JNEST EISSN: 2961-8738 ● PISSN: 2961-8916 ● DOI: 10.56741/jnest.v5i03.2525
Article Received 20 July 2026, Revised 11 October 2026

Comparative Evaluation of Conventional and Modular Formwork Systems Through a Cost Time Decision Making Framework

Dhena Arthamevia*, Lilya Susanti, and Yatnanta Padma Devia

***Abstract*—Formwork costs can account for 20–25% of total construction costs, making the selection of an appropriate formwork system an important aspect of improving cost and time efficiency in multi-story building projects. This study employed a comparative descriptive approach based on Building Information Modeling (BIM) simulation and Life Cycle Cost Analysis (LCCA) to compare the time and cost performance of conventional and modular formwork systems for the beam, column, and slab elements of Building X, a 9-story reinforced concrete building in East Java. A 3D BIM model was developed in Autodesk Revit to extract structural volumes, which were converted into formwork areas and then analyzed using productivity coefficients from SNI 7394:2008 and the AHSP of the Ministry of Public Works and Housing (PUPR) for time analysis (4D BIM), budget plan (RAB) unit prices for cost analysis (5D BIM), and a gate-to-gate LCCA complemented by Break-Even Analysis (BEA). Modular formwork achieved a time efficiency of 50.35% and an initial cost efficiency of 20.59%, with a total life cycle cost 68.65% more economical. The BEA results show that modular formwork becomes more economical starting from the third use cycle, with reuse cost as the most dominant parameter, contributing 89.25% of the difference in total LCC. The evaluation framework based on 4D–5D BIM integrated with LCCA and BEA proved effective as a structured, data-driven decision-making framework for formwork system selection in multi-story building projects.**

***Index Terms*—4D-5D BIM, Break Even Analysis, Decision Making Framework, Life Cycle Cost Analysis, Modular Formwork**

I. INTRODUCTION

THE document success of a multi-storey building construction project is determined by the ability to simultaneously satisfy three main parameters, namely cost, quality and time. According to Statistics Indonesia [1], the construction sector contributed 10.43% to Indonesia's Gross Domestic Product in the fourth quarter of 2024, in line with the priorities of the National Medium-Term Development Plan (RPJMN) 2025-2029 [2]. With the increasing complexity of multi-storey building projects in Indonesia, cost and time efficiencies are becoming more important, requiring sound management of every structural work component to support project success.

One of the components that has the greatest influence on the cost and duration of structural works is formwork. Formwork is stated in SNI 7860:2015 [1] as a temporary construction element that determines the shape, position, and surface quality of reinforced concrete during the casting and hardening process. Terzioglu and Polat [3] put emphasis that formwork is one of the main bottlenecks in the construction cycle, amounting to 20–25% of the total costs of a concrete structure. Moreover, Supriyono et al. [4] elaborated that formwork work also has a significant impact on the project duration, because the type of formwork system used influences the speed of the installation and removal. For example, steel formwork is installed faster than wood formwork. Therefore, the choice of the formwork system is a key factor affecting cost efficiency, time, and construction cycle, especially for beams, columns, and slabs as the main components of multi-story buildings [3], [5]. The significance of these three elements is further highlighted by the results of Agriansyah et al. [5], that structural work costs are mostly made up of beams (35.2%), slabs (29.3%) and columns (23.9%).

Ultimately, the success of a construction project depends on the balance between cost, quality and time, which BIM-based solutions can help to manage [6]. As a temporary system that molds fresh concrete until it gains strength, formwork remains one of the major cost drivers in modern concrete construction [7].

Selecting the appropriate formwork system is a strategic decision influenced by many interrelated factors. An incorrect formwork selection can lead directly to cost and time overruns [8], while conventional timber formwork is also associated with poor social and environmental sustainability performance [9]. In Indonesia, conventional timber formwork still dominates field practice. According to SNI 7394:2008 [6], conventional formwork has a durability of 2 uses, whereas modular formwork of the LICO/PERI type generally has a durability of 5 uses or more according to the AHSP PUPR. Unlike concrete or reinforcement, which are permanent, formwork is a repetitive temporary system that directly determines the geometry and quality of casting [6]–[7]. Gaddam and Achuthan [10] found that newly emerging formwork systems can reduce labor requirements and improve productivity and cost efficiency compared with conventional formwork. However, the use of modular formwork in Indonesia remains limited due to its high initial investment and a lack of understanding of long-term cost-benefit analysis. In field practice, formwork selection decisions are often based solely on initial cost considerations without comprehensively accounting for time, technical, resource, and sustainability factors, which are increasingly recognized as integral to formwork engineering decisions [11]. Therefore, a structured framework capable of integrating all of these considerations into a single, systematic, and measurable evaluation system is needed.

Dhena Arthamevia (Corresponding Author), **Lilya Susanti**, and **Yatnanta Padma Devia** are with the Department of Civil Engineering, Universitas Brawijaya, Malang, Indonesia. Corresponding Author Email: dhena.arthamevia@gmail.com

© 2026 IISTR

The Indonesian government, through the Ministry of Public Works and Housing (PUPR), has promoted digital transformation in the construction industry through the implementation of Building Information Modeling (BIM). Minister of Public Works and Housing Regulation No. 22/PRT/M/2018 [12] governs the application of BIM in government-funded construction projects, with a target of improving cost and time efficiency by 10–15% by 2030. 4D BIM, which integrates the time dimension, and 5D BIM, which integrates the cost dimension, offer significant potential for formwork system optimization Rehman et al. [13] demonstrated through a systematic review that 4D BIM implementation consistently improves project time control, while 5D BIM improves cost estimation accuracy and supports financial decision-making across the project life cycle [14]–[15]. In addition to BIM, Life Cycle Cost Analysis (LCCA), developed by Fuller and Petersen [16] and adapted for construction by Stanford [17], serves to account for the total cost of asset ownership over its service life. The Digital Construction Framework developed by Sacks et al. [18] affirms that digital technology can create more efficient and sustainable construction systems. BIM is also recognized as supporting project management functions across cost and schedule knowledge areas [19].

Although several previous studies have shown the potential of BIM and modular formwork systems, several research gaps still exist. First, studies such as Lee et al. [20] and Yoo et al. [21] have applied BIM to formwork systems but have not conducted a thorough comparison between conventional and modular formwork within a single framework integrated with life cycle cost aspects. Second, the integration of 4D-5D BIM, LCCA, and BEA in formwork system selection is still very limited, particularly for multi-story building projects in Indonesia. Although Wan Abdul Basir et al. [22] developed a 4D-5D BIM integration for project management, its application has not been specifically directed at formwork system evaluation. Similarly, Hammad et al. [23] developed a BIM-based framework contrasting conventional and modular construction, but focused on sustainability factors rather than formwork life cycle cost. Third, most studies still focus on initial costs without considering life cycle costs and the economic break-even point. Yusriyya Huwaida et al. [24] and Yogiswara et al. [25] compared the time and initial cost aspects of the two formwork systems but did not comprehensively integrate LCCA and BEA. These gaps form the basis for developing a more comprehensive and structured evaluation framework in this study.

