

## Modeling of Factors Influencing the Adoption of Digital Twins Infrastructure to Support Construction Project Automation in Indonesia

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Keywords	Abstract
Infrastructure Digital Twins; Construction Automation; Technology Adoption; Construction 4.0; Indonesia.	<p>The construction industry continues to face persistent challenges related to project delays, cost overruns, low productivity, safety risks, and limited integration of digital technologies, particularly in developing countries such as Indonesia. In response to these issues, Infrastructure Digital Twins (IDTs) have emerged as an advanced digital approach capable of integrating real-time data, simulation, prediction, and optimization to support construction project automation. This study aims to develop and test an empirical model of the factors influencing IDT adoption in Indonesian construction projects by integrating technical, organizational, and external environmental perspectives. The research applies a confirmatory quantitative approach using Partial Least Squares Structural Equation Modeling (PLS-SEM), supported by Focus Group Discussions to validate findings and formulate strategic recommendations. The study examines constructs including digital infrastructure readiness, system interoperability, data security and quality, top management support, human resource competence, organizational readiness, regulatory support, competitive pressure, external ecosystem support, adoption intention, and adoption rate. The findings indicate that IDT adoption is shaped not only by technological readiness but also by managerial commitment, organizational capacity, regulatory alignment, and industry ecosystem support. The study concludes that successful IDT implementation requires an integrated strategy involving construction organizations, project stakeholders, and policymakers to accelerate digital transformation, strengthen data-driven decision-making, and enhance sustainable construction project automation in Indonesia.</p>

### INTRODUCTION

The construction industry is globally recognized as one of the sectors with the highest level of complexity and relatively stagnant performance compared to other industries. Various studies show that project delays, cost overruns, low productivity, and high occupational safety risks remain chronic problems that are difficult to address systemically (Asiedu & Ameyaw, 2021; Gurumayum, 2025; Oswald et al., 2020). These challenges are further compounded by the demands of sustainable development, energy efficiency, and carbon emission reduction, which require the construction sector to undergo fundamental transformation — not only at the operational level but also in terms of decision-making and project governance (van der Heijden, 2023; Jaiswal et al., 2024).

In response to these challenges, the Construction 4.0 paradigm has emerged, emphasizing the use of digital technologies such as Building Information Modeling (BIM), the Internet of Things (IoT), Artificial Intelligence (AI), and data-based sensor and automation systems. The

integration of these technologies enables real-time monitoring of project conditions, predictive analysis of project performance, and greater transparency and accountability in construction management (Adejumobi, 2024; Diameh et al., 2025; Zhu et al., 2022). However, although digital technology adoption has shown significant progress in developed countries, its implementation in developing countries tends to remain partial, fragmented, and insufficiently integrated within project management systems (Nguyen Van Tam et al., 2024; Opoku et al., 2023).

Within the broader context of digital technology development, Infrastructure Digital Twins (IDTs) have emerged as a more advanced and holistic approach than earlier digital technologies. IDTs serve not only as static representations of physical assets but as dynamic digital systems that integrate real-time data, information models, and analytics capabilities to support the monitoring, simulation, prediction, and optimization of infrastructure performance throughout the project lifecycle (Beitelmal & Alruwaythi, 2025; Hakimi et al., 2023; Poorzare et al., 2025). Various studies indicate that the implementation of Digital Twins has the potential to increase productivity, reduce safety risks, improve cost and time control, and support decision-making automation in large-scale and complex construction projects (Omran et al., 2023; Saif et al., 2024).

Despite this potential being increasingly recognized globally, IDT adoption in developing countries, including Indonesia, remains very limited. The obstacles encountered are not only technical in nature but also include high initial investment costs, limited digital competencies among human resources, weak regulatory frameworks and implementation standards, and concerns related to project data governance and security (Daniel et al., 2024; Zio & Miqueles, 2024). Moreover, most previous studies have focused on the technical development of Digital Twins, system architectures, or case studies in developed countries with relatively mature digital ecosystems. Empirical studies that systematically analyze the determinants of IDT adoption at the organizational and construction project level in developing countries remain relatively scarce (Yan et al., 2023).

Furthermore, the literature has generally not comprehensively integrated the perspectives of technological readiness, organizational readiness, and external environmental pressures within a single analytical framework, nor has it explicitly linked IDT adoption to the strategic objective of increasing the level of construction project automation. In practice, the successful implementation of IDTs is not only determined by the availability of technology but also by organizational readiness, regulatory support, perceptions of benefit, and the industry's capacity to manage the transition toward a more digital and automated construction system.

