JPPIPA 12(4) (2026)

Jurnal Penelitian Pendidikan IPA

http://jppipa.unram.ac.id/index.php/jppipa/index

Probabilistic Cost Optimization of Green Retrofitting in Transit-Oriented Development Using Monte Carlo Simulation and CASBEE Criteria

Reza Dwi Rukmono[1*], Mawardi Amin, Budi Susetyo[1]

[1] Faculty of Engineering, Universitas Mercubuana, City, Indonesia.

Received: January 31, 2026
Revised: March 03, 2026
Accepted: April 25, 2026
Published: April 30, 2026

Corresponding Author:
Reza Dwi Rukmono
reza_dwi_rukmono@yahoo.com

DOI: 10.29303/jppipa.v12i4.14472

Abstract: Bekasi City faces serious environmental issues due to climate change, rapid urbanization, and high urban activity, which have resulted in increased carbon emissions, air pollution, and declining environmental quality. The application of green building and green infrastructure concepts, including the utilization of building rooftops, renewable energy, and air management, is an effective solution to improve energy efficiency and urban environmental quality. This study aims to improve the cost efficiency of green retrofitting in Transit Oriented Development (TOD) by utilizing CASBEE (Comprehensive Assessment System for Built Environment Efficiency) guidelines and Montecarlo @Oracle Crystal Ball probabilistic simulation technology. This study was conducted at the Eastern Green TOD in Bekasi, where the cost of implementing green building concepts in urban environments is increasingly becoming a major concern. With this approach, the study throws up various factors that influence cost performance and implements Montecarlo @Oracle Crystal Ball probabilistic simulation methods to obtain more accurate predictions regarding costs and efficiency. This study has the potential to become a reference for developers in implementing green building principles in TOD areas, as well as supporting better decision-making regarding costs and project sustainability.

Keywords: CASBEE; Green Retrofitting; Montecarlo; Transit oriented development

Introduction

Bekasi, as one of the most densely populated and rapidly urbanizing cities in Indonesia, is currently facing escalating environmental challenges driven by climate change. As a strategic urban hub supporting governmental, economic, and social activities in the Greater Jakarta metropolitan area, Bekasi has been increasingly exposed to rising global temperatures, shifting rainfall patterns, and heightened climate variability. Rapid urban expansion, population growth, and intensive land-use change have significantly reduced environmental carrying capacity, making the city highly vulnerable to climate-related risks such as recurrent flooding, prolonged droughts, urban heat island effects, and deteriorating air quality. These conditions demonstrate that climate change is no longer a distant global concern but has evolved into an immediate urban threat that directly affects daily life, infrastructure resilience, and long-term economic sustainability. The increasing frequency and severity of flood events in Bekasi and its surrounding regions further highlight the sensitivity of urban systems to extreme rainfall and land-cover transformation (Li et al., 2025).

In parallel, Indonesia continues to experience mounting environmental pressures associated with declining air quality, particularly in highly urbanized areas (Amoah & Smith, 2024; He et al., 2019; Kussumardianadewi, Latief, Ilyas, et al., 2024). Transportation emissions, dense built environments, and inefficient energy consumption patterns contribute significantly to pollution accumulation, posing serious risks to public health and environmental sustainability

How to Cite:
Rukmono, R. D., Amin, M., & Susetyo, B. (2026). Probabilistic Cost Optimization of Green Retrofitting in Transit-Oriented Development Using Monte Carlo Simulation and CASBEE Criteria. *Jurnal Penelitian Pendidikan IPA*, *12*(4), 840–849. https://doi.org/10.29303/jppipa.v12i4.14472

(Faccioli et al., 2025; Kaashi & Vilventhan, 2023). Within this context, the building sector has been widely recognized as one of the major contributors to energy consumption, greenhouse gas emissions, and resource depletion throughout both construction and operational phases (Kussumardianadewi, Latief, Trigunarsyah, et al., 2024; Madushika & Lu, 2023). Consequently, improving the environmental performance of existing buildings and urban infrastructure has become a critical strategy for mitigating climate impacts and enhancing urban resilience (Husin et al., 2024; Madushika & Lu, 2023; Mughal et al., 2024).

One practical and increasingly relevant approach to addressing these challenges is the implementation of green retrofitting, particularly within strategic urban development zones (Madushika & Lu, 2025a; Ojelabi et al., 2024). Green retrofitting aims to improve operational efficiency by reducing energy and water consumption, enhancing indoor and outdoor environmental quality, and integrating green infrastructure and sustainable design solutions into existing developments. Despite its proven long-term environmental and operational benefits, green retrofitting often requires substantial upfront investment and is characterized by significant uncertainty in cost estimation. Cost instability may arise from fluctuations in material prices, technical complexity, limited availability of skilled labor, and original building designs that were not intended to accommodate green technologies. These uncertainties frequently discourage stakeholders from adopting green retrofit strategies, despite their potential contribution to sustainable urban development (Yang et al., 2023).

To address this challenge, probabilistic decision-support tools are required to manage uncertainty and support more reliable investment planning (Judi et al., 2025; Madushika & Lu, 2025b; Tetteh et al., 2022). Monte Carlo Simulation, implemented through probabilistic software such as Oracle Crystal Ball, offers a robust method for modeling cost uncertainty and generating realistic projections across multiple scenarios, including optimistic, most-likely, and pessimistic conditions. This approach enables stakeholders to quantify risk, improve decision-making accuracy, and identify cost-optimal retrofit strategies under real-world variability. The application of Monte Carlo simulation is particularly relevant in Transit-Oriented Development (TOD) projects, where retrofit costs tend to be high, complex, and uncertain due to integrated transportation, building, and urban infrastructure systems (Saroji et al., 2023; Tanoz-Sargeant, 2019; Zhang, 2025).