Based on these research gaps, this study aims to determine the most effective and economical formwork system for multi-story building projects by constructing a decision-making framework based on the integration of 4D-5D BIM, Life Cycle Cost Analysis (LCCA), and Break-Even Analysis (BEA). Accordingly, the objectives of this study are to: (1) develop a decision-making framework that integrates 4D–5D BIM, LCCA, and BEA for the selection of conventional and modular formwork systems; (2) validate the framework through a case study of Building X, a 9-story building project in Indonesia; and (3) identify the parameters that significantly affect the time and cost efficiency of formwork execution as a basis for selecting a more effective and economical formwork system.

II. METHODS

This study used a comparative descriptive method with a case study approach, aiming to construct a comparison framework and evaluate the application of two formwork systems, conventional and modular, for the beam, column, and slab elements of Building X, a 9-story reinforced concrete building in East Java. The research methodology was organized into two main stages: (1) development of a decision-making framework integrating 4D-5D BIM, LCCA, and BEA for the selection of conventional and modular formwork systems; and (2) application of the framework to the Building X case study to compare the two formwork systems in terms of time and cost.

A. Development of the Formwork System Selection Decision-Making Framework

This study constructed a decision-making framework for selecting between modular and conventional formwork systems in three sequentially interconnected main layers. The framework was developed with reference to the Digital Construction Framework of Sacks et al. [18], in which BIM serves as the digital representation foundation that enables integrated and measurable time and cost simulation.

The consideration factor input is the stage of identifying all factors influencing formwork system selection, grouped into six main categories: (A) Project Characteristics, covering building type and function, structural volume, number of floors, degree of element repetition, geometric complexity, and project scale; (B) Time Factors, covering target project duration, casting cycle, and erection and dismantling speed; (C) Economic Factors, covering initial formwork cost, reuse potential, labor cost, total life cycle cost, and capital availability; (D) Resources, covering the availability of materials, equipment, skilled labor, and supporting technology; (E) Technical Factors, covering concrete surface quality, dimensional precision and tolerance, ease of installation, flexibility and adaptability, and system stability and safety; and (F) Environment and Sustainability, covering material waste, recycling and reuse potential, carbon emissions, and compatibility with green building requirements.

The decision process is the core of the framework and consists of a multi-criteria evaluation of two alternative formwork systems. Alternative 1 is Conventional Formwork. Characteristics: Timber/Plywood Materials; Ability to Form Non-Standard Shapes; Low Initial Investment; Labour Intensive Execution; Suitability for Small/Non-Repetitive Projects. Alternative 2 is Modular Formwork Characteristics: Aluminum/Steel System Materials; High Repetition and Precision; Multiple Reusability; Faster and More Efficient Erection; Suitability for Medium to Large and High Rise Projects. The multi-criteria evaluation was conducted using a 4D-5D BIM approach integrated with LCCA and BEA.

Project Impact/Performance is the output generated by applying the evaluation framework, covering six performance dimensions: (A) Time Performence,

including construction time efficiency, cycle time per floor, work productivity, and schedule adherence; (B) Cost Performance, including total cost efficiency, savings from reuse and recycling, labor cost reduction, and repair/rework cost reduction; (C) Quality Performance, including concrete surface quality, dimensional precision and accuracy, and structural quality consistency; (D) Occupational Health and Safety (OHS) Performance, including work safety, formwork system stability, work accident risk, and worker ergonomics; (E) Environmental Performance, including construction waste reduction, material reuse and recycling rates, carbon emissions, and sustainable construction performance; and (F) Management Performance, including ease of planning and control, process standardization, and execution risk. In accordance with the defined scope, the analysis in this study focused on Time Performance (A) and Cost Performance (B) among all these performance dimensions.

B. Data Collection

Data collection methods in this study included field observation and a literature review. Secondary data were obtained from project documents in the form of the project budget plan (RAB), shop drawings, the schedule, and the Work Unit Price Analysis (AHSP). These data represent the Consideration Factor Input in the framework, particularly the Economic Factor and Project Characteristics dimensions. The research parameters and assumptions were established based on applicable national technical standards and scientific references, comprising: (a) labor productivity coefficients for conventional formwork based on SNI 7394:2008 [6], namely 0.30 person-days (OH)/m² for columns and beams and 0.12 OH/m² for slabs; (b) productivity coefficients for modular formwork based on the AHSP PUPR, namely 0.07 OH/m² for columns and 0.066 OH/m² for beams and slabs; (c) a durability of 2 uses for conventional formwork (SNI 7394:2008) and 5 uses for LICO/PERI modular formwork (AHSP PUPR); (d) economic parameters comprising a discount rate of r = 6% based on the 2024 BI Rate, daily wages of IDR 189,020/OH (conventional) and IDR 125,000/OH (modular), maintenance rates of 1% and 3% of initial cost, and residual values of 2% and 10% of initial cost for the respective systems. The scope of the study was limited to column, beam, and slab elements with a gate-to-gate life cycle approach, covering material procurement, installation, use during casting and curing, dismantling, reuse, maintenance, and the residual value of materials.

C. 3D BIM Modeling and Volume Extraction

The 3D BIM modeling was performed in Autodesk Revit based on the shop drawing data of the Building X project. This stage implements the Project Characteristics of Layer 1 of the framework, in which the structural volumes and dimensions of the beam, column, and slab elements are precisely identified. Revit's schedule and quantity takeoff features were used to automatically extract the concrete volume of each structural element. Since formwork elements are generally not modeled directly in BIM due to their temporary nature [26], the concrete volumes extracted from Revit were then converted into formwork areas using the following geometric conversion coefficients in equation (1)-(3):

For columns: $$\frac{A}{V} = \frac{2(b+h)}{b \times h} \quad (1)$$

For beams: $$\frac{A}{V} = \frac{(2h+b)}{b \times h} \quad (2)$$

For slabs: $$\frac{A}{V} = \frac{1}{t} \quad (3)$$

where b is the section width, h is the section height, t is the slab thickness, and A/V is the formwork area coefficient (m²/m³). This BIM-based approach is consistent with studies that leverage BIM for automated formwork design optimization and quantity extraction [27]–[28].

D. 4D BIM-Based Time Analysis

The 4D BIM-based time analysis in this study constitutes the calculation of the Time Factor in Layer 1 of the framework and produces the Time Performance output in Layer 3. The formwork area data were used as the basis for calculating execution duration using a productivity-based formula in (4):

$$T = \frac{Productivity\ Coefficient\ (OH/m^2) \times Volume\ (m^2)}{Number\ of\ Workers\ (persons)} \quad (4)$$

The labor productivity values for each formwork system refer to the coefficients stated in the RAB and AHSP documents. The dismantling duration was assumed to be 1.5 times faster than installation, based on Peurifoy and Oberlender [29], who state that dismantling can generally be performed about 1.5–2 times faster than installation. The concrete curing time was assumed to be 28 days and was counted as one full cycle of structural work.

