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A System Dynamics Approach to Optimizing Building Design for Constructability and Maintainability

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ABSTRACT
Many projects in Indonesia experience delays and budget overruns due to designs that do not align with field implementation and project cycles. This study introduces a System Dynamics (SD) approach as a breakthrough for modeling the complex, dynamic relationships among Design, Constructability, and Maintainability factors in building projects. The research's novelty lies in applying holistic, predictive dynamic simulation modeling to quantify the interplay among variables that have previously been analyzed only partially. Simulation results reveal that social, economic, and environmental aspects significantly influence design. A maintainability-focused strategy increases the Maintainability Index to 1.00, but reduces Constructability to 0.50. Conversely, prioritizing Constructability raises the Constructability Index to 1.00, while decreasing Maintainability by 30% (0.70). A hybrid scenario yields moderate improvements (Constructability 0.80, Maintainability 0.70), confirming that partial optimization results in suboptimal system performance. The implementation prospects are robust for the Indonesian construction industry. This model provides a quantitative basis for encouraging best practices such as early contractor and supplier involvement and more strategic integration of Building Information Modeling (BIM). Scenario simulations demonstrate that a balanced optimization strategy is significantly superior to a partial approach. Stakeholders can adopt these findings as a decision-making tool to allocate resources more effectively, improve construction efficiency, and ensure the long-term sustainability of building performance, thereby accelerating sustainable infrastructure development.

Keywords: *System Dynamics; Building Design; Constructability; Maintainability.*

1. Introduction

Infrastructure is the driving force of a country's economy, so infrastructure development contributes to national development. This activity is reflected in the construction sector. According to the Indonesian Standard Industrial Classification (KBLI), construction is an economic activity involving general construction and the construction of buildings and civil engineering structures. The construction sector has played a significant role in Indonesia's Gross Domestic Product (GDP) over the past 10 years, with an average contribution of 10.53%. In the first quarter of 2022, its contribution to the national GDP reached 10.42% [1]. Therefore, construction technology and management must continue to be developed to increase the industry's contribution.

The built environment significantly impacts global sustainability, and the construction industry is constantly seeking ways to improve construction performance. One approach identified by researchers is the development of a comprehensive dynamic design model to address critical issues related to constructability and maintainability [2], [3]. Traditional design methods focus solely on completing the design phase, ignoring the project's complexity during implementation and the maintenance and upkeep of the designed structure. This impacts the entire project life cycle. Compliance with relevant codes, regulations, and standards is a critical performance criterion for

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construction projects. Proper compliance not only ensures the safety and security of building occupants but also contributes to the overall quality of the building's lifecycle, including durability [2], expandability, maintainability [4], reliability, risk [5], simplicity, quality, and value.

Conventional building design practices often prioritize static, predictable operating conditions, resulting in structures that lack the adaptability needed to respond to the dynamic, uncertain environments they usually encounter [6]. Although previous studies have examined constructability and maintainability, these investigations typically treat the two aspects separately, using partial, linear, or static models that fail to capture the reciprocal, time-dependent interactions between them. This creates a clear research gap, as no existing framework integrates both factors into a holistic, feedback-driven system that can represent how design decisions evolve and influence downstream performance. To address this gap, developing a dynamic building design model is essential, as it simultaneously incorporates constructability and maintainability within a unified system that reflects real-world complexity and supports more adaptive, evidence-based decision-making.

Based on the background above, this study will identify and explore the relationships among design factors influencing management performance throughout the building lifecycle, specifically constructability and maintainability. This study aims to develop a dynamic model that can optimize the influence of design factors on constructability and maintainability in the Indonesian building construction industry.

2. Materials and Methods

2.1. Design Process

The design and planning process for complex buildings is highly complex. Therefore, design tools are needed that can effectively integrate the entire design. One such tool is BIM, a digital prototyping platform that allows testing of various aspects of design and production before physical construction begins. With a comprehensive digital model, the project team can identify potential issues, clashes, and inconsistencies early in the project cycle, thereby reducing the risk of rework and negative impacts [7], [8], [9]. However, BIM is limited to a tool that relies heavily on the operator's operating skill. On the other hand, construction design must now consider sustainable projects to meet global demands.

The building and construction sector significantly impacts the global environment, underscoring the need for a more sustainable approach to design and planning. The history of architecture includes numerous examples of buildings with low environmental impact, from vernacular architecture to modern innovations [10]. Today, the design process focuses on creating solutions that are not only cost-effective and energy-efficient but also have social and cultural value. To achieve this, decision-makers need sophisticated strategies to evaluate and rank the sustainability of various potential solutions [11]. This assessment can be holistic, encompassing the economic, social, and environmental pillars, or partial, focusing on a single aspect. Currently, technologies such as Building Information Modeling (BIM) [12] are one of the methods used to facilitate sustainable architectural design [13], [14], [9].