In addition to cost optimization, sustainability assessment frameworks are essential to ensure that retrofitting interventions achieve measurable and comparable environmental performance outcomes. This study adopts the Comprehensive Assessment System for Built Environment Efficiency for Urban Development (CASBEE_UD) as the primary sustainability evaluation framework. Unlike building-scale assessment tools, CASBEE_UD evaluates sustainability performance at the urban development scale, making it particularly suitable for TOD contexts. However, the application of CASBEE_UD in Indonesia remains limited, and comprehensive evaluations of green TOD projects using this framework are still scarce. The absence of an integrated green TOD assessment model highlights the need for localized frameworks that align international sustainability standards with Indonesia's urban development characteristics.

The urgency of this research is further reinforced by Indonesia's national development agenda, particularly the National Medium-Term Development Plan (RPJMN) 2020–2024, which prioritizes sustainable housing and settlement infrastructure in alignment with the Sustainable Development Goals (SDGs), especially SDG 11 on sustainable cities and communities. Within this policy framework, TOD has emerged as a strategic approach to reducing congestion, emissions, and urban sprawl through the integration of mass transportation systems and sustainable urban planning. Implementing green retrofitting within TOD areas offers dual benefits: mitigating environmental impacts while improving cost efficiency and long-term operational performance.

The novelty of this research lies in the integration of probabilistic cost optimization using Monte Carlo Simulation (Oracle Crystal Ball) with a CASBEE_UD–based sustainability assessment framework, specifically applied to Transit-Oriented Development. Unlike conventional retrofit studies that rely primarily on deterministic cost calculations, this study proposes a risk-based optimization model that explicitly captures uncertainty through probability distributions, enabling more realistic and robust investment decision-making. Furthermore, this research contributes to the literature by applying CASBEE_UD within the Indonesian TOD context, particularly in the case of Eastern Green Bekasi, a developing TOD area that has not yet achieved higher sustainability performance categories.

Existing studies on green retrofitting generally focus on sustainability assessment or cost analysis as separate dimensions. Integrated research that combines urban-scale sustainability rating systems with probabilistic cost optimization in TOD environments remains limited, especially in Indonesia. Therefore, this study aims to fill this gap by offering an integrated decision-support framework that evaluates green TOD retrofitting from both environmental performance and risk-aware cost perspectives. The findings are expected to support policymakers, planners, and investors in accelerating sustainable urban transformation in climate-vulnerable cities such as Bekasi.

Method

This study employs a quantitative approach with a survey method to identify factors influencing cost performance in the implementation of green retrofitting in Transit Oriented Development (TOD) projects. The data analysis is conducted using Structural Equation Modeling (SEM) with SMART PLS 3.0 to examine the relationships between variables and determine the dominant factors affecting cost performance. The research is conducted among stakeholders involved directly or indirectly in construction projects, including academics, field practitioners such as planning and supervision consultants, construction service providers (contractors), and relevant government authorities. The minimum sample size of 66 respondents is determined using Slovin's formula based on a population of 211 sub-factors. The study involves both independent and dependent variables.

The independent variables include Green Retrofitting Environment (X1), Green Retrofitting Economic (X2), and Green Retrofitting Society (X3), each with specific main factors and sub-factors. For example, X1 consists of Smart Location and Connectivity (X1.1, 9 sub-factors), Area Pattern and Design (X1.2, 15 sub-factors), and Nature (Green Spaces and Biodiversity) (X1.3, 7 sub-factors). The dependent variable is Cost Performance (Y), which includes Direct Cost (Y1.1, 4 sub-factors) and Indirect Cost (Y1.2, 2 sub-factors). Data collection is carried out using a questionnaire based on a 6-point Likert scale, where 1 represents "Strongly Disagree" and 6 represents "Strongly Agree." The questionnaire items are developed based on sub-factors obtained from literature review and the Ministerial Circular No. 01/SE/M/202**2**, ensuring that the questions are relevant to the research objectives. The questionnaires are distributed to selected respondents and returned data are checked for completeness and accuracy. The responses are then tabulated and grouped according to respondents' occupation, position, and education level to ensure reliability and validity. Data analysis is performed using SEM-PLS 3.0 in three stages: first, weight estimation is conducted to generate latent variable scores; second, path coefficient estimation is used to determine relationships between latent variables and compute loading factors for each indicator; and third, parameter estimation identifies the dominant factors affecting cost performance.

This analysis addresses the research questions: identifying the key determinants that significantly influence cost performance (RQ1) and determining the most dominant elements in CASBEE assessment implementation (RQ2 and RQ3). The results of this study are expected to reveal the most significant variables and primary indicators that can guide effective and sustainable implementation of green retrofitting in TOD projects, thereby improving overall cost performance in accordance with CASBEE standards.

Result and Discussion

To realize a green-concept building, certain requirements must be fulfilled—particularly when an official institution assesses the "greenness" level of an industrial building in order to verify environmental performance and enable the project to receive incentives or administrative facilitation from the local government. In practice, some stakeholders may still be unaware that there are already many institutions worldwide, including in Indonesia, that provide green assessments for Transit Oriented Development (TOD). Based on the questionnaire results, the most dominant drivers for implementing the green concept in industrial developments are management policies and commitment**,** especially in managing energy-use efficiency**,** water-use efficiency**,** and site management as core factors of Green TOD, which can ultimately deliver additional operational benefits. Government support through regulations and policy instruments also emerges as one of the most influential factors in implementing a green-oriented TOD. Examples include property tax exemptions, simplified building permit (IMB) processes, or regulatory requirements such as withholding IMB approval if a building does not adopt green principles, or restricting TOD development if it fails to meet green criteria. These mechanisms reflect a government strategy to encourage (or compel) wider adoption of green buildings, reduce environmental burdens, and improve overall quality of life.