E. 5D BIM-Based Cost Analysis

The 5D BIM-based cost analysis constitutes the calculation of the Economic Factor in Layer 1 of the framework and produces the Cost Performance output in Layer 3. Using the same formwork area data, the cost analysis was performed by applying the AHSP for each formwork system. Following Pishdad and Onungwa [30], the quantity takeoff data from the BIM model were exported to Microsoft Excel and then integrated with unit price data. The cost components considered include material costs, labor costs, and equipment costs per unit of formwork area (IDR/m²).

F. Life Cycle Cost Analysis (LCCA)

LCCA is the multi-criteria evaluation component in Layer 2 of the framework that considers the Economic Factor comprehensively across the entire formwork use cycle. The cost components considered include the Initial Cost (Ci), Operating Cost (Copt), Maintenance Cost (Cmaint), Reuse Cost, and Residual Value (RV). The LCCA formula used refers to ISO 15686-5 [31], as given in (5):

$$LCC = C_i + \sum_{t=1}^{n} \frac{C_{opt,t} + C_{maint,t} + C_{reuse,t}}{(1+r)^t} - RV \quad (5)$$

where r is the discount rate (6%, 2024 BI Rate) and t is the time period (1 construction project cycle). The use of a discount rate is necessary because inflation-driven fluctuations in building material prices can significantly affect construction costs over time [32]. The gate-to-gate life cycle approach spans the installation, dismantling, and

reuse stages of the formwork over the course of construction.

G. Break-Even Analysis (BEA)

BEA is the final stage of the Decision Process (Layer 2) of the framework, which determines the economic feasibility threshold of modular formwork relative to conventional formwork. This analysis directly supports formwork system selection decisions based on long-term Economic Factor considerations. The BEA formula used is given in formula (6):

$$BEA = \frac{FC_{modular} - FC_{conventional}}{VC_{conventional} - VC_{modular}} \quad (6)$$

where FC is the fixed cost (initial investment/procurement cost), and VC is the variable cost per cycle (material + labor per floor).

The framework was applied to a real project as a case study to validate the usefulness and reliability of the formwork system selection decision-making framework that had been developed. The case study project is Building X, a multi-story reinforced concrete building located in East Java, Indonesia. Building X consists of 9 floors (Floor 1 to the Roof) with main structural elements comprising columns of type K1 (60×80 cm), K2 (40×40 cm), and K3 (20×20 cm); beams of type B1 (35×70 cm), B2 (25×50 cm), B3 (20×40 cm), B4 (20×30 cm), and B5 (15×30 cm); and floor slabs 12–15 cm thick. Building X was selected as the case study based on the availability of complete and representative project data, ease of access to planning documents (RAB, shop drawings, AHSP, time schedule), and the suitability of the project characteristics to the research topic, namely a multi-story building with repetitive formwork on column, beam, and slab elements. Fig. 1 presents the resulting 3D model of Building X developed in Autodesk Revit, wich served as the basis for the subsequent structural volume extraction and formwork analysis.

The framework was implemented on Building X in stages following the three-layer flow of the framework. In Layer 1, the Consideration Factor Inputs were identified by analyzing the project characteristics of Building X (9 floors, repetitive elements), time factors (productivity coefficients from SNI 7394:2008 and the AHSP PUPR), economic factors (unit prices from the project RAB and economic parameters from applicable standards), resources (a workforce of 50 workers), technical factors (specifications of conventional timber formwork and LICO/PERI modular formwork), and environmental aspects (gate-to-gate approach). Layer 2 Decision Process was carried out in four sequential analysis stages: (1) 3D BIM modeling in Autodesk Revit for the extraction of structural volume and transformation into formwork areas; (2) 4D BIM time analysis in Microsoft Excel with the application of productivity coefficients; (3) 5D BIM cost analysis using the project's AHSP unit prices; and (4) LCCA and BEA evaluation for long-term economic viability. In Layer 3, the Time Performance and Cost Performance outputs were quantified and compared between the two alternative formwork systems to produce data-driven decision recommendations.

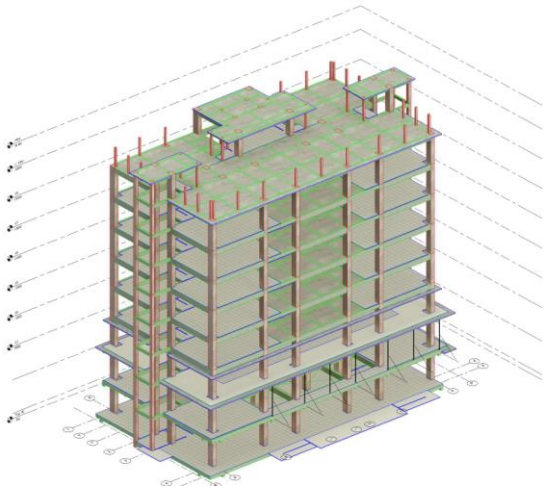

Fig. 1. 3D model of Building X

III. Result and Discussion

A. Formwork System Selection Decision Framework

The Formwork System Selection Decision-Making Framework developed in this study is the main contribution that structures the entire comparative analysis of conventional and modular formwork. The framework is designed as a comprehensive decision support tool that integrates three interconnected layers Consideration factor Input, Decision Process, and Projrct Impact/Performance each corresponding to a specific analytical stage of the evaluation, as shown in Fig. 2.

The first layer (Consideration Factor Input) serves as the comprehensive data identification and collection stage. The Project Characteristics (dimension A) were retrieved from the 3D BIM model in Autodesk Revit, which offered information about the concrete structural volume. The Time Factor (dimension B) is represented by labor productivity coefficients from SNI 7394:2008 and the AHSP PUPR. The Economic Factor (dimension C) is represented by work unit prices from the project RAB. The second layer (Decision Process) is the core of the framework, in which the multi-criteria evaluation of conventional and modular formwork is carried out through four sequential analysis stages: 4D BIM, 5D BIM, LCCA, and BEA. The third layer (Project Impact/Performance) produces evaluation outputs focused on Time Performance and Cost Performance.

The development of this framework is in line with Sacks et al. [18], who emphasize that a Digital Construction Framework integrating BIM as the digital representation foundation enables the optimization of construction decision-making based on real-time simulation of various conditions. Terzioglu and Polat [33] also demonstrated that a BIM based multi criteria evaluation approach that simultaneously considers multiple factor dimensions, including sustainability and occupational safety, produces more optimal formwork system selection decisions than single-criterion evaluations.