Based on the above, a clear research gap exists: the absence of an empirical model capable of comprehensively explaining the factors that influence IDT adoption in the context of construction projects in developing countries, particularly Indonesia, and their relationship with construction project automation. Therefore, this study aims to develop and test an empirical model of IDT adoption by integrating technical, organizational, and external environmental factors, and to analyze their influence on adoption intention and the utilization rate of IDTs in supporting construction project automation. This research is expected to make an academic contribution by enriching the literature on digital technology adoption in construction management, as well as a

practical contribution for government and industry stakeholders in formulating strategies to accelerate the digital transformation of the national construction sector.

Based on the research background outlined above, this study focuses on understanding the factors that influence the adoption of Infrastructure Digital Twins (IDTs) in construction projects in Indonesia. The primary issues examined concern how technical, organizational, and external environmental factors either facilitate or hinder the utilization of IDTs in the construction sector. In addition, this study is directed toward formulating an empirical model based on Structural Equation Modeling–Partial Least Squares (SEM-PLS) that is capable of representing the interrelationships among the factors influencing IDT adoption, including their effects on adoption intention and the rate of utilization of the technology in construction projects. In line with these issues, the objectives of this research are to identify and analyze the factors determining IDT adoption, to construct and test an empirical model representing the causal relationships among variables, and to formulate strategic recommendations for industry stakeholders and government. These recommendations are intended to encourage the optimization of IDT use in accelerating digital transformation, improving project efficiency, and supporting sustainable infrastructure development in Indonesia.

## **METHOD**

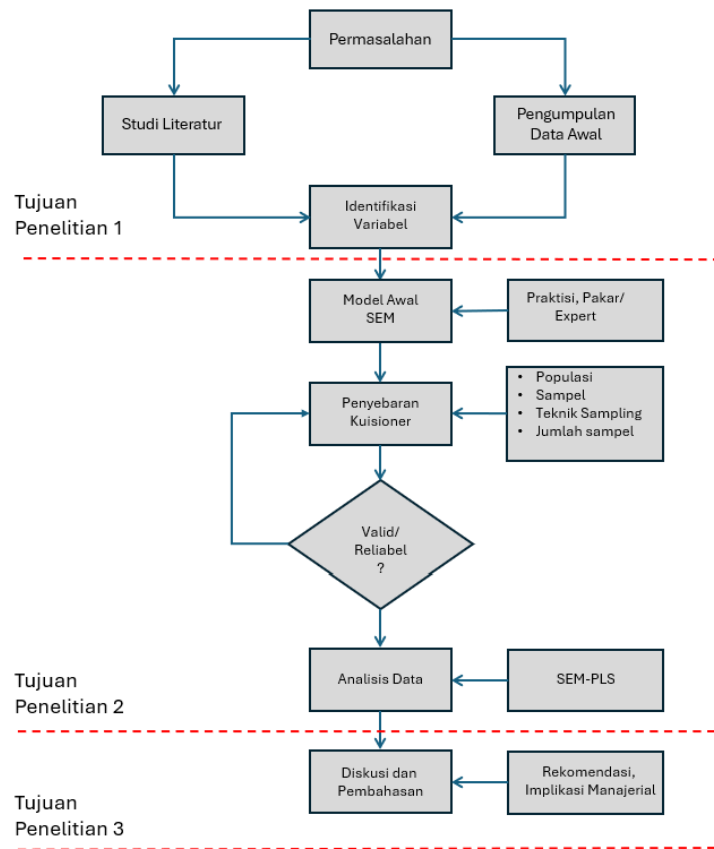
### **Types and Approaches to Research**

This study is a confirmatory quantitative research that aims to empirically test the theoretical model of the factors influencing the adoption of Infrastructure Digital Twins (IDTs) in construction projects in Indonesia. The quantitative approach was chosen because it allows the testing of causal relationships between latent constructs based on measurable data in the context of technology adoption at the organizational and project levels. Methodologically, this study uses Structural Equation Modeling based on Partial Least Squares (SEM-PLS) with a Confirmatory Factor Analysis (CFA) approach to validate the representativeness of indicators to the latent constructs measured. SEM-PLS was chosen because it is suitable for testing models that are complex, involve abstract constructs, and do not require the assumption of multivariate normality and large sample sizes. This approach is relevant for analyzing the adoption of digital technologies influenced by technical, organizational, and environmental factors, as well as the mechanisms of intention and actual use. In addition to the quantitative approach, this study is equipped with qualitative elements in the final stage through expert discussions or Focus Group Discussions (FGD) to validate and translate statistical findings into strategic recommendations that are applicable to stakeholders.