2.2. Constructability

Constructability is a concept that aims to streamline the construction process by integrating knowledge and experience into project planning and design. However, many construction projects experience design failures or difficulties in implementing the design, making implementation increasingly urgent [15]. Several project cases also demonstrate that unimplemented designs actually increase the costs of the work implementation method. This leads to unplanned increases in project costs.

Research [15] shows that implementing constructability in construction projects faces various obstacles, categorized into five main factors: organizational, managerial, technical, contractual, and environmental. The most significant barriers stem from organizational, technical, and managerial factors, including ineffective communication that leads to numerous design changes during project implementation, misalignment between project objectives and the initial plan, and an organizational culture that does not support innovation to achieve project efficiency and effectiveness.

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Implementing constructability in construction projects plays a crucial role in improving efficiency, safety, sustainability, and decision-making. Research [16] develops a comprehensive framework for evaluating and enhancing constructability across various project phases, from conceptual planning, design, and procurement to field operations. By recommending the involvement of related parties from the early stages of the project, as well as the use of Building Information Modeling (BIM) technology for better planning, construction will result in an effective and efficient project cycle, as it leverages a strong database and best practices [17]. Therefore, in the design phase, constructability factors should be appropriately considered.

2.3. Maintainability

Maintainability is defined as the ability of a building element or system to maintain or restore its required function easily, safely, accurately, and economically throughout its life cycle. Furthermore, maintainability is closely related to design for maintainability, ensuring safe and economical maintenance throughout the building's lifespan [18].

Building Information Modeling (BIM) can improve data management efficiency and interpretation accuracy by integrating real-time sensor data into the BIM model. Other challenges identified include the complex management of sensor data and the need to develop integrated technologies such as IoT and digital twins to improve the effectiveness of building monitoring and maintenance [12].

Managing maintainability throughout a building's life cycle is crucial for maintaining its economic lifespan and improving sustainability and cost efficiency. Key factors influencing maintainability include applying the Design for Maintainability (DfM) methodology, conducting audits, and integrating operations and maintenance expertise from the planning and design stages [18].

Research [19] shows that early supplier involvement (Early Supplier Involvement/ESI) in the building design stage can significantly improve building maintainability. The design of the construction form, the selection of materials during design, and the preparation of a construction monitoring system will also substantially impact maintenance implementation.

2.4. System Dynamic

Systems Dynamic is an approach that integrates feedback theory and systems analysis with computer simulation to model complex systems. It explores how internal interactions between various factors, both positive and negative feedback, shape the system's overall behavior [20]. Changes in an interconnected system trigger the exchange of components or parameters that alter state variables, which, in turn, recursively influence the system's dynamics. These input-output interactions form complex feedback loops that, together, determine the system's state and behavioral patterns as they evolve. System structure and feedback loops are the primary basis for deciding system behavior, with causal relationships between variables represented as positive or negative causal chains [21].

In analyzing a complex system in an integrated manner, there are reciprocal or feedback relationships between these variables. As explained in the subsection above, design influences constructability and maintainability; conversely, constructability can influence design and maintainability, and maintainability can influence design. These conditions should not be viewed partially or separately. Partial analysis will fail because it ignores the reciprocal or feedback relationships between the two [22]. This is where system dynamics excels in solving these problems. With its holistic approach, system dynamics can analyze the entire system, including its interrelated cause-and-effect relationships, thereby providing a more accurate understanding of the system's behavior [23].

2.5. The Relationship between the Design Process, Constructability, and Maintainability

The relationship among the design process, constructability, and maintainability is closely linked in the management of construction projects [24]. A good design process must consider the constructability aspect to ensure the design can be realized efficiently and effectively in the field.

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Constructability itself includes an assessment of the ease of construction implementation, including selecting appropriate methods and materials. In addition, maintainability is an important factor that must be considered from the design stage, because a design that considers ease of maintenance will reduce maintenance costs and time throughout the building's life cycle [25]. With BIM integration, these three aspects can be managed simultaneously through in-depth simulation and analysis, resulting in a building that is not only easy to build but also easy to maintain and operate throughout its useful life [26]. The causal-loop diagram of design, constructability, and maintainability is shown in Figure 1.