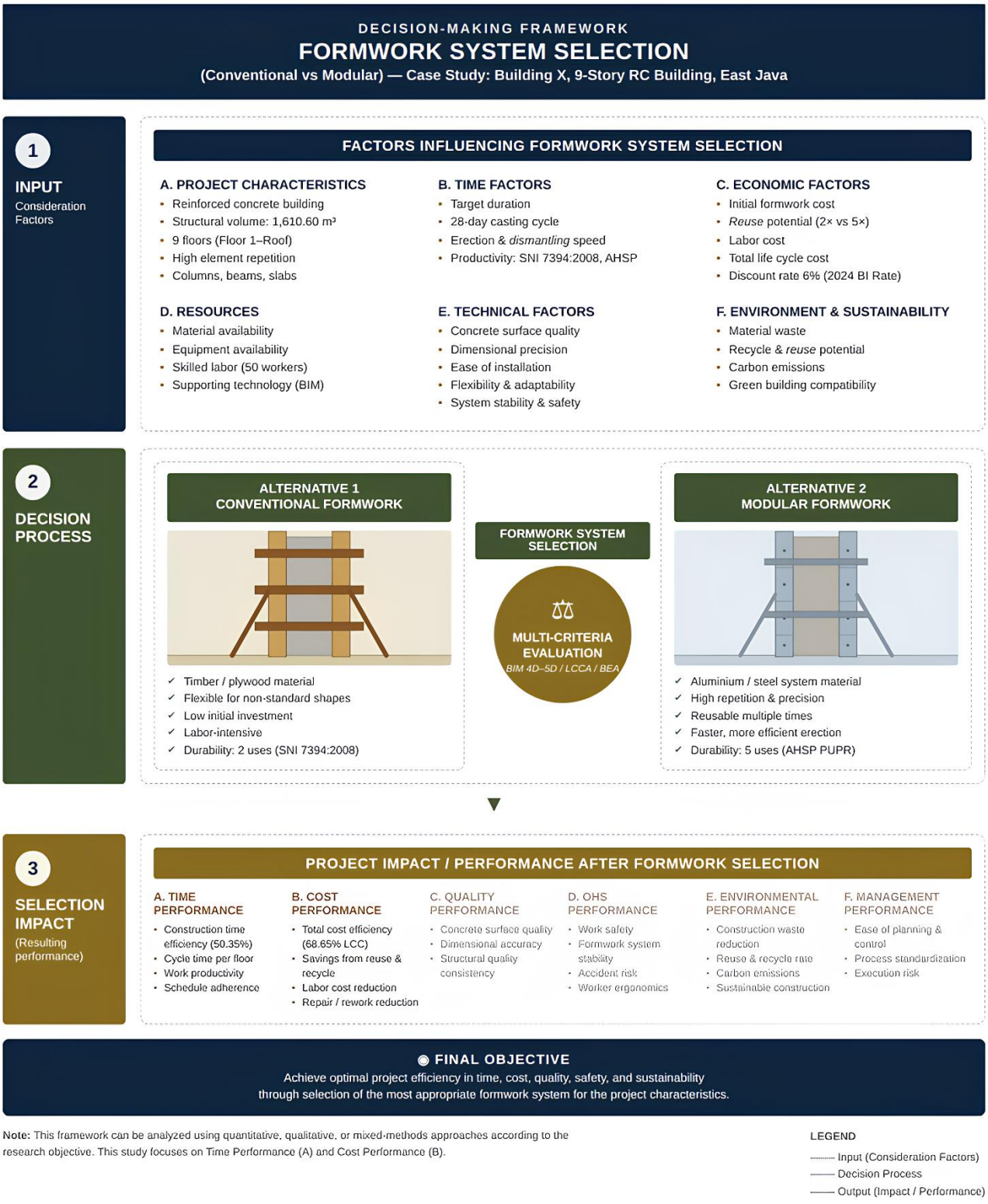

Fig. 2. Formwork system selection decision making framework, showing the three sequential analytical layers (Consideration factor Input, Decision Process, and Project Impact/Performance) use to evaluate and select between conventional and modular formwork systems

B. Consideration Factor Input: 3D BIM Modeling and Structural Volumes

In accordance with Layer 1 of the framework in the Project Characteristics dimension, the 3D BIM modeling of Building X was performed in Autodesk Revit by modeling the beam, column, and slab structural elements across 9 floors. The volume data extracted from Revit represent the Project Characteristics in the form of structural volumes, which form the basis of all subsequent calculations. The total structural volumes obtained are summarized in Table I.

TABLE I
SUMMARY OF STRUCTURAL VOLUMES

Element	Revit (m^3)
Columns	442.54
Beams	514.46
Slabs	653.60

Table I presents the structural volumes obtained from the Revit model for the three main structural elements. The column volume is 442.54 m³, the beam volume is 514.46 m³, and the slab volume is 653.60 m³. The use of BIM for quantity takeoff in this study is in line with the findings of Saavedra et al. [34], who showed that BIM-based QTO produces more accurate quantities than CAD, with differences reaching 2.32% for concrete and 10.02% for steel, while formwork differences remain small (0.81%). This is confirmed by Monteiro and Poças Martins [35], who showed that BIM-based quantity takeoff significantly reduces the drawing misinterpretation and data inconsistency that often occur in conventional 2D drawing-based methods, providing a more reliable basis for construction cost and time planning. Olsen and Taylor [36] likewise reported that BIM-based QTO is faster and more accurate than manual takeoffs, although the accuracy still depends on model quality and modeling method [37], underscoring the importance of consistent modeling criteria.

The formwork areas were then calculated using the geometric coefficients for each type of structural element. The total formwork areas obtained are presented in Table II.

TABLE II
SUMMARY OF FORMWORK AREAS

Element	Formwork Area (m²)
Columns	2,829.13
Beams	2,791.37
Slabs	4,981.83
Total	**10,602.33**

Table II shows the total formwork area required for each structural element of Building X. Slabs require the largest formwork area at 4,981.83 m² (46.99% of the total), followed by columns at 2,829.13 m² (26.68%) and beams at 2,791.37 m² (26.33%). The overall formwork area to be installed across all floors of Building X is 10,602.33 m². Differences in formwork area are influenced by the number and dimensions of the structural elements. Slabs have the largest formwork area because they cover the entire floor area, while beams and columns have relatively similar areas due to their similar shapes and dimensions.

Converting concrete volume into formwork area using geometric coefficients is an approach that has been validated in construction practice. Khosakitchalert et al. [26] explain that concrete formwork is an element that is generally not modeled directly in BIM due to its temporary nature, so its quantities must be derived from the structural elements available in the model through conversion coefficients. Lee et al. [20], in their study of BIM-based productivity measurement for structural formwork, also used a similar approach, in which formwork areas were calculated from the dimensions of the concrete elements modeled in BIM, and the results proved accurate in supporting time and cost estimation of formwork execution in the field.

C. Decision Process Stage 1: Time Analysis (4D BIM) – Time Performance

The 4D BIM-based time analysis is the first stage of the Decision Process (Layer 2), which evaluates the Time Factor from Layer 1 of the framework. Installation durations were calculated using productivity coefficients from SNI 7394:2008 for conventional formwork (0.30 OH/m² for columns and beams; 0.12 OH/m² for slabs) and the AHSP PUPR for modular formwork (0.07 OH/m² for columns; 0.066 OH/m² for beams and slabs), assuming a workforce of 50 workers. The time analysis results are presented in Tables III and IV.

TABLE III
CONVENTIONAL FORMWORK DURATIONS

Formwork	Installation (days)	Curing (days)	Dismantling (days)	Total (days)
Columns	16.97	28	11.32	28.29
Beams	16.75	28	11.17	27.91
Slabs	11.96	28	7.97	19.93
Total	**45.68**	**84**	**30.46**	**104.13**

Table III shows the durations of conventional formwork activities for each structural element. The installation duration of columns has the longest duration (16.97 days), followed by beams (16.75 days) and slabs (11.96 days). The dismantling duration of each element was assumed to be 1.5 times faster than installation; thus, columns require 11.32 days, beams 11.17 days, and slabs 7.97 days for dismantling. Adding the 28-day concrete curing time as one full cycle, the total conventional formwork duration for all of Building X reaches 104.13 days (rounded to 105 days). The long durations for columns and beams are caused by their larger labor coefficient (0.30 OH/m²) compared with slabs (0.12 OH/m²), reflecting the complexity of installing formwork for vertical elements and elements with more complex profiles.