In applying the green concept, the author attempted to validate the research hypotheses by using Transit Oriented Development (TOD) as the study object, implementing a Green Infrastructure approach supported by the Monte Carlo method to ensure that green cost performance remains manageable during implementation. Monte Carlo analysis—recognized as an important requirement in sustainable procurement—serves as a primary tool for evaluating economic efficiency across the total life-cycle budget. In this study, the researcher conducted a self-assessment of green implementation in the TOD area using CASBEE and its predefined parameters. Prior to conducting the self-assessment, the researcher held discussions and interviews with certified Green Infrastructure experts holding a Green Professional (GP) certification to obtain additional parameters, scoring calculations, assessment procedures, and validation of results in order to achieve the planned target outcomes.

Green Infrastructure Building Assessment Using CASBEE

At the green infrastructure assessment stage, the study adopted recommendations based on the Japanese guideline CASBEE (Comprehensive Assessment System for Built Environment Efficiency). The TOD was assessed starting from its initial condition, and scores were assigned to evaluate whether the development meets green infrastructure requirements. After accumulating the scores, a re-evaluation was conducted by simulating improvements for components considered suboptimal. The objective was to achieve outcomes aligned with CASBEE green infrastructure standards, which are classified into five rating levels: Excellent, Very Good, Good, Fairly Poor, and Poor. The differences in scoring across these categories are presented in Table 1.

Table 1. CASBEE Rating Benchmarks

CASBEE Rating	CASBEE Score
Excellent	3.0 or more & Q is 50 or more
Very Good	1.5 to < 3.0 & Q is < 50
Good	> 1.0 to < 1.5
Fairly Poor	> 0.5 to < 1.0
Poor	< 0.5

Source: CASBEE_UD 2014

Green infrastructure buildings are developments that comply with specific technical criteria and demonstrate strong effectiveness in conserving energy, water, and other resources by applying green building principles according to their designated functions and classifications at each phase of development. In this study, the assessment is conducted using CASBEE (Comprehensive Assessment System for Built Environment Efficiency) to evaluate green infrastructure performance.

After conducting the assessment of the current green building condition using the CASBEE criteria and the scoring calculation examples described above for green infrastructure performance, a cumulative score was obtained during the building's operational phase. This score is then compared with the expected benchmark after implementing green infrastructure improvements, as illustrated in Table 3.

Table 2. Standard Scoring and Rating CASBEE

CASBEE Criteria		Point Allocations
	Q1 – ENVIRONMENT	
1.1	Resource	
	Water Resource	0.5
	Resources recycling	0.5
1.2	Nature (Greenery and Biodiversity)	
	Greenery	0.5
	Biodiversity	0.5
1.3	Artifact (Building)	
	Environmentally Considerate Building	1.0
	Score Q1 – Environment	3.0
	Q2 – SOCIETY	
2.1	Compliance	
	Complience	0.5
	Area Management	0.5
2.2	Security/ Safety	
	Disaster Prevention	0.3
	Traffic Safety	0.3
	Crime Prevention	0.3
2.3	Amenity	
	Convenience/ Welfare	0.5
	Culture	0.5
	Score for Q2 – Society	2.9
	Q3 – ECONOMY	
3.1	Traffic/ Urban Structure	
	Traffic	0.5
	Urban Structure	0.5
3.2	Growth Potential	
	Population	0.5
	Economic Development	0.5
3.3	Efficiency/ Rationality	
	Information System	0.5
	Energy System	0.5
	Score for Q3 – Economy	3.0
	Total CASBEE Score Available	8.9

Source: CASBEE_UD 2014

Table 3. Assessment Target Achievement Green Infrastructure with CASBEE

Item	Green Infrastructure Criteria with CASBEE Parameters				
	Excellent	Very Good	Good	Fairly Poor	Poor
Standard Criteria	> 3.0	1.5 – 3.0	1.0 – 1.5	0.5 – 1.0	< 0,5
Target Achievement Point Score	5.0	3.0	1.5	1.0	Initial Point
Total Point Score					8.7 Point Score

Source: CASBEE_UD 2014

Table 4. Green Infrastructure Assessment Results with CASBEE

CASBEE Criteria		Point Allocations	Achievement Score				
			Excellent	Very Good	Good	Fairly Poor	Poor
Q1 – ENVIRONMENT							
1.1	Resource						
	Water Resource	0.5	0.5	0.5	0.5	0.5	0.5
	Resources recycling	0.5	0.5				

CASBEE Criteria		Point Allocations	Achievement Score				
			Excellent	Very Good	Good	Fairly Poor	Poor
1.2	Nature (Greenery and Biodiversity)						
	Greenery	0.5					
	Biodiversity	0.5					
1.3	Artifact (Building)						
	Environmentally Considerate Building	1.0	1.0				
	Score Q1 – Environment	3.0	2.0	0.5	0.5	0.5	0.5
Q2 – SOCIETY							
2.1	Compliance						
	Complience	0.5					
	Area Management	0.5	0.5	0.5			
2.2	Security/ Safety						
	Disaster Prevention	0.3					
	Traffic Safety	0.3	0.5	0.5	0.5		
	Crime Prevention	0.3					
2.3	Amenity						
	Convenience/ Welfare	0.5	0.5	0.5			
	Culture	0.5					
	Score for Q2 – Society	2.9	1.5	1.5	0.5	0	0
Q3 – ECONOMY							
3.1	Traffic/ Urban Structure						
	Traffic	0.5	0.5	0.5	0.5	0.5	
	Urban Structure	0.5					
3.2	Growth Potential						
	Population	0.5					
	Economic Development	0.5	0.5				
3.3	Efficiency/ Rationality						
	Information System	0.5					
	Energy System	0.5	0.5	0.5			
	Score for Q3 – Economy	3.0	1.5	1.0	0.5	0.5	0.0
	Total CASBEE Score Available	8.9	5.0	3.0	1.5	1.0	0.5

Source: CASBEE_UD 2014

Implementation of CASBEE-Based Green Infrastructure Assessment for Transit Oriented Development (TOD)

Based on the data obtained from the green building assessment described above, the study concludes that the initial condition achieved a score of 0.5 points. This result places the initial condition in the "Poor" category (unclassified/poor performance) because the score is below 1.0 point. Furthermore, the assessment benchmarks indicate that the Excellentrating corresponds to a target score of 5.0 points, Very Good corresponds to 3.0 points, Good corresponds to 1.5 points, and Fairly Poor corresponds to 1.0 point.