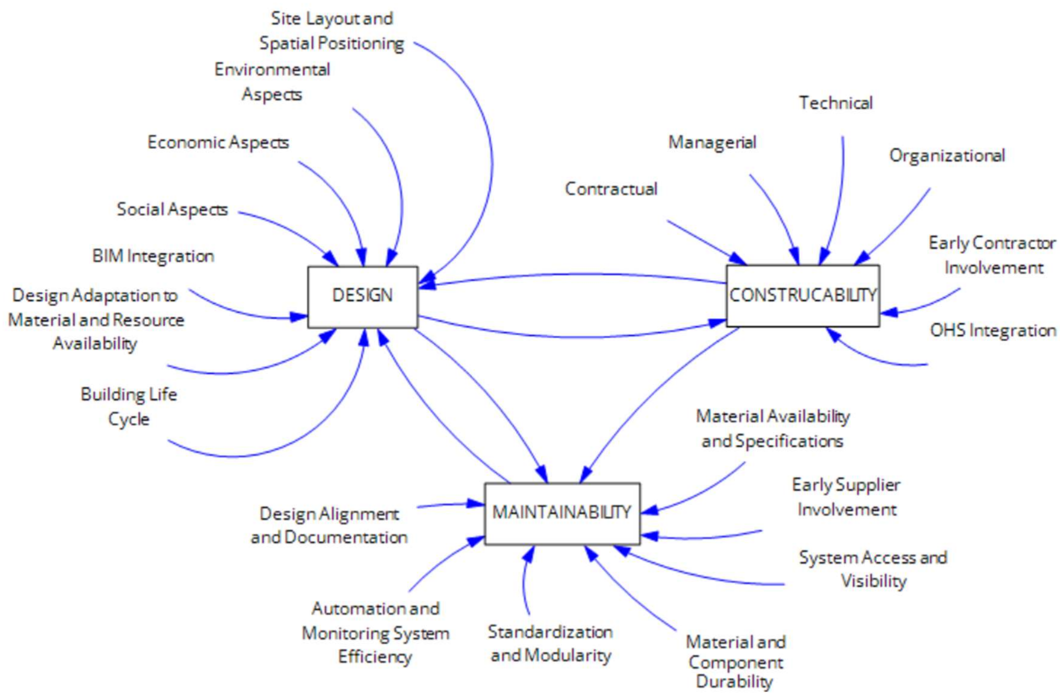

Figure 1. Causa-Loop Diagram Design-Constructability-Maintainability.

Figure 1 presents a Causal Loop Diagram (CLD) illustrating the dynamic, interconnected relationships among the three primary components of a building project: Design, Constructability, and Maintainability. These three variables do not stand alone; each has a reciprocal relationship (a feedback loop) that shapes the behavior of the overall system throughout the building's life cycle.

1. Design as the Starting Point and Primary Driver
   The Design element is depicted at the center of a series of incoming arrows, indicating that design is influenced by numerous sub-variables, including site layout and spatial position, environmental factors, social and economic factors, BIM integration, design adaptation to material and resource availability, and building lifecycle considerations. All of these factors contribute to design quality, which, in turn, forms the basis for planning decisions that affect construction effectiveness and ease of maintenance.
2. Design–Constructability Relationship
   The two-way arrow between Design and Constructability indicates a reinforcing feedback loop. This means that good design will improve ease of implementation in the field (constructability). Conversely, input from constructability aspects—such as early contractor involvement, contract clarity, risk management, implementing organizations, and OHS implementation—will provide valuable feedback to refine the design. This two-way interaction emphasizes that the design process cannot be conducted entirely theoretically or on-site, but rather requires ongoing field evaluation.
3. Design–Maintainability Relationship

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Design also has a direct relationship with maintainability, as indicated by the arrow connecting the two variables. In this context, a design that considers system accessibility, modularity, standardization, material durability, and the need for a monitoring system will result in a building that is easier to maintain and operate. Conversely, experience with maintenance issues can provide valuable feedback to enhance the completeness of design documents, refine material specifications, and optimize construction details for improved maintainability. This relationship reflects the principles of Design for Maintainability (DfM).

4. Constructability–Maintainability Relationship
   There is also bidirectional feedback between constructability and maintainability, indicating that: Proper construction processes, including correct installation, appropriate materials, and accurate documentation, will improve maintainability. On the other hand, maintainability requirements—for example, panel access, system visibility, and inspection requirements—will influence construction methods, material choices, and building details during the assembly phase. Thus, construction and maintenance implementation form a feedback loop that continuously improves each other.
5. Feedback System Structure
   This diagram highlights three types of feedback:
   Reinforcing Loop (R): A two-way relationship between variables that reinforce each other. For example, responsive design enhances construction quality, ultimately leading to improved design.
   Balancing Loop (B): Several relationships maintain the system's balance. For example, poor construction can signal subsequent design corrections.
   Cross-Loop Integration: These three elements interact with each other, making the system nonlinear and incapable of partial analysis.

2.6. Research Methods and Stages

This type of causal research uses relevant or important sources to examine causal relationships between variables. Caustic research aims to investigate the possibility of cause-and-effect relationships. This research aims to analyze the relationships between design factors that influence constructability and maintainability, and to develop a model to predict the magnitude of their influence on improving constructability and maintainability in building projects.

This research was conducted based on stages tailored to the research objectives. The research stages carried out in this study were: (i) problem identification and literature review; (ii) design variable analysis, constructability variable analysis, and maintainability variable analysis; (iii) conducting a pre-survey on limited respondents to verify the variables; (iv) questionnaire design and distribution; (v) conducting normality and reliability tests; (vi) dynamic system analysis; and (vii) interpretation of research results and discussion.