### **Research Stages**

This research is carried out through structured and systematic stages to ensure the achievement of the research objectives and the validity of the results obtained. The research stage begins with the formulation of a conceptual framework and the development of a research model based on theoretical synthesis and empirical studies related to the adoption of Infrastructure Digital Twins (IDTs). Furthermore, research instruments and data collection were carried out through surveys to the main stakeholders of the construction project. The collected data was then analyzed

using Structural Equation Modeling based on Partial Least Squares (SEM-PLS) to test the validity, reliability, and causal relationships between constructs in the research model. In the final stage, the results of the quantitative analysis are deepened through expert discussions to validate empirical findings and formulate applicable strategic recommendations. Figure 3.1 below is a visualization of the stages of this research.



**Figure 1.** Research Stages

### Literature Study

The literature study in this study aims to build a strong theoretical and methodological foundation to examine the adoption of Infrastructure Digital Twins (IDTs) in construction projects. The study focused on five main groups of literature. First, the literature on construction project management and Construction 4.0 is reviewed to understand the role of digital transformation and automation in overcoming project performance problems. Second, the literature related to Digital Twins and Infrastructure Digital Twins is studied to understand their characteristics, architecture, and role in supporting data-driven monitoring and decision-making. Third, technology adoption theories including Technology–Organization–Environment (TOE), Innovation Diffusion Theory (IDT), as well as Technology Acceptance Model (TAM) and Unified Theory of Acceptance and Use of Technology (UTAUT) are used as a conceptual basis in modeling the determinants of adoption and mechanisms of intention and use of technology. Fourth, previous empirical research

on the adoption of digital technology in the construction sector, especially in the context of developing countries, was reviewed to identify patterns of research findings and gaps. Fifth, the literature on the Structural Equation Modeling methodology based on Partial Least Squares (SEM-PLS) was studied as the basis for the development and testing of the research model. Through this literature study, the research obtained a relevant and integrated conceptual framework to support the analysis of the adoption of IDTs in construction project automation in Indonesia.

### **Initial data collection (Pre-Survey)**

The pre-survey was conducted as the initial stage of the research to obtain an overview of the level of understanding, readiness, and experience of stakeholders towards the implementation of Infrastructure Digital Twins (IDTs) in construction projects. The initial data collected included the characteristics of respondents and organizations, the level of use of digital technologies (such as BIM, IoT, and data-based monitoring systems), initial perceptions of the benefits and challenges of IDTs, and the state of technological readiness, organization, and external environment. Pre-survey data sources were obtained through exploratory questionnaires and brief interviews with key stakeholders of the construction project, namely contractors, planning consultants/supervisors, and project owners, who have a role in decision-making and implementation of digital technology. The results of the pre-survey were used to validate the relevance of the research construct, refine the main questionnaire indicators, and ensure the suitability of the research model with the empirical conditions of the construction industry in Indonesia.

### **Variable Identification / Construct of Proposed Model**

(Fix 1) The variables and indicators in this study are grouped based on the synthesis of three main theoretical frameworks, namely Technology-Organization-Environment (TOE), Technology Acceptance Model (TAM)/UTAUT, and Innovation Diffusion Theory (IDT). The grouping process is carried out by mapping the operational characteristics of construction projects into the following theoretical dimensions:

1. **Technical Factors:** Grouped based on the Technology dimension in the TOE and the characteristics of innovation in the IDT. The P1-P3 (Infrastructure, Interoperability, and Data Security) indicators were chosen because they reflect the technical readiness and relative advantages of IDTs technology over conventional systems.
2. **Organizational Factor:** Refers to the Organization dimension in the TOE. The P4-P6 indicators (Management Support, Human Resource Competence, and Culture) reflect the organization's internal capacity and managerial readiness in managing digital change.
3. **External Factors:** Based on the Environment dimension of the TOE and institutional perspective. The P10-P12 indicators (Regulation, Competitive Pressure, and Ecosystem) capture the influence of the industrial environment and government policies on adoption decisions.
4. **Intent and Adoption Rate:** Grouped based on behavioral mechanisms in TAM/UTAUT. The P7-P9 indicator focuses on the perception of benefits and intent (intention), while the P13-P15 measures the actual implementation and sustainability of use as the end result of the adoption process.