By applying Structural Equation Modeling–Partial Least Squares (SEM-PLS) in this study, the author identified the key factors that influence the integration of green building practices in Transit Oriented Development (TOD) based on the CASBEE_UD green infrastructure certification framework. Various variables related to the research problem were examined in order to develop and validate a causal statistical model. The findings indicate that there are ten significant factors affecting the implementation of green building initiatives in TOD building structures, namely stormwater management, infrastructure energy efficiency, reduction of waste disposal volume, development of traffic facilities, bicycle facilities, pedestrian facilities, land use optimization, transit facilities, community outreach and engagement, and renewable energy production. Overall, these findings are expected to increase awareness and collective interest in adopting sustainable building practices and environmentally friendly development strategies, which can contribute to creating more energy-conscious areas, reducing operational costs, and improving satisfaction among surrounding communities. Modelling Using the Monte Carlo Method with the Probabilistic Software Oracle Crystal Ball

In the next section, the researcher discusses the additional benefits of using a probabilistic (uncertainty-based) approach through Oracle Crystal Ball. Oracle Crystal Ball is a Microsoft Excel–based software package used for Monte Carlo simulation, sensitivity analysis, probabilistic forecasting, and decision optimization. In the context of cost reduction related to compliance with green building standards (e.g., CASBEE, LEED, GREENSHIP), Oracle Crystal Ball plays an important role in modelling uncertainty, measuring cost risk, and evaluating green retrofit investment scenarios realistically.

The role of Oracle Crystal Ball in Monte Carlo simulation for green retrofitting is to evaluate the cost efficiency of green retrofit implementation in TOD buildings using a probabilistic approach to: Retrofit investment costs, Operational savings (energy, water, and maintenance), Technical risks and unexpected costs, Impacts on the building's long-term value

Oracle Crystal Ball Implementation

After the self-assessment was completed using the CASBEE_UD parameters, the next stage involved developing a representation for each evaluation component in Oracle Crystal Ball to improve the efficiency of green cost arising from green infrastructure adjustments. The modelling process was carried out by the researcher based on quantity take-off activities conducted in the Transit Oriented Development (TOD) construction project. The formulation of these representations was derived from data collected and analysed during the earlier evaluation stage.

Implementation of Oracle Crystal Ball for the "Poor" Rating Category

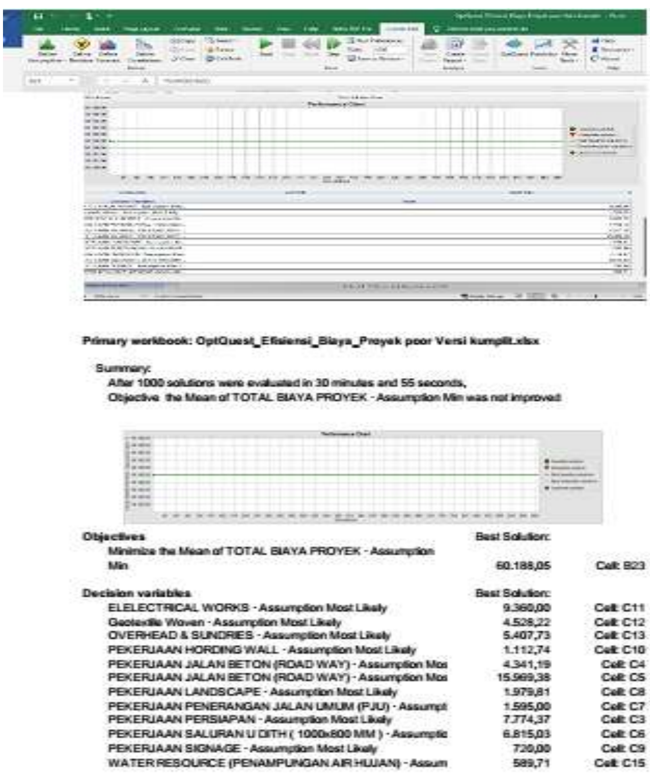

Figure 1. Implementation of oracle crystal ball for the "poor" rating

After the data were entered into Oracle Crystal Ball for the Poor rating category, the simulation reduced the green cost item to IDR 589,710,000, down from IDR 629,520,000. Therefore, under the Poor rating scenario, the cost efficiency achieved was 6.32% of the initial additional green infrastructure cost.

In terms of total project cost, the value decreased from IDR 60,233,000,000 to IDR 60,193,190,000. Thus, for the Poor rating scenario, the overall cost efficiency achieved was 0.08% of the initial additional green infrastructure cost.

Implementation Oracle Crystal Ball on the predicate rating Fairly Poor

After the data were entered into Oracle Crystal Ball for the Fairly Poor rating category, the simulation produced a green cost efficiency value of IDR 683,530,000, reduced from IDR 709,190,000. Thus, under the Fairly Poor rating scenario, the cost efficiency achieved was 3.62% of the initial additional green infrastructure cost.