A questionnaire aimed to assess the relationships between variables obtained from the literature review. Respondents in this section were asked to determine the magnitude of the relationship between the variables. This was like the first section. In the second section, respondents were asked to provide their agreement with the variables used in the study using a numeric Likert scale ranging from 1 to 5. Perceptions of strong influence were given a weighting of 5, influential a weighting of 4, moderately influential a weighting of 3, less influential a weighting of 2, and very uninfluential a weighting of 1. The variables in this study are shown in **Table 1**.

Table 1. Level of Influence of Variables on Sub-Variables.

Variable	Sub Variable
Design (Level of Influence on Design)	- Site Layout and Spatial Positioning [27] - Environmental Aspects [10], [27] - Economic Aspects [10] - Social Aspects [10], [9] - BIM Integration [10], [9] - Design Adaptation to Material and Resource Availability [17]

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Variable	Sub Variable
	- Building Life Cycle [9]
Constructability (Level of Influence on Constructability)	- Contractual [15] - Managerial [15] - Technical [15] - Organizational [15] - Early Contractor Involvement [17] - Occupational Health and Safety (OHS) Integration [17]
Maintainability (Level of Influence on Maintainability)	- Material Availability and Specifications [28] - Early Supplier Involvement (ESI) [28] - System Access and Visibility [18], [19] - Material and Component Durability [18], [19], [12] - Standardization and Modularity [18] - Automation and Monitoring System Efficiency [18] - Design Alignment and Documentation [18]

The causal analysis of variables in this study requires a method for analyzing the interrelated components of the system. The technique chosen is System Dynamics. A dynamic system is a collection of entities that interact to achieve a specific goal. The system dynamics method developed by [29] has the main characteristics of solving complex problems and analyzing changes in system behavior due to causal relationships between variables over time and at a stationary point. The stages in this analysis are: (i) compiling CLD; (ii) creating SFD; (iii) filling in the formulation; (iv) simulating the system; and (v) interpreting the results and determining the model scenario.

3. Result and Discussion

3.1. Research Object

This research uses several respondents directly involved in project implementation. Target respondents included project owners, planning consultants, supervisory consultants/MK, contractors, and suppliers. Respondents were selected using a purposive random sampling method, with a total of 42 chosen to match the predetermined target distribution. Respondent profiles will be presented graphically to demonstrate that respondents are project stakeholders with strong skills and experience, thereby ensuring the reliability of their responses. The respondents' profile data includes workplace, educational background, and work experience. The results of the respondent profile analysis are presented in Figures 2, 3, and 4.

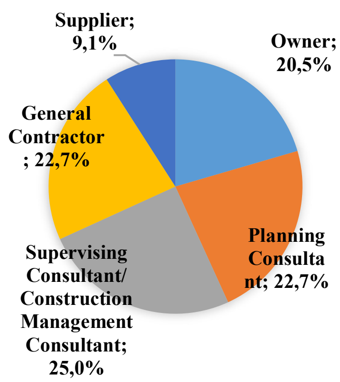

Figure 2. Respondent Data by Occupation

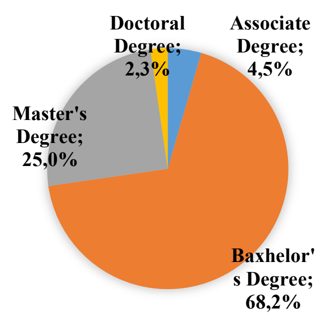

Figure 3. Respondent Educational Background

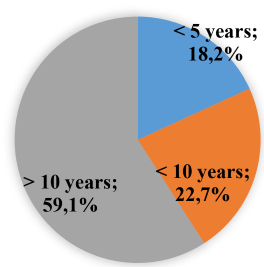

Figure 4. Respondent Experience

A questionnaire was distributed to respondents to obtain their views on the most influential variables at each project stage (design variables, constructability variables, and maintainability

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variables). In addition, respondents were asked for their opinions on the magnitude of design's influence on constructability and maintainability, the influence of constructability on design and maintainability, and the influence of maintainability on design. The influence values were measured using a Likert scale (1-5). Respondents' responses were tested for validity and reliability using the Pearson Product-Moment method (by comparing item scores with the total score) and Cronbach's Alpha method (measuring the internal consistency of all items).