Details of the variables, indicators, and their operational descriptions are presented in the following Table 2:

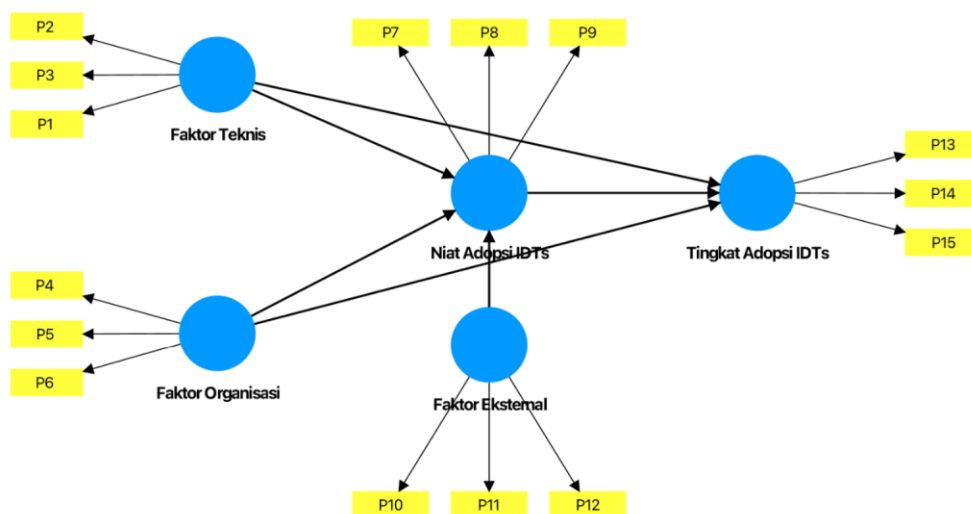
**Table 2.** Research Variables and Indicators

<b>Factor (Construct)</b>	<b>Indicator</b>	<b>Code</b>	<b>Variable Type</b>	<b>Operational Description</b>
<b>Technical Factors</b>	Digital Infrastructure Readiness	<b>P1</b>	Eksogen	Availability and adequacy of technology infrastructure (hardware, software, network) to support the implementation of Infrastructure Digital Twins (IDTs).
	System Interoperability	<b>P2</b>	Eksogen	Ability to effectively integrate and exchange data between project digital systems (BIM, IoT, sensors, data platforms).
	Data Security and Quality	<b>P3</b>	Eksogen	The level of reliability, security, and quality of digital data used in the operation of IDTs.
<b>Organizational Factors</b>	Top Management Support	<b>P4</b>	Eksogen	The level of commitment and support of the organization's leadership to the adoption and investment of IDTs technology.
	HR Competencies	<b>P5</b>	Eksogen	The level of ability, skills, and knowledge of human resources in operating digital technology and IDTs.
	Organizational Culture and Readiness	<b>P6</b>	Eksogen	The level of readiness of the organization in accepting digital changes and innovations in the construction project process.
<b>External Factors</b>	Regulatory Support	<b>P10</b>	Eksogen	The existence and effectiveness of government policies and regulations that encourage the adoption of digital technology in construction.
	Competitive Pressure	<b>P11</b>	Eksogen	The influence of market pressures, industry competition, and project owners' demands on the use of IDTs technology.
	Ecosystem and External Incentives	<b>P12</b>	Eksogen	The availability of incentives, industry-academia partnerships, and digital ecosystem support in the implementation of IDTs.
<b>IDTs Adoption Intention</b>	Perception of Benefits	<b>P7</b>	Endogenous (Mediator)	Organizational perception of the strategic benefits of IDTs in improving

Factor (Construct)	Indicator	Code	Variable Type	Operational Description
				project efficiency, quality, and performance.
	Intent of Use	P8	Endogenous (Mediator)	The level of intent and willingness of the organization to adopt and use IDTs in construction projects.
	Readiness of Adoption Decision	P9	Endogenous (Mediator)	The level of confidence and readiness of the organization in making decisions on the implementation of IDTs.
IDTs Adoption Rate	Actual Implementation	P13	Endogenous	The level of real implementation of IDTs in project planning, implementation, and control activities.
	Utilization Intensity	P14	Endogenous	The breadth and depth of use of IDTs in supporting automation and data-driven decision-making.
	Sustainability of Use	P15	Endogenous	Consistency and sustainability of the use of IDTs as part of the project management system.

