo achieved the highest actual productivity among all vendors while employing fewer workers than MKS. This suggests higher labor efficiency and better workflow management.

Mandor Ahmad applied the sliding formwork method with 28 workers. The planned and actual productivity were both 7 m/day, indicating that performance aligned precisely with the project schedule but did not exceed expectations. Although the sliding form method is generally associated with higher mechanization and operational continuity, the productivity rate in this segment remained stable rather than accelerated. The findings reveal that both vendors using the phenolic-hollow formwork method surpassed their planned productivity targets, with Metalindo achieving the highest actual productivity (13 m/day). In contrast, the sliding form method demonstrated consistent but moderate productivity (7 m/day) under the observed manpower configuration. These results suggest that productivity performance is influenced not only by the formwork system employed but also by workforce management, coordination efficiency, and execution strategy.

3.3. Quality Performance Evaluation

Quality evaluation focuses on the condition of the concrete surface, joint visibility, dimensional accuracy, and the extent of additional finishing required. The conventional phenolic-hollow formwork method frequently produces visible joints and surface irregularities, necessitating corrective finishing work that increases labor input and extends execution time. In contrast, the sliding formwork system produces smoother, more uniform concrete surfaces with minimal joint visibility. Its improved dimensional precision reduces the need for post-casting corrections, thereby enabling subsequent construction activities to proceed without delay. These findings indicate that the higher execution speed achieved through the sliding formwork method does not compromise construction quality; rather, it enhances structural consistency and overall reliability.



Figure 5. Sliding Formwork System (a); Phenolic-Hollow Formwork System (b).

4. Discussion

The integrated evaluation of cost, time, and quality confirms that formwork performance cannot be adequately assessed using a single parameter. Construction management literature consistently emphasizes the interdependence of project cost, schedule, and quality outcomes, often referred to as the “iron triangle” of project performance (Atkinson, 1999). Focusing solely on initial unit cost may lead to suboptimal decision-making, particularly in repetitive, time-sensitive infrastructure projects such as the construction of Multi-Utility Tunnels (MUTs). The findings of this study demonstrate that although conventional phenolic hollow formwork offers lower initial unit prices in certain contract packages, its comparatively lower productivity and greater need for finishing work may reduce overall execution efficiency. This observation is consistent with prior research indicating that method selection significantly influences labor productivity, rework incidence, and schedule performance (Hanna et al., 2002; Love et al., 2009).

The productivity analysis shows that vendors using phenolic hollow formwork exceeded their planned targets; however, performance variability remained dependent on workforce coordination and operational control. Previous studies have shown that labor-intensive construction methods are highly sensitive to crew management, supervision quality, and work sequencing (Jarkas, 2010). In contrast, mechanized systems such as sliding formwork are designed to standardize repetitive operations and reduce manual handling variability. Slipform and sliding systems have been reported to shorten construction cycles and enhance continuity in linear and repetitive structures (Hwang et al., 2014). The present findings align with this body of evidence, demonstrating that sliding formwork improves workflow consistency and minimizes idle periods between work stages.

From a quality perspective, the smoother, more uniform concrete surfaces produced by sliding formwork reduce the need for corrective finishing, thereby decreasing the likelihood of rework. Rework has been widely recognized as a significant contributor to cost overruns and schedule delays in construction

projects (Love et al., 2009). The reduction of visible joints and dimensional deviations observed in sliding form applications supports the argument that improved mechanization enhances structural precision and workmanship quality. Furthermore, improved dimensional accuracy contributes to long-term durability and maintenance efficiency, particularly for underground infrastructure systems where access for future repairs may be constrained. Although the sliding formwork method applied by Mandor Ahmad resulted in higher unit costs than the conventional method, its broader performance implications extend beyond initial expenditure. Research on construction innovation suggests that greater upfront investment in advanced construction technologies can yield lifecycle benefits by improving productivity, quality, and reliability and reducing corrective interventions (Pan et al., 2012). In the context of large-scale national infrastructure projects such as MUT development, schedule reliability and quality assurance may justify moderate cost premiums.