Validity and reliability tests were conducted to ensure that the questionnaire instrument used in this study was appropriate and capable of measuring variables consistently. The instrument used a Likert scale of 1–5 and was analyzed in two stages: (1) validity testing using the Pearson Product-Moment method, and (2) reliability testing using the Cronbach's Alpha method. The number of respondents in this study was 42, resulting in an r-table value of 0.05 at a significance level of 0.05. Validity testing was conducted by comparing the correlation value of each statement item (r-count) with the total variable score. An item was declared valid if the r-count > r-table (0.304) and the significance value <0.05. Based on the calculation results, all Design Variables (7 statement items), Constructability Variables (6 statement items), and Maintainability Variables (7 statement items) met the validity test criteria, with r-count >0.304 and a significance value <0.05. Therefore, all instrument items for all three variables were declared valid. Reliability testing was conducted to determine the instrument's internal consistency using Cronbach's Alpha; a variable is considered reliable if the Alpha value is greater than 0.70. The test results showed that the Design, Constructability, and Maintainability variables achieved Cronbach's Alpha values greater than 0.70, indicating that the internal consistency level was in the reliable category.

This study compiled data on the influence values of all design, constructability, and maintainability variables, which it used in the analysis of the Optimizing Building Design for Constructability and Maintainability model. The resulting influence values are arranged into a normalization matrix for each variable to obtain the weights (see Tables 2, 3, and 4). Meanwhile, the influence values between variables are also calculated in the same manner (see Table 5).

Table 2. Level of Influence on Design

Sub. Variable	Weighting
Site Layout and Spatial Positioning (D1)	0,148
Environmental Aspects (D2)	0,146
Economic Aspects (D3)	0,150
Social Aspects (D4)	0,135
BIM Integration (D5)	0,135
Design Adaptation to Material and Resource Availability (D6)	0,143
Building Life Cycle (D7)	0,143

Table 3. Level of Influence on Constructability

Sub. Variable	Weighting
Contractual (C1)	0,148
Managerial (C2)	0,146
Technical (C3)	0,150
Organizational (C4)	0,135
Early Contractor Involvement (C5)	0,143
Occupational Safety and Health (OHS) Integration (C6)	0,143

Table 4. Level of Influence on Maintainability

Sub. Variable	Weighting
Material Availability and Specifications (M1)	0,148
Early Supplier Involvement (M2)	0,146
System Access and Visibility (M3)	0,150
Material and Component Durability (M4)	0,135
Standardization and Modularity (M5)	0,135

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Sub. Variable	Weighting
Automation and Monitoring System Efficiency (M6)	0,143
Design Alignment and Documentation (M7)	0,143

Table 5. Level of Influence on Variable

Variabel	Weighting
Design- Constructability (DC)	0,200
Design- Maintainability (DM)	0,203
Constructability - Design (CD)	0,196
Constructability - Maintainability (CM)	0,203
Maintainability - Desain (MD)	0,198

3.2. Dynamic Model Development

The dynamic modeling in this study uses System Dynamics, developing the Causa-Loop Diagram in Figure 1 into a Stock Flow Diagram (SFD). The resulting Stock Flow Diagram is shown in Figure 5. The SFD consists of three stocks: Design, Constructability, and Maintainability. Each stock has 6-7 parameters (see Figure 5). The input stock formula uses the weighted influence of the parameters on the variables (see Tables 2 to 4). In contrast, the formula for the input stock uses the variable's weighted influence values (see Table 5). The dynamic program is then run using the Vensim application, one of the System Dynamics tools. If Vensim runs successfully without error notifications, the program will run properly.