This long execution duration of conventional formwork is confirmed by several previous studies. Yusriyya Huwaida et al. [24], in their study of a sub-district office building, reported that conventional formwork required approximately 150 days for the structural works of a multi-story building, far longer than the modular alternative. Haron et al. [38] also explain that the main weaknesses of conventional timber formwork are its labor-intensive installation and longer duration due to the absence of component standardization, requiring every element to be fabricated and installed manually on site, which greatly affects overall labor productivity.

TABLE IV
MODULAR FORMWORK DURATIONS

Formwork	Installation (days)	Curing (days)	Dismantling (days)	Total (days)
Columns	3.96	28	2.64	6.60
Beams	3.68	28	2.46	6.14
Slabs	6.58	28	4.38	10.96
Total	**14.22**	**84**	**9.48**	**51.70**

Table IV details the durations of modular formwork activities for each structural element. Unlike conventional formwork, with modular formwork the slab element has the longest installation duration (6.58 days) compared with columns (3.96 days) and beams (3.68 days). This is because the slab formwork area is much larger (4,981.83 m²) than that of columns and beams, even though its productivity coefficient is smaller (0.066 OH/m²). The total modular formwork duration for all of Building X is 51.70 days (rounded to 52 days). The significant difference between column and beam durations for modular formwork (about 6-7 days) compared with conventional

formwork (about 28-29 days) reflects the advantage of modular component standardization, which enables much higher erection speeds for these elements.

This significant duration advantage of modular formwork is supported by Baskova et al. [7], who explain that modular formwork systems made of aluminum or steel have components precisely prefabricated in the factory with standardized locking systems, so on-site installation can be performed much faster without time-consuming manual adjustments. Rehman et al. [13], in a systematic review of 69 4D BIM articles, demonstrated that implementing 4D BIM for monitoring and evaluating modular formwork durations consistently shows significant time savings compared with conventional formwork, with an average improvement in project time control of up to 25% through the use of productivity data integrated in the digital model.

TABLE V
TIME COMPARISON OF CONVENTIONAL AND MODULAR FORMWORK

Formwork	Conventional (days)	Modular (days)	Difference (days)	Efficiency (%)
Columns	28.29	6.60	21.69	76.68%
Beams	27.91	6.14	21.77	77.99%
Slabs	19.93	10.96	8.97	45.01%
Total	**104.13**	**51.70**	**52.43**	**50.35%**

Table V shows that modular formwork has a shorter execution duration than conventional formwork for all structural elements. The maximum efficiencies are obtained for the beams (77.99%) and columns (76.68%) and the efficiency for slabs is less (45.01%) due to the reduced difference in productivity coefficients. The total time of work is decreased by 52.43 days (50.35%) by using of modular formwork, which shortens the structural execution time from 105 days to 52 days.

This high level of time efficiency is consistent with a number of previous studies. For example, in the investigation of the Oyama Plaza project in Jakarta, Yogiswara et al. [25] observed that aluminum modular formwork was 33 days faster than the conventional method, with increased casting quality and precision. Similarly, Supriyono et al. [4] recorded savings of 52 days in a similar project comparing aluminum and conventional formwork, confirming that the 50.35%-time efficiency obtained in this study is within a range consistent with previous findings. Yusriyya Huwaida et al. [24] likewise reported that the modular method reduced the structural work duration by 42% (from 150 to 87 days) compared with the conventional method.

D. Decision Process Stage 2: Cost Analysis (5D BIM) – Initial Cost Performance

The 5D BIM-based cost analysis is the second stage of the Decision Process, which calculates the Economic Factor from Layer 1 of the framework, specifically the initial formwork cost. The unit prices of conventional formwork were obtained from the RAB of the Building X project (assuming 2 uses in accordance with SNI 7394:2008 [6]), while the unit prices of LICO/PERI modular formwork refer to a Value Engineering Analysis journal reference, assuming 5 uses in accordance with the AHSP PUPR. The comparison of unit prices and total costs is presented in Table VI.

TABLE VI
COST COMPARISON OF CONVENTIONAL AND MODULAR FORMWORK

Element	Volume (m^2)	Conventional Unit Price (IDR/m^2)	Modular Unit Price (IDR/m^2)	Total Conventional (IDR)	Total Modular (IDR)
Columns	2,829.13	247,119.80	189,770.00	699,132,804.18	536,883,051.25
Beams	2,791.37	253,119.80	236,940.00	706,551,859.86	661,387,997.60
Slabs	4,981.83	237,645.20	172,270.00	1,183,907,864.85	858,219,765.76
Total	**10,602.33**			**2,589,592,528.88**	**2,056,490,814.61**

Table VI compares the direct costs of executing conventional and modular formwork for each structural element of Building X based on the 5D BIM analysis. For columns, the conventional formwork unit price (IDR 247,119.80/m^2) is 30.2% higher than the modular price (IDR 189,770.00/m^2), producing a total cost difference of IDR 162,249,752.93. For beams, the unit price difference is smaller (IDR 253,119.80/m^2 versus IDR 236,940.00/m^2, or 6.8% higher), with a total cost difference of IDR 45,163,862.26. The largest difference occurs for slabs, where conventional formwork (IDR 237,645.20/m^2) is 38.0% more expensive than modular formwork (IDR 172,270.00/m^2), producing the largest cost difference of IDR 325,688,099.09. In total, the direct cost of conventional formwork reaches IDR 2,589,592,528.88 while modular formwork costs only IDR 2,056,490,814.61, making modular formwork IDR 533,101,714.27 or 20.59% cheaper.

This difference in initial cost between the two formwork systems is confirmed by previous research. Lawdy et al. [39] of Universitas Brawijaya found that semi-system formwork can reduce beam costs by up to 47% and column costs by up to 37% compared with conventional formwork, consistent with the findings of this study.

E. Decision Process Stage 3: Life Cycle Cost Analysis (LCCA)

LCCA is the third stage of the Decision Process, extending the evaluation of the Economic Factor to a long-term perspective. The parameters and assumptions used in the LCCA were established as described in the research method section. The LCCA results for each cost component are presented in Table VII.

Table VII presents the complete LCCA results for the life cycle cost components of conventional and modular formwork for Building X. The total LCC of conventional formwork reaches IDR 10,985,232,483.45, almost three times the total LCC of modular formwork at IDR 3,443,368,713.51.