### Model (Initial) SEM-PLS

Based on the literature review and the identification of variables that have been conducted, this study developed a conceptual framework that describes the hypothetical relationship between factors influencing the adoption of Infrastructure Digital Twins (IDTs). This framework was developed by integrating Technology-Organization-Environment (TOE) theory and empirical findings from recent research.



**Figure 2.** Conceptual Framework of Influencing Factors Adoption of IDTs

## Design and Dissemination of Questionnaires

### Questionnaire Design

The questionnaire design in this study was compiled to empirically measure the factors influencing the adoption of Infrastructure Digital Twins (IDTs) in construction projects in Indonesia. The questionnaire instrument was developed based on the synthesis of Technology Organization Environment (TOE) theory, Technology Acceptance Model (TAM), Unified Theory of Acceptance and Use of Technology (UTAUT), and Innovation Diffusion Theory (IDT), which have been widely used in the study of digital technology adoption. Each construct is represented by a number of reflective indicators formulated in the form of a closed statement using a five-point Likert scale, ranging from strongly disagree to strongly agree. This questionnaire is aimed at key stakeholders of construction projects including contractors, consultants, and project owners who have experience and authority in decision-making related to the application of digital technology. The design of this instrument is expected to be able to capture the perception, readiness, and utilization rate of IDTs comprehensively and reliably. The following table 3.2 is the Factors, Indicators and derivatives of the Questionnaire questions.

**Table 3.** Questionnaire Question Derivation

<b>Factors</b>	<b>/ Indicator</b>	<b>Questionnaire Questions</b>
<b>Constructs</b>		
Measurement scale: Likert 1–5 (1 = strongly disagree ... 5 = Strongly Agree)		
<b>Technical Factors</b>	Digital Infrastructure Readiness	<b>Q1:</b> Our organization/project has sufficient technology infrastructure (hardware, software, and network) to implement Infrastructure Digital Twins (IDTs).
	System Interoperability	<b>P2:</b> The digital systems used (e.g. BIM, IoT, and sensors) can be well integrated and data shared with each other to support IDTs.
	Data Security and Quality	<b>P3:</b> The digital data used in our projects is secure, reliable, and of high quality to support the implementation of IDTs.
<b>Organizational Factors</b>	Top Management Support	<b>P4:</b> Top management actively supports and encourages the adoption of Infrastructure Digital Twins (IDTs) in construction projects.
	HR Competencies	<b>Q5:</b> Human resources in our organization have sufficient capabilities and skills to use IDTs technology.
	Organizational Culture and Readiness	<b>Q6:</b> Our organization is open and ready to accept changes in work processes due to the application of digital technologies such as IDTs.
<b>IDTs Adoption Intention</b>	Perception of Benefits	<b>P7:</b> The implementation of Infrastructure Digital Twins (IDTs) is believed to improve the efficiency and performance of construction projects.

<b>Factors / Constructs</b>	<b>Indicator</b>	<b>Questionnaire Questions</b>
	Intent of Use	<b>Q8:</b> Our organization intends to adopt and use Infrastructure Digital Twins (IDTs) in construction projects.
	Readiness of Adoption Decision	<b>P9:</b> Our organization is ready to make the decision to implement Infrastructure Digital Twins (IDTs) in the near future.
<b>External Factors</b>	Regulatory Support	<b>P10:</b> Current government regulations and policies support the application of digital technologies such as Infrastructure Digital Twins (IDTs) in the construction sector.
	Competitive Pressure	<b>Q11:</b> Industry competition and project owner demands encourage our organization to adopt IDTs technology.
	Ecosystem and External Incentives	<b>P12:</b> The availability of external incentives, collaboration, and digital ecosystems supports the implementation of IDTs in our organization.
<b>IDTs Adoption Rate</b>	Actual Implementation	<b>P13:</b> Infrastructure Digital Twins (IDTs) have been implemented in real terms in the process of planning, implementing, or controlling projects.
	Utilization Intensity	<b>P14:</b> Infrastructure Digital Twins (IDTs) are used intensively to support decision-making and project automation.
	Sustainability of Use	<b>Q15:</b> The use of Infrastructure Digital Twins (IDTs) has become an ongoing part of the project management system in our organization.