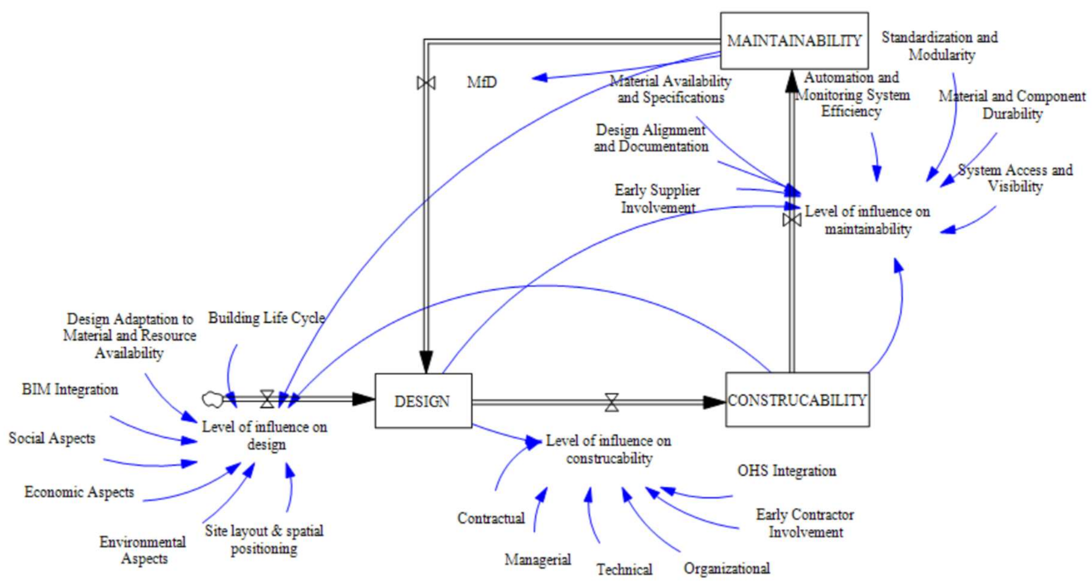

Figure 5. Stock Flow Diagram of Modeling Simulation

Figure 5 presents a Stock Flow Diagram (SFD) depicting the dynamic relationships among the three main components of the system model: Design, Constructability, and Maintainability. After all parameters were entered into the model and simulations were run in Vensim, quantitative results were obtained and summarized in Table 6. This table serves as a basis for understanding how each variable influences the others systematically.

1. Understanding the Model Structure

   In the SFD structure, each primary variable consists of several input parameters derived from the weighting of the questionnaire results. The influence weights represent the relationships between variables. When all parameters are assigned the maximum index (=1.0), the model is expected to demonstrate an ideal condition in which all components perform at their best.

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2. Main Simulation Results (Table 6)

   The simulation results show that when all parameters are set to their maximum values, the five influence indices between the variables reach 1.000. This is as follows:
   Design → Constructability (DC) = 1.000
   This indicates that the optimal design has a full impact on improving constructability.
   Design → Maintainability (DM) = 1.000
   Indicates that the application of Design for Maintainability (DfM) principles under ideal conditions can fully improve the maintainability performance of a building.
   Constructability → Design (CD) = 1.000
   This means that contractor input and the technical aspects of implementation are key components that can significantly improve design quality.
   Constructability → Maintainability (CM) = 1.000
   This illustrates that properly executed construction (compatible materials, correct installation, efficient procedures) fully impacts ease of maintenance.
   Maintainability → Design (MD) = 1.000
   This indicates that maintenance inputs (such as system access, component durability, and inspection requirements) are crucial and significantly influence future design improvements.
   An overall index value of 1.000 under maximum conditions indicates that the SD model performs consistently and realistically. If all variables are refined, the system will produce ideal interactions across all components.
3. Systemic Significance of Simulation Results
   - Model Reflects Strong Interdependence

     The same index value (1.000) indicates that the three main variables are in a robust feedback system. Positive changes in one variable will automatically strengthen the others, demonstrating the characteristics of a reinforcing system.
   - Validity of Model Structure

     Because the model exhibits consistent and linear behavior under ideal conditions, this indicates that: (i) The structure of relationships between variables has been logically constructed; (ii) The weight parameters between variables can represent the actual relationships in the building construction system; and (iii) The model is now ready for use in the next stage, including scenario and sensitivity analysis.
   - Model Predictive Capability

     The simulation results demonstrate that the model accurately describes the system's behavior at full scale. In other words: (i) The model can be used to test various real-world scenarios; (ii) The model can simulate the long-term impacts of design, construction, and maintenance decisions; and (iii) The model can serve as a decision-support tool for project stakeholders.
4. Relationship between the Figure and Table 6

   In the SFD diagram, the arrows connecting the variables indicate the flow of influence. Table 6 provides the numerical representation of each flow. Thus, the relationships in the diagram are visual, while the numerical output in the table provides quantitative evidence that the flow is operating as expected.

3.3. Dynamic Model Simulation

Dynamic program simulation is performed by inputting parameter values for each variable. This simulation ensures that the variable behavior closely resembles real-world conditions. The simulation results show that when all parameters are input with the maximum index value (=1.0), the dynamic program produces a condition index of all design variables that is also maximum (=1), this means that the dynamic model is close to real conditions where when all parameters are given a good index, it turns out the model can provide a good index value too. The simulation results are shown in Table 6.

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Table 6. Results of Modeling Simulation of Inter-Variable Influences

Variable	Index
Design- Constructability (DC)	1,000
Design- Maintainability (DM)	1,000
Constructability - Design (CD)	1,000
Constructability - Maintainability (CM)	1,000
Maintainability - Desain (MD)	1,000

3.4. Model Scenarios

Simulations were conducted across three scenarios to test the model's sensitivity and to understand the dynamics of the influences among variables in the system. These scenarios represented different strategic priority conditions during the design and construction phases. Table 7 presents the initial conditions (inputs) for each variable across the three scenarios. Table 8 presents the simulation results as aggregate performance indices for each key variable.