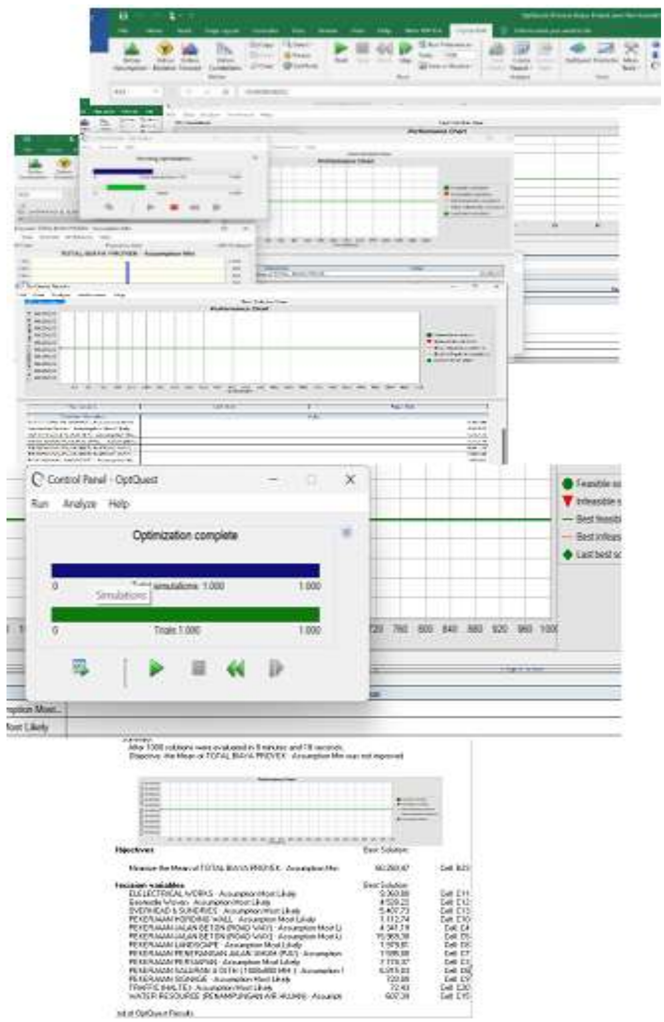

Figure 2. Implementation of oracle crystal ball for the "fairly poor" rating

In terms of total project cost, the value decreased from IDR 60,312,670,000 to IDR 60,287,020,000. Therefore, for this scenario, the overall cost efficiency achieved was 0.09% of the initial additional green infrastructure cost.

Implementation of Oracle Crystal Ball with Good Rating Predicate

After the data were entered into Oracle Crystal Ball for the Good rating category, the simulation produced a green cost efficiency value of IDR 1,033,100,000, reduced from IDR 1,068,540,000. Therefore, under the Good rating scenario, the cost efficiency achieved was 3.32% of the initial additional green infrastructure cost.

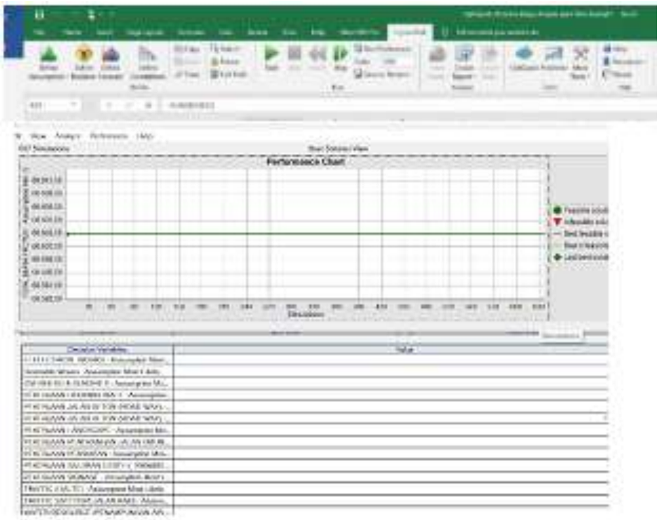

Figure 3. Implementation of oracle crystal ball for the "good" rating

In terms of total project cost, the value changed from IDR 60,636,590,000 to IDR 60,672,020,000. Thus, for this scenario, the overall cost efficiency was 0.09% of the initial additional green infrastructure cost.

Implementation of Oracle Crystal Ball for the "Very Good" Rating

After the data were entered into Oracle Crystal Ball for the Very Good rating category, the simulation resulted in a green cost efficiency value of IDR 1,724,860,000, reduced from IDR 1,795,980,000. Thus, under the Very Good rating scenario, the cost efficiency achieved was 3.96% of the initial additional green infrastructure cost.

In terms of total project cost, the value changed from IDR 61,328,340,000 to IDR 61,399,460,000. Accordingly, for the Very Good rating scenario, the overall cost efficiency achieved was 0.12% of the initial additional green infrastructure cost.