### **Population, Sample, and Sampling Techniques**

The population in this study is the main stakeholders of the construction sector in Indonesia, which includes contractors, consultants, project owners, and government agencies involved in the planning, implementation, or decision-making of construction projects. The sampling technique used is purposive sampling, with the respondent criteria as follows:

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General Criteria of Respondents (Mandatory):

1. Directly involved in infrastructure construction projects (buildings, roads, bridges, dams, TOD, integrated areas, etc.)
2. Have 2 years of work experience or more in the field of construction/infrastructure
3. Work in Indonesia
4. Understand or have come into contact with at least one of the following:
  - a. BIM
  - b. Digital Construction
  - c. Smart Infrastructure
  - d. Project Automation / Construction Technology

5. Engineer (Civil, Structural, Transportation, Geotechnical)

Levels of Support for Policies, Organizations/Institutions:

1. Contractors (SOEs & Private)

2. Consultant (Planner/Supervisor)

3. Owner/Developer/Government involved in projects with Medium - Large scale.

Improvement 3 According to Hair et al. (2017), the minimum sample size in PLS-SEM suggests a ratio of 5 to 10 times of the total study indicators. With 15 indicators, the ideal sample target is 75 to 150 respondents to minimize sampling errors.

### **Validity and Reliability Tests**

#### **Validity Test**

Validity is the level of accuracy of an instrument in measuring what should be measured. A questionnaire is declared valid if the question items are able to represent the concepts or variables that are being researched appropriately. In other words, validity indicates the extent to which the instrument can generate data that is accurate, relevant, and capable of distinguishing small variations in the attributes being measured. In the validity testing of questionnaires, two main types are known: factor validity and item validity. Factor validity is done by correlating the score of a factor with the total score of all factors, while the validity of the item is done by correlating the score of each item to the total score of the item or the score of the factor. A commonly used analysis technique is Pearson Product Moment correlation, with the help of SPSS software. An item is declared valid if it has a significant correlation to the total score at a significance level of 0.05, i.e. if the calculated  $r$  value is greater than or equal to the  $r$  of the table. These results show that the item is feasible to be used to validly measure research variables.

#### **Reliability Test**

Reliability is a measure of the consistency of an instrument in producing stable and reliable data. A questionnaire is said to be reliable if it produces consistent answers over time to the same measurements. According to Sugiharto and Sitinjak (2006), reliability shows the extent to which a measuring instrument can be trusted as a data collection tool that is able to reveal actual information in the field. Ghazali (2009) emphasized that reliability is used to test the consistency of answers between items in a questionnaire that represent a construct. Thus, a reliable instrument is an instrument that provides steady, stable, and reliable measurement results. In practice, reliability is tested using Cronbach's Alpha coefficient to assess the internal consistency between items. An alpha value  $\geq 0.70$  is considered to indicate a sufficient level of reliability, while a value above 0.80 indicates high reliability. If the alpha value  $< 0.50$ , then the reliability is considered low, and the items in the instrument need to be reviewed. The closer the value is to 1.00, the higher the reliability of a measuring instrument. Therefore, in this study, reliability tests were performed to ensure that all items in the questionnaire were consistent in measuring the same construct, and the tests were performed with the help of SPSS software.

## **Data Analysis (PLS-SEM)**

The data analysis in this study uses Partial Least Squares Structural Equation Modeling (PLS - SEM), which is a multivariate statistical method used to test the causal relationship between latent variables in one integrated model.

Improvement 7 The selection of the Partial Least Squares Structural Equation Modeling (PLS-SEM) method compared to Covariance-Based SEM (CB-SEM) in this study is based on several fundamental methodological considerations, namely:

1. **Research Objectives (Exploratory/Predictive):** Unlike CB-SEM which aims to test or confirm established theories (theory testing), PLS-SEM is more appropriate to be used for the development of theories and predictive purposes. Given that the adoption of Infrastructure Digital Twins (IDTs) is a new phenomenon in Indonesia with a still developing literature, this study aims to identify key determinants (predictors), making PLS-SEM more relevant.
2. **Model Complexity:** PLS-SEM has high flexibility in handling complex structural models with many latent variables and indicators without causing model identification issues, which is common with CB-SEM if the model is very complex.
3. **Data Distribution Flexibility:** PLS-SEM is a non-parametric method that does not require the assumption of a strict distribution-free distribution of data. This provides an advantage in construction industry research where questionnaire data is often asymmetrical.

PLS-SEM consists of two main components, namely a measurement model to assess the validity and reliability of constructs through their indicators, and a structural model to test causal relationships between constructs according to the research hypothesis (Hair et al., 1998). The stages of PLS-SEM analysis include testing the measurement model through convergent validity, discriminant validity, and construct reliability. Structural model testing through path coefficient analysis, R-square value, and significance test using bootstrapping techniques. This approach is expected to result in a valid, reliable, and relevant Infrastructure Digital Twins adoption model as a basis for strategic decision-making in Indonesia's construction sector.