Table 7. Simulation Results of Modeling the Influences Between Variables

Sub. Variable	Scenario		
	1	2	3
Design			
Site Layout and Spatial Positioning (D1)	1	1	1
Environmental Aspects (D2)	1	1	1
Economic Aspects (D3)	1	1	1
Social Aspects (D4)	1	1	1
BIM Integration (D5)	1	1	1
Design Adaptation to Material and Resource Availability (D6)	1	1	1
Building Life Cycle (D7)	1	1	1
Constructability			
Contractual (C1)	0	1	0
Managerial (C2)	0	1	0
Technical (C3)	0	1	0
Organizational (C4)	0	1	0
Early Contractor Involvement (C5)	0	1	0
Occupational Safety and Health (OHS) Integration (C6)	0	1	0
Maintainability			
Material Availability and Specifications (M1)	1	0	0
Early Supplier Involvement (M2)	1	0	0
System Access and Visibility (M3)	1	0	0
Material and Component Durability (M4)	1	0	0
Standardization and Modularity (M5)	1	0	0
Automation and Monitoring System Efficiency (M6)	1	0	0
Design Alignment and Documentation (M7)	1	0	0

Table 8. Simulation Results of Modeling the Influence Between Variables

Variable	Index Based Scenario		
	1	2	3
Design	1	1	1
Maintainability	1	0,7	0.7
Constructability	0.5	1	0.8

a. Scenario 1: Maintainability Optimization Strategy

This scenario simulates a situation in which the project's primary focus is optimizing Maintainability. All maintainability variables (M1 to M7) are set to their maximum value (=1), indicating a full commitment to material availability, accessibility, durability, and standardization

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for ease of maintenance. As a trade-off, all constructability variables (C1 to C6) are turned off (value = 0), indicating a lack of attention to construction's contractual, managerial, and technical aspects from the outset. The simulation results show that although the Design and Maintainability indices reach a perfect score (=1), the constructability index drops to 0.5 (see Table 8). This reveals a paradox: despite the design being highly maintainable and ignoring constructability, the constructability index drops to 0.5, indicating that the design still contributes to constructability, albeit with limited support. However, a design that neglects constructability can create challenges during construction, ultimately jeopardizing Maintainability in the long term.

b. Scenario 2: Constructability Optimization Strategy

This scenario tests the opposite scenario, focusing on optimizing constructability aspects. All constructability variables are enabled (value = 1), reflecting the implementation of best practices such as early contractor involvement, OHS integration, and strong management. Meanwhile, all maintainability variables are turned off (value = 0). The simulation results yield a perfect constructability index (1), but the maintainability index drops to 0.7. Interestingly, the design index remains at 1. This finding suggests that focusing on constructability does not necessarily compromise design quality but does significantly compromise long-term Maintainability. A 30% decrease in the maintainability index highlights the risk asset owners face in the future, where buildings may be quicker and easier to construct but more difficult and expensive to maintain.

c. Scenario 3: Hybrid Strategy (Status Quo)

The third scenario simulates a hybrid or compromise approach, which may represent standard industry practice. Constructability and maintainability variables are turned off (value = 0). The scenario results show that the Constructability Index (0.8) is higher than the Maintainability Index (0.7). This result indicates that the design generally emphasizes Constructability more than Maintainability. This result confirms that a partial design approach is insufficient for optimal results. Although some construction aspects are well managed, neglecting Maintainability still leaves the building vulnerable throughout its life cycle. The Constructability value that does not reach the maximum also indicates that complete optimization of construction aspects requires simultaneously activating all key factors.

3.5. Design Parameter Sensitivity

A parameter sensitivity analysis was conducted to identify the design subsystem variables that significantly influence the model output. This analysis aimed to determine which parameters offer the most effective leverage points for designers and project managers to intervene and optimize the overall system for constructability and maintainability. The simulation results of the parameter sensitivity analysis on the design variables are shown in Table 9.

Table 9. Simulation Results of Modeling Influence on Design

Sub. Variable	Index
Site Layout and Spatial Positioning (D1)	0,717
Environmental Aspects (D2)	0,719
Economic Aspects (D3)	0,719
Social Aspects (D4)	0,720
BIM Integration (D5)	0,715
Design Adaptation to Material and Resource Availability (D6)	0,715
Building Life Cycle (D7)	0,717

Based on the simulation results in Table 9, the influence index values for the seven parameters on the Design variable show a very narrow range, between 0.715 and 0.720. This indicates that all modeled variables make significant, roughly equal contributions, with none more dominant than the others.

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a. Interpretation of Sensitivity Results

Uniform Sensitivity Level: The very tight range of values (only 0.005 points between the highest and lowest values) indicates that this dynamic system model is not very sensitive to changes in any single parameter when viewed in isolation. In this context, all design aspects function as an integrated package. Improvements in one aspect without accompanying changes in others will have only a minimal impact on the overall outcome.

b. Variables with the Highest and Lowest Influence

The Social Aspect (D4) recorded the highest index value (0.720), implying that factors such as community acceptance, social impact, and end-user comfort have the greatest, albeit very slight, influence. These findings align with sustainable construction trends that emphasize the human and social aspects of a building.