TABLE VII
LCCA CALCULATION RESULTS

Cost Component	Conventional (IDR)	Modular (IDR)	Difference (IDR)	Contribution (%)
Initial Cost (Ci)	2,589,592,528.88	2,056,490,814.61	533,101,714.27	7.07%
Operating Cost (Copt)	719,526,379.42	148,139,611.70	571,386,767.72	7.58%
Maintenance Cost (Cmaint)	25,895,925.29	61,694,724.44	−35,798,799.15	−0.47%
Reuse Cost	8,208,855,408.75	1,478,244,263.05	6,730,611,145.70	89.25%
Residual Value (RV)	51,791,850.58	205,649,081.46	153,857,230.88	2.04%
Total LCC	**10,985,232,483.45**	**3,443,368,713.51**	**7,541,863,769.94**	**68.65%**

The total LCC difference between the two is IDR 7,541,863,769.94, which is a saving of 68.65% in the case of modular formwork. The reuse cost is the main contributor to the difference in the LCC, accounting for 89.25% of the total difference, followed by operating cost (7.58%), initial cost (7.07%) and residual value (2.04%). The maintenance cost is the only component that is higher for modular formwork (difference −IDR 35,798,799.15 or −0.47%), but the value is very small and does not affect the overall conclusion. The labor operating cost of conventional formwork (IDR 719,526,379.42) is almost 5 times of modular formwork (IDR 148,139,611.70), which reflects the tangible impact of the duration difference identified in the earlier 4D CAD BIM analysis.

The benefits of using modular formwork for LCCA are confirmed by Tighnavard Balasbaneh et al [40], who showed that in a multi-cycle LCC analysis, metal materials, which are more expensive at the start, are more cost-effective in the long run compared to wood-based materials, particularly when the factors of reuse and residual value are taken into account. Altaf et al. [41]–[42] obtained similar results, in which life cycle cost analysis (LCCA) showed that modular formwork provides significant long-term benefits: despite its larger initial investment, its long service life and time and labor efficiency make its total cost over the project life much lower than that of conventional formwork, fully consistent with the findings of this study.

F. Decision Process Stage 4: Break-Even Analysis (BEA) – Basis for Decision Recommendation

BEA is the final stage of the Decision Process, serving as the determinant of the formwork system selection recommendation based on actual project conditions.

TABLE VIII
LCC COMPARISON AT VARIOUS NUMBERS OF REUSES

Number of Modular Reuses (n)	Conventional LCC (IDR/Cycle)	Modular LCC (IDR/Cycle)	Difference (IDR)	Remarks
1×	2,014,322,644	2,394,938,211	−380,615,568	Conventional More Economical
2×	2,014,322,644	2,204,630,427	−190,307,784	Conventional More Economical
3×	**2,014,322,644**	**1,176,385,020**	**+837,937,624**	**Modular More Economical**
4×	2,014,322,644	833,636,550	+1,180,686,093	Modular More Economical
5×	2,014,322,644	662,262,316	+1,352,060,328	Modular More Economical

Table VIII shows that modular formwork becomes more economical than conventional formwork starting from the 3rd reuse (break-even point). The savings continue to grow as the number of reuses increases, reaching IDR 1,352,060,328 under the actual conditions of Building X with 5× reuse. Therefore, the selection of modular formwork for Building X is quantitatively proven to be more economical.

The finding of a break-even point at the 3rd reuse is supported by Putra et al. [43], found that the material cost for system formwork is only paid during the first use, all other costs are labor costs, and it is more economical with the use of every cycle. This reuse capacity supports the economic feasibility of modular formwork on projects with a sufficient number of use cycles. Mei et al. [44] further showed that formwork reuse, including cooperative reuse among construction sites, yields substantial economic benefits, reinforcing reuse as the key driver of modular formwork economics.

G. Project Performance Impact: Summary of Framework Outputs and Significant Parameters

Referring to Layer 3 of the framework (Project Impact/Performance), Table IX presents a summary of the evaluation outputs, focused on Time Performance and Cost Performance, from the implementation of the framework on Building X.

TABLE IX
SUMMARY OF TIME AND COST PERFORMANCE (FRAMEWORK OUTPUT)

Performance Component	Indicator	Conventional	Modular	Modular Efficiency
Time Performance	Total Duration (days)	104.13	51.70	50.35% faster
	Column cycle time (days)	28.29	6.60	76.68% faster
	Beam cycle time (days)	27.91	6.14	77.99% faster
	Slab cycle time (days)	19.93	10.96	45.01% faster
Cost Performance	Initial Cost (IDR)	2,589,592,528.88	2,056,490,814.61	20.59% cheaper
	Total LCC (IDR)	10,985,232,483.45	3,443,368,713.51	68.65% cheaper
	Reuse Cost (IDR)	8,208,855,408.75	1,478,244,263.05	82.00% cheaper
	Operating Cost (IDR)	719,526,379.42	148,139,611.70	79.42% cheaper
BEA	Minimum modular reuse	—	3×	Achieved at 3×

Table IX summarizes all Time Performance and Cost Performance outputs produced by applying the Formwork System Selection Decision-Making Framework to Building X. In the Time Performance dimension, modular formwork consistently outperforms across all structural elements, with cycle time efficiencies ranging from 45.01% to 77.99% and a total efficiency of 50.35%. In the Cost Performance dimension, the advantage of modular formwork grows in the long-term perspective: the 20.59% initial cost efficiency increases to a 68.65% total LCC efficiency once all life cycle cost components are accounted for. The BEA results show that the recommendation to use modular formwork is highly robust: it is feasible starting from 3× reuse.

Overall, the application of the framework to Building X successfully demonstrates that modular formwork is quantitatively superior to conventional formwork in both performance dimensions analyzed. This result is consistent with Wan Abdul Basir et al. [22], who confirmed that integrating 4D–5D BIM in an evaluation framework yields significant and measurable differences in time and cost efficiency between construction execution alternatives. Lee et al. [20] also demonstrated that an integrated 4D-5D BIM system can be used effectively to measure labor productivity, estimate costs, and monitor formwork project progress daily, making it a comprehensive and reliable evaluation tool for supporting optimal formwork system selection decisions.

IV. Conclusion

The formwork system selection decision-making framework was constructed in three interconnected layers: the consideration factor input, which identifies six factor dimensions (project characteristics, time factors, economic factors, resources, technical factors, and environment and sustainability); the decision process, which integrates multi-criteria evaluation through 4D BIM, 5D BIM, LCCA, and BEA; and the project impact/performance layer, which produces time performance and cost performance outputs. The framework is able to integrate all consideration factors with structured quantitative analysis, so it can be used as a comprehensive decision-support tool.

Implementation of the framework on the Building X case study (9 floors, East Java) shows that modular formwork performs more efficiently than conventional formwork for beam, column, and slab elements. In the time performance dimension, modular formwork achieved an efficiency of 50.35% (52 days versus 105 days), with the highest cycle time efficiencies for beams (77.99%) and columns (76.68%). In the cost performance dimension, modular formwork is 20.59% cheaper in initial cost and 68.65% cheaper in total LCC. The BEA results show that modular formwork is economically feasible starting from the 3rd use cycle.

The parameter with the most significant influence on cost efficiency, as identified through the application of the framework, is the reuse cost, contributing 89.25% of the total LCC difference, which is directly related to the economic factor (reuse potential) and the project characteristics (number of floors) in Layer 1 of the framework. The next parameters are operating cost (7.58%), related to the time factor; initial cost (7.07%); and residual value (2.04%), related to the environment and sustainability dimension.