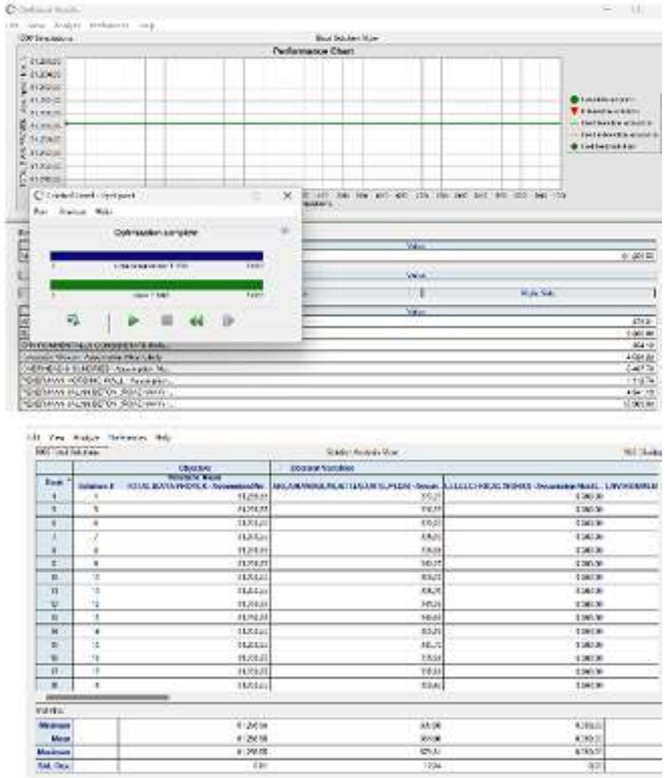

Figure 4 Implementation of oracle crystal ball for the "very good" rating

Implementation of Oracle Crystal Ball for the "Excellent" Rating

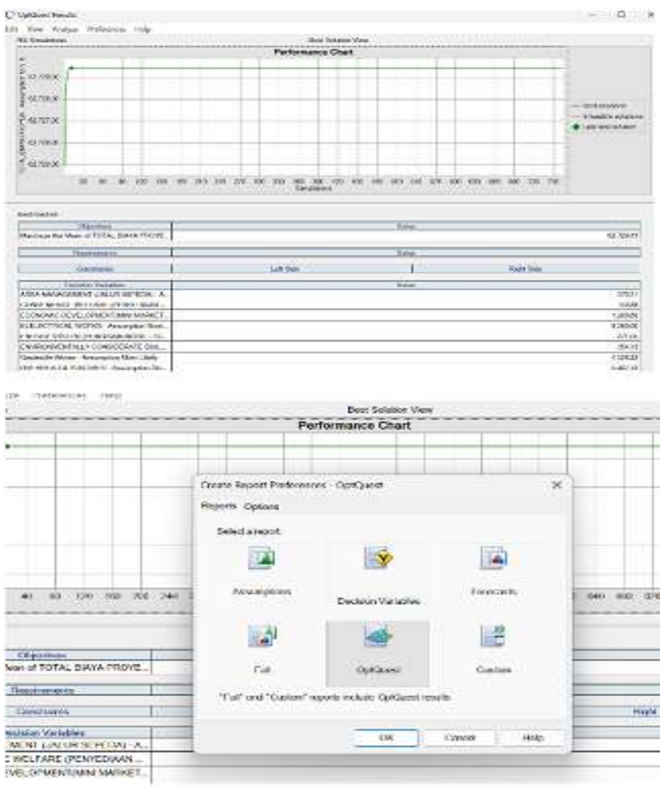

Figure 5. Implementation of oracle crystal ball for the "excellent" rating

After the data were entered into Oracle Crystal Ball for the Excellent rating category, the simulation produced a green cost efficiency outcome of IDR 3,194,820,000, reduced from IDR 3,421,600,000. This means that, under the Excellent rating scenario, the efficiency achieved was 6.48% of the initial additional green infrastructure cost.

In terms of total project cost, the value decreased from IDR 63,025,080,000 to IDR 62,798,310,000. Therefore, for the Excellent rating scenario, the overall cost efficiency achieved was 0.38% of the initial additional green infrastructure cost.

Summary of Oracle Crystal Ball Implementation (Recapitulation)

The results indicate that green retrofitting costs in TOD areas tend to be high and unstable, driven by factors such as fluctuations in material prices, inadequate initial design readiness, and limited availability of skilled labor for implementing green building technologies. This suggests that the retrofit process requires a more accurate predictive and managerial approach so that investment decisions can be made more effectively.

NO	DESCRIPTION		TOTAL INITIAL COST	TOTAL INITIAL COST + GREEN COST				
				Poor	Fairly Poor	Good	Very Good	Excellent
1	PREPARATORY WORK		7.774.367.379,06	7.774.367.379,06	7.774.367.379,06	7.774.367.379,06	7.774.367.379,06	7.774.367.379,06
2	CONCRETE ROAD WORK (ROAD WAY)		4.341.190.846,06	4.341.190.846,06	4.341.190.846,06	4.341.190.846,06	4.341.190.846,06	4.341.190.846,06
3	CONCRETE ROAD WORK (ROAD WAY)		15.969.382.977,21	15.969.382.977,21	15.969.382.977,21	15.969.382.977,21	15.969.382.977,21	15.969.382.977,21
4	U-DITCH CHANNEL WORK (1000X800 MM)		6.815.032.190,00	6.815.032.190,00	6.815.032.190,00	6.815.032.190,00	6.815.032.190,00	6.815.032.190,00
5	PUBLIC STREET LIGHTING WORK (PJU)		1.595.000.000,00	1.595.000.000,00	1.595.000.000,00	1.595.000.000,00	1.595.000.000,00	1.595.000.000,00
6	LANDSCAPE WORK		1.979.811.200,00	1.979.811.200,00	1.979.811.200,00	1.979.811.200,00	1.979.811.200,00	1.979.811.200,00
7	SIGNAGE WORK		720.000.000,00	720.000.000,00	720.000.000,00	720.000.000,00	720.000.000,00	720.000.000,00
8	HORDING WALL WORK		1.112.741.600,00	1.112.741.600,00	1.112.741.600,00	1.112.741.600,00	1.112.741.600,00	1.112.741.600,00
9	ELELECTRICAL WORKS		9.360.000.000,00	9.360.000.000,00	9.360.000.000,00	9.360.000.000,00	9.360.000.000,00	9.360.000.000,00
10	WOVEN GEOTEXTILE WORK		4.528.222.680,00	4.528.222.680,00	4.528.222.680,00	4.528.222.680,00	4.528.222.680,00	4.528.222.680,00
11	OVERHEAD & SUNDRIES		5.407.734.367,15	5.407.734.367,15	5.407.734.367,15	5.407.734.367,15	5.407.734.367,15	5.407.734.367,15
12	GREEN COST							
12.1	*Water Resource (rainwater storage)*	*Green Cost*		*629.517.269*	*629.517.269*	*629.517.269*	*629.517.269*	*629.517.269*
12.2	*Environmentally Considerate Building (TPS)*	*Green Cost*					*354.128.279*	*354.128.279*
12.3	*Area Management (bicycle)*	*Green Cost*					*373.310.000*	*373.310.000*
12.4	*Traffic Safety (Pedestrians)*	*Green Cost*				*359.350.000*	*359.350.000*	*359.350.000*
12.5	*Convenience/ Welfare (provision of ATM boxes)*	*Green Cost*						*153.882.000*
12.6	*Traffic (Halte)*	*Green Cost*			*79.669.700*	*79.669.700*	*79.669.700*	*79.669.700*
12.7	*Economic Development(Mini market)*	*Green Cost*						*1.200.689.762*
12.8	*Energy System (SPKLU)*	*Green Cost*						*271.049.650*
	TOTAL SUMMARY Green Cost		**59.603.483.239**	**60.233.000.508**	**60.312.670.208**	**60.672.020.208**	**61.399.458.487**	**63.025.079.900**
	GREEN COST			**629.517.269**	**709.186.969**	**1.068.536.969**	**1.795.975.248**	**3.421.596.660**
	GREEN COST PRECENTAGE (%)			**1,06%**	**1,19%**	**1,79%**	**3,01%**	**5,74%**
	TOTAL SUMMARY (REDUCE)		**59.603.483.239**	**60.193.191.670**	**60.287.018.044**	**60.636.586.356**	**61.328.343.163**	**62.803.453.726**
	GREEN COST			**589.708.431**	**683.534.805**	**1.033.103.117**	**1.724.859.924**	**3.199.970.486**
	GREEN COST PRECENTAGE (%)			**0,99%**	**1,15%**	**1,73%**	**2,89%**	**5,37%**
	DEVIASI			0,07%	0,04%	0,06%	0,12%	0,37%
	PRESENTASE			6,32%	3,62%	3,32%	3,96%	6,48%