From a regulatory and technical standpoint, the enhanced surface precision achieved through sliding formwork aligns more closely with workmanship and dimensional tolerance requirements specified in national construction standards. Compliance with technical tolerances reduces inspection-related delays and strengthens quality assurance processes. Studies on construction performance measurement emphasize that compliance with technical specifications is strongly associated with improved project delivery outcomes (Hwang et al., 2013). Therefore, formwork selection should be based not solely on initial cost comparisons but on a comprehensive evaluation of productivity, quality consistency, and project execution strategy. This study reinforces the argument that construction method selection must adopt a multi-criteria perspective. While conventional formwork may remain economically attractive for smaller or less time-sensitive projects, sliding formwork offers advantages for repetitive, linear, and schedule-driven infrastructure projects. The integration of cost, time, and quality analysis provides a more balanced framework for decision-making and supports the selection of strategic methods in complex infrastructure environments.

5. Conclusions

This study concludes that the selection of formwork methods significantly influences the integrated performance of cost, time, and quality in MUT Type 1 construction. The findings demonstrate that the sliding formwork system provides substantial advantages in projects characterized by uniform geometry and repetitive alignment. Although its initial unit cost may exceed that of conventional phenolic-hollow formwork in certain contract arrangements, sliding formwork achieves superior execution speed, more stable productivity, and improved concrete surface quality. The enhanced dimensional precision and reduced need for corrective finishing contribute to greater construction consistency and more reliable schedule performance. Conversely, conventional phenolic hollow formwork remains applicable for shorter segments, non-uniform structures, or projects with lower repetition intensity, where flexibility and lower initial investment are prioritized.

From a theoretical perspective, this study reinforces the importance of evaluating construction methods through a multi-criteria framework rather than relying solely on direct cost comparison. The results contribute to construction management literature by empirically demonstrating that productivity gains and quality improvements may offset higher upfront costs, supporting broader performance-based evaluation models in infrastructure project delivery. The integration of cost, time, and quality dimensions provides a more holistic basis for method selection in repetitive underground construction. In practical terms, early-stage planning should incorporate feasibility assessments of methods, including geometric standardization, repetition length, and capacity for resource mobilization. For future MUT projects, sliding formwork should be considered during the design and procurement stages to fully leverage its productivity advantages. Strategic planning of equipment mobilization, crew training, and workflow sequencing is essential to maximize operational efficiency and minimize transitional delays.

At the policy level, government agencies and project owners involved in national strategic infrastructure programs should encourage performance-based procurement frameworks that evaluate contractors not only on bid price but also on demonstrated productivity capability and quality control systems. Standardized productivity benchmarking for MUT construction may support more transparent decision-making and promote the adoption of technology in large-scale projects. This study is subject to several limitations. First, the analysis is based on a single project case within the IKN development area, which may limit generalizability across different site conditions and project scales. Second, lifecycle cost analysis and long-term maintenance implications were not examined in detail. Third, external factors such as weather conditions, supply chain variability, and workforce skill differentials were not quantitatively modeled. Future research may extend this work by conducting multi-project comparative studies, incorporating lifecycle cost evaluation, and developing predictive productivity models for sliding formwork applications across diverse infrastructure contexts.

Author Contributions: Conceptualization, A.E.L.; methodology, A.E.L.; software, A.E.L.; validation, A.E.L.; formal analysis, A.E.L.; investigation, A.E.L.; resources, A.E.L.; data curation, A.E.L.; writing—original draft preparation, A.E.L.; writing—review and editing, A.E.L.; visualization, A.E.L.; project administration, A.E.L.; funding acquisition, A.E.L. Author has read and agreed to the published version of the manuscript.

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A.E.L.: Annisa Eka Liani

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors would like to thank Universitas 17 Agustus 1945 Samarinda, Indonesia for its support of this research and publication. We also thank the reviewers for their constructive comments and suggestions.

Conflicts of Interest: The authors declare no conflict of interest.

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