Based on these results, it is recommended that 4D–5D BIM implementation be optimized from the project planning stage by integrating it into a comprehensive formwork system selection decision-making framework. The use of modular formwork is recommended for multi-story building projects, especially those with a high number of floors and repetitive work. For future research, it is recommended to extend the analysis to the other performance dimensions of the framework, such as quality performance, OHS performance, environmental performance, and management performance.

Acknowledgment

The authors sincerely express their gratitude to all parties who contributed to the completion of this research, particularly the Department of Civil Engineering, Faculty of Engineering, Universitas Brawijaya, for the support provided, and the colleagues and reviewers whose constructive feedback improved the quality of this work.

References

[1] Badan Standardisasi Nasional (BSN), *SNI 2847:2019: Persyaratan Beton Struktural untuk Bangunan Gedung dan Penjelasan*, Jakarta: BSN, 2019.

[2] Bappenas, *Rencana Pembangunan Jangka Menengah Nasional (RPJMN) 2025–2029*, Jakarta, 2025.

[3] T. Terzioglu, G. Polat, and H. Turkoglu, "Formwork system selection criteria for building construction projects: A structural equation modelling approach," *Buildings*, vol. 12, no. 2, e204, Feb. 2022, doi: 10.3390/buildings12020204.

[4] A. S. Supriyono, I. N. D. P. Putra, and B. Trigunarsyah, "Comparative analysis of formwork systems: Cost efficiency and time management in construction projects," *Adv. Sustainable Sci. Eng. Technol.*, vol. 7, no. 2, e0250204Feb. 2025, doi: 10.26877/asset.v7i2.1320.

[5] E. Agriansyah, A. Suryo, and E. Arifi, "Selection of methods of carrying out floor plate Bekesting Work with cost comparison," *Appl. Res. Civil Eng. Environ. (ARCEE)*, vol. 05, no. 01, pp. 14–23, 2024, doi: 10.32722/arcee.v5i01.5753

[6] Badan Standardisasi Nasional (BSN), *SNI 7394:2008: Tata Cara Perhitungan Harga Satuan Perkerjaan Beton untuk Konstruksi Bangunan Gedung dan Perumahan*, Jakarta: BSN, 2008.

[7] R. Baskova, A. Tazikova, Z. Strukova, M. Kozlovska, and J. Cabala, "A dynamic model for effective and optimal planning of formwork in construction projects," *Buildings*, vol. 13, no. 7, e1794, Jul. 2023, doi: 10.3390/buildings13071794.

[8] V. Rajeshkumar, S. Anandaraj, V. Kavinkumar, and K. S. Elango, "Analysis of factors influencing formwork material selection in construction buildings," *Mater. Today Proc.*, vol. 37, pp. 880–885, Jan. 2021, doi: 10.1016/J.MATPR.2020.06.044.

[9] M. T. Al-Ashwal, R. Abdullah, and R. Zakaria, "Traditional formwork system sustainability performance: Experts' opinion," *IOP Conf. Series: Materials Sci. Eng.*, Dec. 2017. doi: 10.1088/1757-899X/271/1/012108.

[10] M. S. Gaddam and A. Achuthan, "A comparative study on newly emerging type of formwork systems with conventional type of form work systems," *Mater. Today Proc.*, vol. 33, pp. 736–740, Jan. 2020, doi: 10.1016/J.MATPR.2020.06.090.

[11] J. Nilimaa, Y. Gamil, and V. Zhaka, "Formwork engineering for sustainable concrete construction," *CivilEng*, vol. 4, no. 4, pp. 1098–1120, Dec. 2023, doi: 10.3390/civileng4040060.

[12] Kementerian Perkerjaan Umum dan Perumahan Rakyat (PUPR), *Peraturan Menteri PUPR no. 22/PRT/M/2018 tentang Pembangunan Gedung Negara*, Jakarta, 2018.

[13] I. U. Rehman, K. M. Mazher, and I. Y. Wuni, "Systematic review of 4D BIM benefits in construction projects," *Results in Eng.*, e107091, 2025, doi: 10.1016/j.rineng.2025.107091.

[14] Q. Lu, J. Won, and J. C. P. Cheng, "A financial decision making framework for construction projects based on 5D Building