BIM Integration (D5) and Design Adaptation to Material and Resource Availability (D6) recorded the lowest index values (0.715). This does not mean these two variables are unimportant. Instead, it can be interpreted to mean that the optimal benefits of BIM and material adaptation can be achieved only when supported by the other six design variables. They are powerful enablers, but their effectiveness depends on a solid design foundation.

c. Implications for Project Management and Design

This analysis conveys a key strategic message: A piecemeal design optimization approach will be ineffective. Stakeholders must adopt a holistic and balanced approach rather than focusing exclusively on one or two design aspects (e.g., pursuing only economic efficiency or BIM integration). Resources and efforts must be allocated to ensure that all design aspects—layout, environmental, economic, social, technology integration, and lifecycle considerations—are simultaneously improved. Strengthening one "weak" area (with a relatively lower index) may yield better results than continuously maximizing an already "strong" area.

4. Conclusion

This research successfully demonstrated that the System Dynamics (SD) approach is a highly effective tool for modelling and analysing the complex, dynamic interrelationships among Design, Constructability, and Maintainability factors in building projects. The strong and dynamic interconnections among these three primary variables (Design, Constructability, and Maintainability) form a complex feedback system. Improvements in one variable directly affect the others, creating a chain effect that can strengthen or weaken the entire system.

Key Leverage Points from the simulation results reveal that the Design-to-Maintainability (DM) relationship has a significant influence. This indicates that investment in the Design for Maintainability (DfM) phase significantly impacts long-term building performance. Construction-to-Design feedback confirms that early input from contractors and suppliers (such as through Early Contractor Involvement (ECI) can fundamentally improve the quality and feasibility of a design.

Sensitivity analysis shows that all design variables have an equal influence. A single superstar factor does not determine success; rather, it is the simultaneous balance and integration of all factors. Scenario simulation results demonstrate that strategies that sacrifice one aspect to enhance another (e.g., focusing solely on maintainability or constructability) yield suboptimal outcomes. However, upon closer examination, the dominant influence of social and environmental factors on the design subsystems, with social aspects (D4) and environmental aspects (D2) having the greatest impact. This shifts the paradigm from a design focused solely on technical and economic aspects to one that is sustainable and responsive to the community's social context.

The findings of this study are highly likely to be implemented in the Indonesian construction industry because: (i) they are based on local practice and context. The research data is obtained from Indonesian professionals directly involved in the project, making the resulting model and findings

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highly relevant to the challenges and opportunities in the field; (ii) the SD model provides a quantitative basis for encouraging practices that have been considered "good" but whose ROI is challenging to measure, such as Early Contractor Involvement (ECI) and Design for Maintainability (DfM). This facilitates decision-makers (owners and project managers) in allocating resources; (iii) The model can be calibrated for different project types (e.g., infrastructure, housing, commercial buildings) by changing the weights of specific parameters, making its application highly flexible; and (iv) Simulations of three scenarios (Maintainability Optimization, Constructability Optimization, and Hybrid) provide concrete and easily understood evidence of the consequences of various design strategies, thereby convincing stakeholders to adopt a more balanced approach.

The results of this study provide several strategic recommendations for various stakeholders, namely: (i) For Project Owners (Owners/Developers) and the Government: Require Early Involvement in contract documents to ensure feedback on construction and maintainability is included from the conceptual design phase; Adopt System Dynamic Models as Decision-Aid Tools because they have simulation capabilities to evaluate various design scenarios and project policies before final decisions are made; Provide incentives for Sustainable and Integrated Design that prioritizes the balance of social, environmental, constructability, and maintainability aspects, as demonstrated by the research results; (ii) For Planning Consultants and Designers: Shift Mindset to Holistic Design that considers constructability and maintainability as an integral part of the creative process, not as an afterthought; Use BIM platforms not only for 3D visualization and clash detection, but also to simulate the construction process (4D), life cycle cost analysis (5D), and maintenance planning (6D/7D) that align with research findings; Prioritize DfM (Design for Maintainability) Proactively incorporate principles such as standardization, modularity, accessibility for maintenance, and durable material selection in every design, considering the high leverage of design on maintainability; and (iii) For Contractors and Suppliers: Be Proactive; Invest in Knowledge.

Despite the robustness of the findings, this study has several limitations that should be acknowledged. The System Dynamics model is developed based on perceptions and expert judgment from Indonesian construction professionals, which may limit its generalizability to other regions or project delivery contexts. Additionally, the simulation outcomes are theoretical and have not yet been validated directly through real-world project data or longitudinal performance measurements. Model scalability also remains a challenge, as expanding the framework to incorporate additional variables—such as risk, resilience, or digital-twin integration—may require further structural refinement.

Future research should therefore focus on conducting real-world validation through case studies or pilot projects, testing the model's predictive accuracy in active construction environments, and exploring its adaptability to various building types and infrastructure sectors. Enhancing the model with machine learning components, digital-twin data streams, or multi-criteria decision-making tools would further strengthen its applicability and scalability for broader industry use.

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