## **Content/Face Validity Testing**

Content validity testing is carried out through expert judgement, which is testing based on face validity carried out by experts who understand the research construct to be carried out, or by using statistical calculations. Display validity test is a concept of measuring measuring instruments, such as questionnaires, which are prepared based on the opinions of experts or professionals. Through this test, the items in the questionnaire are ensured to be able to measure the constructs that have been set. In the questionnaire statement test, feasibility is assessed by an expert in his field. Furthermore, instrument validation was carried out using statistical calculations using the Partial Least Square (PLS) method assisted by the SmartPLS 4.0 program.

## **Evaluation of the Outer Model**

Outer model measurement involves measuring indicators related to the variables being studied through the paths that connect them. This analysis was carried out to assess the relationship by conducting a convergent validity test and a discriminant validity test. Meanwhile, to evaluate

the level of reliability of the constructed construct that has been designed, a composite reliability test is carried out.

### **Convergent Validity**

It is used to see the extent to which indicators (manifest variables) are positively correlated with constructs (latent variables), i.e. by measuring the level of validity of each relationship between the indicator and its latent variables. In the SmartPLS application, the convergent validity value is obtained from the amount of the loading factor (LF) value in each indicator of latent variables. The loading factor (LF) value that meets the validity rule is  $> 0.7$ .

### **Discriminatory Validity**

Discriminant validity is a method used to evaluate the extent to which a construct is completely different from another. This implies that each construct is unique in capturing phenomena that are not represented by other constructs in the model. In other words, the set of indicators used is expected to have multidimensionality. These values, called cross loading factors, are useful for assessing whether a construct has adequate discriminating capabilities, by comparing the loading value of the intended construct with the loading value of another construct. In the SmartPLS application, discriminant validity information can be obtained from: (1) Cross loading table on the PLS algorithm, (2) Fornell-Larcker criteria table, and (3) HTMT (Heterotrait Monotrait Ratio) table, HTMT value below 0.90 indicates that the construction of the path model is conceptually different or not unidimensional.

### **Composite Reliability**

To measure internal consistency, which is a value that shows the consistency or reliability of each indicator in measuring constructs. This value varies between 0 and 1. Getting closer to 1 indicates a higher level of reliability. In the SmartPLS application, the CR value is displayed in 4 criteria, namely: (1) alpha cronbach, (2) rho c, (3) composite reliability, and (4) AVE (Average Variance Extracted). The expected reliability value for all of the above criteria is  $> 0.7$ , but the research explores the reliability values of CR, rho c, and Alpha Cronbach 0.6 is still allowed. Except for AVE values, the AVE reliability criterion is  $> 0.5$ . The Average Variance Extracted (AVE) value is used to assess how much variation the construct can explain compared to the variation caused by measurement errors. The AVE value must be greater than or equal to 0.5 giving meaning to how far the overall variable can explain the variation of the measurement item.

### **Inner Model Evaluation**

Structural models (inner models) are used to evaluate the strength of relationships between latent variables studied through bootstrapping calculations. In this structural model test, several measures were used, including the value of multicollinearity with variance inflation factor (VIF), R-Square value, and path coefficient.

### **Collinearity**

The value of the Variance Inflation Factor (VIF) in the predictor construct should be below 5 and preferably below 3 for that corlinearity has no substantial effect on the structural model's estimates. If the VIF shows a critical level of collinearity, we may want to consider eliminating the construct, or combining the predictors into a single construct to address the problem of

collinearity, In SmartPLS applications, (Hair Jr 2017) Inner VIF is used for multicollinear inspection of structural model measurements.

### **Coefficient of determination**

R-squared is used to evaluate how much variation in dependent variables can be explained by independent variables in regression models. The R-squared value ranges from 0 to 1, where getting closer to 1 indicates that the model can explain variations in dependent variables well. According to Hair, et.al., 2017, the R square value  $< 0.75$  means that the independent variable has a high influence,  $0.50 < R^2 < 0.75$  means that it has a moderate effect, and  $0.25 < R^2 < 0.5$  has a weak effect.

### **Path coefficients & hypothesis proof**

After running the PLS-SEM algorithm, an estimate will be made for the structural model relationship, expressed in path coefficients. The path coefficient describes the strength and direction of the hypothetical relationship between constructs. In determining the significance of the path coefficient, bootstrapping is used to obtain T-values and P Values. In addition, it also evaluates the relevance of significant relationships, as not all significant relationships have a great impact. By combining significance and relevance assessments, it is possible to better understand how the relationships between variables in a structural model contribute to a deeper understanding of the phenomenon being studied (Hair Jr, 2017).