Figure 6. Summary of oracle crystal ball implementation (recapitulation)

Therefore, a Monte Carlo simulation was applied to model the cost distribution under various scenarios—optimistic, realistic, and pessimistic. The simulation provides a more realistic picture of risks and opportunities in retrofit cost planning. The findings show that efficiency can be improved by up to 15–20% if green building strategies are integrated from the early stages of project planning. In addition, the CASBEE_UD rating system offers a more relevant approach for comprehensively evaluating area-level sustainability. CASBEE simulation results show that the Eastern Green area has currently only reached the "Good" (B+) category and has not yet met the sustainability standards of "Very Good" (A) or "Excellent" (S). The main weaknesses lie in environmental quality (Q), particularly air quality, availability of green open space, and the integration of social aspects and public infrastructure.

The study also found that social factors and spatial planning have not fully supported sustainable TOD principles. Limited pedestrian facilities, a lack of open public spaces, and weak intermodal connectivity are major obstacles to improving area efficiency. This directly affects the sustainability score based on CASBEE indicators.

Overall, this study concludes that controlling green retrofitting costs in TOD can be achieved through two main approaches: (1) strong early planning with integration of green elements starting from the conceptual design stage, and (2) the use of data-driven simulation to estimate risk and cost fluctuations. CASBEE_UD and the Monte Carlo method were proven effective as evaluation and decision-support tools for sustainable TOD area development in Indonesia.

The main findings also show that green retrofitting costs in TOD areas such as Eastern Green Bekasi tend to be high and volatile. This is consistent with La Roche et al. (2014), who argue that retrofitting existing buildings with green technologies requires significant upfront investment, especially if it is not planned from the conceptual design stage. This study strengthens that view by showing that cost efficiency can only be achieved when green strategies are applied from the beginning of the project.

Furthermore, the Monte Carlo approach used in this research extends the results of Avlijaš (2022), who state that probabilistic simulation can address construction cost uncertainty in large-scale projects. However, this study provides a more specific context by applying Monte Carlo to an area-based TOD project in Indonesia ßßan approach that has not been widely explored locally. By using Oracle Crystal Ball, this study simulates cost ranges across multiple scenarios, thereby supporting risk-based decision making.

Regarding area sustainability assessment, the results are also aligned with Murakami et al. (2007) and Mao (2024), who show that CASBEE_UD is more suitable for evaluating urban areas because it assesses efficiency in a spatial and comprehensive manner, compared to other systems such as LEED or Greenship that are more oriented toward individual buildings. However, unlike their studies focusing on Japan and China, this research emphasizes the importance of adopting CASBEE_UD within the Indonesian TOD context, where it has not yet been officially implemented.

This study also confirms the findings of Han & Kim (2019) and Siwi et al. (2014) on the importance of social and spatial planning aspects in TOD development. As shown in their studies, public infrastructure, green open spaces, and intermodal connectivity are key indicators for creating livable and sustainable areas. This study reinforces those findings by noting that the CASBEE_UD score of Eastern Green remains low in the environmental quality (Q) dimension due to suboptimal open space provision, pedestrian facilities, and community participation.

This research introduces scientific novelty in sustainable area planning by focusing on the cost efficiency of green retrofitting in Transit Oriented Development (TOD), a topic that has rarely been examined in depth in the Indonesian context. The main novelty lies in integrating Monte Carlo simulation methods with the CASBEE_UD area sustainability assessment system, applied simultaneously to evaluate and design strategies for improving cost efficiency in TOD retrofitting.

Most previous studies focus only on technical aspects of green buildings at the single-building level and still use deterministic approaches for project cost estimation. In contrast, this study uses a probabilistic approach through Oracle Crystal Ball, which simulates multiple scenarios of cost uncertainty and produces more realistic and practical predictions for decision-making in area-level projects.