Information Modeling (BIM)," *Int. J. Project Manag.*, vol. 34, no. 1, pp. 3–21, Jan. 2016, doi: 10.1016/j.ijproman.2015.09.004.
[15] U. Haider, U. Khan, A. Nazir, and M. Humayon, "Cost comparison of a building project by manual and BIM," *Civil Eng. J. (Iran)*, vol. 6, no. 1, pp. 34–49, Jan. 2020, doi: 10.28991/cej-2020-03091451.
[16] S. K. Fuller and S. R. Petersen, "Life-cycle costing manual for the federal energy management program," NIST Handbook 135, National Institute of Standards and Technology, Gaithersburg, MD, 1995. doi: 10.6028//NISHT.HB.135-1995.
[17] Stanford University, *Guidelines For Life Cycle Cost Analysis*, 2005.
[18] R. Sacks, C. M. Eastman, G. Lee, and P. M. Teicholz, *BIM Handbook: A Guide to Building Information Modeling for Owners, Designers, Engineers, Contractors, and Facility Managers, 3rd ed*, Hoboken, NJ, USA: John Wiley & Sons, 2018.
[19] M. S. Raza, B. A. Tayeh, Y. I. Abu Aisheh, and A. M. Maglad, "Potential features of building information modeling (BIM) for application of project management knowledge areas in the construction industry," *Heliyon*, vol. 9, no. 9, Sep. 2023, doi: 10.1016/j.heliyon.2023.e19697.
[20] J. Lee, Y. J. Park, C. H. Choi, and C. H. Han, "BIM-assisted labor productivity measurement method for structural formwork," *Autom. Constr.*, vol. 84, pp. 121–132, Dec. 2017, doi: 10.1016/j.autcon.2017.08.009.
[21] B. Yoo, H. Yoon, Y. Kim, and K. M. Lee, "Stepwise application of BIM-based parametric modeling to tapered slip-form system," in *Procedia Eng.*, pp. 112–119, 2016, doi: 10.1016/j.proeng.2016.04.028.
[22] W. N. F. A. W. A. Basir, U. Ujang, and Z. Majid, "Adaptation 4D and 5D BIM for BIM/GIS data integration in construction project management," in *IOP Conf. Series: Earth and Environ. Sci.*, vol. 1274, no. 1, e012002, 2023, doi: 10.1088/1755-1315/1274/1/012002.
[23] A. W. Hammad, A. Akbarnezhad, P. Wu, X. Wang, and A. Haddad, "Building information modelling-based framework to contrast conventional and modular construction methods through selected sustainability factors," *J. Clean. Prod.*, vol. 228, pp. 1264–1281, Aug. 2019, doi: 10.1016/J.JCLEPRO.2019.04.150.
[24] N. Y. Huwaida, F. S. Handayani, and M. Rifai, "Perbandingan biaya dan waktu antara metode konvensional dengan metode modular menggunakan Microsoft project," *J. Ris. Rekayasa Sipil*, vol. 8, no. 1, pp. 18-26, 2024. doi: 10.20961/jrrs.v8i1.95314.
[25] R. Yogiswara, A. Andreas, and R. T. Lestari, "Analisis faktor penyebab keterlambatan dan perbandingan pekerjaan pemasangan bekisting aluminium-bekisting konvensional ditinjau dari segi waktu, biaya, dan mutu: Studi kasus proyek Oyama Plaza Apartemen dan Hotel Jakarta," *J. Artesis*, vol. 3, no. 1, pp. 49-61, 2023, doi: 10.35814/artesis.v3i1.5022.
[26] C. Khosakitchalert, N. Yabuki, and T. Fukuda, "Automatic concrete formwork quantity takeoff using building information modeling," in *The 19th Int. Conf. on Construction Appl. of Virtual Reality Bangkok, Thailand*, pp. 21-28, 2019. [Online]. Available: https://www.researchgate.net/publication/337286106_Automatic_Concrete_Formwork_Quantity_Takeoff_Using_Building_Information_Modeling
[27] C. Hyun, C. Jin, Z. Shen, and H. Kim, "Automated optimization of formwork design through spatial analysis in building information modeling," *Autom. Constr.*, vol. 95, pp. 193–205, Nov. 2018, doi: 10.1016/J.AUTCON.2018.07.023.
[28] D. Mansuri, D. Chakraborty, H. Elzarka, A. Deshpande, and T. Gronseth, "Building information modeling enabled cascading formwork management tool," *Autom. Constr.*, vol. 83, pp. 259–272, Nov. 2017, doi: 10.1016/J.AUTCON.2017.08.016.
[29] R. L. Peurifoy and G. D. Oberlender, *Formwork for Concrete Structures 4th ed.*, New York, NY. USA: McGraw-Hill," 2011.
[30] P. Pishdad and I. O. Onungwa, "Analysis of 5d BIM for cost estimation, cost control, and payments," *J. Inf. Technol. Construct.*, vol. 29, pp. 525–548, 2024, doi: 10.36680/j.itcon.2024.024.
[31] *Buildings and constructed assets - Service life planning - Part 5: Life-cycle costing ISO 15686-5*, 2017. [Online]. Available: https://www.iso.org/standard/61148.html
[32] M. A. Musarat, W. S. Alaloul, M. S. Liew, A. Maqsoom, and A. H. Qureshi, "Investigating the impact of inflation on building materials prices in construction industry," *J. Building Eng.*, vol. 32, e101485, Nov. 2020, doi: 10.1016/J.JOBE.2020.101485.
[33] T. Terzioglu and G. Polat, "Formwork system selection in building construction projects using an integrated rough AHP-EDAS approach: A case study," *Buildings*, vol. 12, no. 8, e1084, Aug. 2022, doi: 10.3390/buildings12081084.
[34] R. Saavedra, W. Meléndez, and G. Garcés, "Comparative analysis of quantity take-off in concrete, steel bars and formwork in apartment buildings based on cad and BIM methodologies," *J. Inf. Technol. Construct.*, vol. 30, pp. 159–184, 2025, doi: 10.36680/j.itcon.2025.008.
[35] A. Monteiro and J. P. Martins, "A survey on modeling guidelines for quantity takeoff-oriented BIM-based design," *Autom. Constr.*, vol. 35, pp. 238–253, 2013, doi: 10.1016/j.autcon.2013.05.005.
[36] D. Olsen and J. M. Taylor, "Quantity take-off using Building Information Modeling (BIM), and its limiting factors," *Procedia Eng.*, vol. 196, pp. 1098–1105, Jan. 2017, doi: 10.1016/J.PROENG.2017.08.067.
[37] S. A. Vassen, "Impact of BIM-based quantity take off for accuracy of cost estimation," *Int. J. Construct. Eng. Manag.*, vol. 2021, no. 3, pp. 55–69, 2021, doi: 10.5923/j.ijcem.20211003.01.
[38] N. A. Haron, I. S. Hassim, Mohd. R. Abd. Kadir, and Mohd S. Jaafar, "Building cost comparison between conventional and formwork system: A case study of four-storey school buildings in Malaysia," *Am. J. Appl. Sci.*, vol. 2, no. 4, pp. 819–823, 2005, doi: 10.3844/ajassp.2005.819.823.
[39] M. D. V. Lawdy, E. Arifi, M. N. Wijaya, B. Krisnawan, and T. Rochman, "On the methodology of conventional and semi-system formwork project comparison," *MethodsX*, vol. 13, Dec. 2024, doi: 10.1016/j.mex.2024.102824.
[40] A. T. Balasbaneh, W. Sher, and M. H. W. Ibrahim, "Life cycle assessment and economic analysis of Reusable formwork materials considering the circular economy," *Ain Shams Eng. J.*, vol. 15, no. 4, Apr. 2024, doi: 10.1016/j.asej.2023.102585.
[41] M. Altaf, W. S. Alaloul, M. A. Musarat, and A. H. Qureshi, "Life cycle cost analysis (LCCA) of construction projects: sustainability perspective," *Environ. Dev. Sustain.*, vol. 25, no. 11, pp. 12071–12118, Nov. 01, 2023, *Springer Science and Business Media B.V.* doi: 10.1007/s10668-022-02579-x.
[42] M. Altaf, R. Jaffari, W. S. Alalaoul, M. A. Musarat, and S. Ammad, "Developing automated strategy of life cycle cost analysis (LCCA) with building information modeling (BIM) integration for building projects," *Results in Eng.*, vol. 25, Mar. 2025, doi: 10.1016/j.rineng.2025.104179.
[43] A. B. Putra, D. O. I. Putra, G. A. Sentosa, and R. A. Saputra, "Cost analysis and method comparison on high-rise building column formworks by three formwork methods," *IOP Conf. Series: Earth Environ. Sci.*, vol. 1324, no. 1, e012007, 2024, doi: 10.1088/1755-1315/1324/1/012007.
[44] Z. Mei, M. Xu, H. Li, Z. Huang, and S. Luo, "Cooperation mode for concrete formwork reuse among construction sites," *Sustain. Cities Soc.*, vol. 95, e104584, Aug. 2023, doi: 10.1016/J.SCS.2023.104584.



Dhena Arthamevia is a master's student in the Department of Civil Engineering Faculty of Engineering, Universitas Brawijaya, Malang 65145, Indonesia. Her research focuses on formwork systems, and life cycle cost analysis in construction management. (email: dhena.arthamevia@gmail.com).



Lilya Susanti is a lecturer and researcher in the Department of Civil Engineering, Faculty of Engineering, Universitas Brawijaya, Malang 65145, Indonesia. She specializes in Structural Engineering, with research interests in structural mechanics and material engineering innovation relevant to reinforced concrete construction. (email: lilya_st@ub.ac.id).



Yatnanta Padma Devia is the Head of the Master Program and a researcher in the Department of Civil Engineering, Faculty of Engineering, Universitas Brawijaya, Malang 65145, Indonesia. She specializes in Construction Management, with research interests in sustainable construction, construction demolition waste, and green building. (email: yatnanta@ub.ac.id).