### **Discussions, Discussions and Managerial Implications**

#### **Discussion and Discussion**

The discussion and discussion subchapter is focused on the interpretation of the results of the SEM-PLS analysis in explaining the mechanism of adoption of Infrastructure Digital Twins (IDTs) in construction projects in Indonesia. The discussion began with an evaluation of the significance and strength of the relationship between constructs according to the research hypothesis (H1–H6), especially the role of technical factors, organizational factors, and external factors in shaping the adoption intention and the level of adoption of IDTs. The empirical results are then critically compared with the findings of previous research and the theoretical foundations used (TOE, TAM/UTAUT, and Innovation Diffusion Theory) to identify suitability, differences, and new contributions that emerge from the context of this research. In addition, the discussion also highlighted constructs that have a dominant influence, insignificant relationship paths, and their implications for understanding digital technology adoption which is complex and organization-based. With this approach, the discussion not only answers the research questions, but also enriches the academic discourse on the adoption of IDTs in developing countries.

#### **Managerial Implications**

The managerial implications in this study are compiled based on empirical results and key findings from the IDTs adoption model, with the aim of providing practical guidance for construction sector stakeholders. These implications include several key aspects, namely: (1) strategic implications for project management and construction organizations in prioritizing technology readiness, human resource competency development, and leadership support to accelerate the adoption of IDTs; (2) operational implications related to the use of IDTs as a tool to

support automation, real-time monitoring, and data-driven decision-making in medium to large-scale projects; and (3) policy implications for governments and regulators in formulating regulations, standards, and incentives that encourage wider and sustainable adoption of digital technology. Thus, the managerial implications presented are expected to bridge the gap between academic findings and the practical needs of the construction industry in supporting digital transformation and project automation in Indonesia.

Improvement 6 The formulation of strategic recommendations in this study is not only based on statistical findings alone, but is carried out through a method triangulation approach to ensure the applicability and depth of analysis. The stages of recommendation formulation are carried out as follows:

1. Integration of Literature and Empirical Findings: The results of hypothesis testing from the SEM-PLS model will be contrasted with theoretical foundations (TOE, TAM, IDT) as well as previous research to identify specific gaps or obstacles found in the Indonesian construction industry.
2. Validation Through Focus Group Discussion (FGD): The qualitative stage is carried out by inviting experts representing elements of regulators (government), practitioners (contractors/consultants), and academics. This discussion aims to validate the resulting empirical models as well as provide practical perspectives on the most relevant policies or incentives to accelerate the adoption of IDTs.
3. Qualitative Descriptive Analysis: Data from the FGD is analyzed descriptively to categorize recommendations into three managerial levels, namely the strategic level (organizational leadership), the operational level (project management), and the policy level (regulator/government).
4. Preparation of Transformation Roadmap: As the final output, the integration of literature results, quantitative findings, and expert input will be summarized into a draft strategic recommendation that is applicable to the digital transformation of the national construction sector.

## **CONCLUSION**

Based on the discussion presented in this manuscript, this study concludes that the adoption of Infrastructure Digital Twins (IDTs) in Indonesian construction projects represents an important strategy for supporting project automation, improving efficiency, enabling data-driven decision-making, and advancing the digital transformation of the national construction sector. The research model developed through the SEM-PLS approach demonstrates that successful IDT adoption depends not only on technological readiness — encompassing digital infrastructure, system interoperability, and data security and quality — but is also influenced by organizational factors such as top management support, human resource competence, and organizational readiness culture, as well as external factors including regulatory support, competitive pressure, and the digital ecosystem. By integrating the TOE, TAM/UTAUT, and IDT frameworks, this study provides a conceptual and empirical foundation for understanding the relationships among

adoption intention, the rate of IDT utilization, and construction project automation. Future research is therefore recommended to test this model with a larger and more diverse sample of respondents, encompassing various types of infrastructure projects and regions across Indonesia, and to strengthen the analysis with longitudinal data so that the progression of IDT adoption can be observed more thoroughly. Future studies may also incorporate additional variables such as investment readiness, data literacy, BIM maturity, cybersecurity risk, and government policy support, so that the IDT adoption model becomes more comprehensive and practically applicable to the Indonesian construction industry.

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