Moreover, this study is among the first to apply CASBEE_UD (Comprehensive Assessment System for Built Environment Efficiency – Urban Development) in the context of TOD areas in Indonesia. CASBEE_UD has been widely used in Japan, while in Indonesia it has not been formally used to assess the sustainability of integrated urban developments such as TOD. Therefore, this research contributes by introducing and testing the relevance of CASBEE_UD in a tropical and rapidly developing urban context, while also demonstrating its potential adaptation to local rating systems such as Greenship Neighborhood or national standards (e.g., PUPR).

Finally, this research fills a gap in the literature that has rarely discussed the combination of quantitative cost-planning approaches with spatial and social area-level sustainability indicators. By integrating financial simulation with area-quality evaluation based on environmental and social indicators, this study offers a holistic and interdisciplinary analytical framework for achieving sustainable TOD development.

Conclusion

This study concludes that implementing green retrofitting in the Eastern Green Bekasi TOD area can improve district-level sustainability performance when assessed using CASBEE_UD, because the indicators help identify measurable environmental improvement priorities. However, green retrofit costs tend to be high and unstable due to material price fluctuations, technical complexity, and limited design readiness, making deterministic cost estimates insufficient for reliable planning. Monte Carlo simulation using Oracle Crystal Ball is shown to be effective for modeling cost uncertainty and producing more realistic scenario-based projections, thereby supporting risk-informed investment decisions. Overall, integrating CASBEE_UD assessment with Monte Carlo–based cost optimization provides a stronger decision-support framework for balancing sustainability targets and cost performance in TOD development in Indonesia.

Acknowledgments
The authors would like to express their sincere gratitude to all individuals and institutions who contributed to the completion of this research.

Author Contributions
Conceptualization, R.D.R., M.A., B.S methodology, R.D.R., M.A., B.S,; software, R.D.R., M.A., B.S.; validation R.D.R., M.A., B.S..; formal analysis, R.D.R., M.A., B.S.; investigation, R.D.R., M.A., B.S.; resources, R.D.R., M.A., B.S.; data curation, R.D.R., M.A., B.S.; writing—original draft preparation, R.D.R., M.A., B.S.; writing—review and editing, X.X.; visualization, R.D.R., M.A., B.S.; supervision, R.D.R., M.A., B.S.; project administration, R.D.R., M.A., B.S.; funding acquisition, R.D.R., M.A., B.S.

Funding
This research received no external funding.

Conflicts of Interest
The authors declare no conflict of interest.

References

Amoah, C., & Smith, J. (2024). Barriers to the green retrofitting of existing residential buildings. *Journal of Facilities Management*, *22*(2). https://doi.org/10.1108/JFM-12-2021-0155

Avlijaš, G. (2022). Using Earned Value Management for More Sustainable Project Schedule Control. *Management:Journal of Sustainable Business and Management Solutions in Emerging Economies*. https://doi.org/10.7595/management.fon.2022.0011

Faccioli, M., Lucarelli, C., Mazzoli, C., & Severini, S. (2025). What are the Policy Drivers to Undertake Green Retrofitting Investments? The Role of Tax Incentives and Communication in Italian Households' Decision-Making. *Italian Economic Journal*, *11*(3). https://doi.org/10.1007/s40797-024-00283-5

He, Q., Zhao, H., Shen, L., Dong, L., Cheng, Y., & Xu, K. (2019). Factors influencing residents' intention toward green retrofitting of existing residential buildings. *Sustainability (Switzerland)*, *11*(15).

https://doi.org/10.3390/su11154246
Husin, A. E., Kristiyanto, & Kussumardianadewi, B. D. (2024). Blockchain-BIM: reducing cost in green retrofitting for sustainable construction development. *Sinergi (Indonesia)*, *28*(3). https://doi.org/10.22441/sinergi.2024.3.009
Judi, S. S., Muhammad, W. M. N. W., Shaharuddin, N. S., & Ibrahim, I. H. (2025). Towards Sustainable Housing: Challenges in Architectural Design for Green Retrofitting in Malaysia. *International Journal of Research and Innovation in Social Science*, *9*(10). https://doi.org/10.47772/ijriss.2025.910000640
Kaashi, S., & Vilventhan, A. (2023). Development of a building information modelling based decision-making framework for green retrofitting of existing buildings. *Journal of Building Engineering*, *80*. https://doi.org/10.1016/j.jobe.2023.108128
Kussumardianadewi, B. D., Latief, Y., Ilyas, T., & Rarasati, A. D. (2024). Increasing the cost accuracy of implementing green retrofitting in high-rise office buildings. *Journal of Infrastructure, Policy and Development*, *8*(5). https://doi.org/10.24294/jipd.v8i5.3779
Kussumardianadewi, B. D., Latief, Y., Trigunarsyah, B., Rarasati, A. D., & Widiani, W. (2024). Development of Work Breakdown Structure (WBS) in High-Rise Office Buildings using Green Retrofitting based on GBCI and Minister of PUPR Regulation No. 21 of 2021 to Improve the Quality of Resource Planning. *Civil Engineering and Architecture*, *12*(2). https://doi.org/10.13189/cea.2024.120207
Li, L., Zhang, Q., Zhu, L., Zeng, G., Huang, H., Chen, Z., Zhou, X., Wang, X., Xu, Z., Wu, C., Yang, D., Zhai, X., Yang, S., Lu, Z., Gan, Y., & Lu, Z. (2025). Patients' loyalty to primary care institutions and associated factors in China: a cross-sectional study. *BMC Health Services Research*, *25*(1). https://doi.org/10.1186/s12913-025-12244-4
Madushika, U. G. D., & Lu, W. (2023). Green retrofitting application in developing economies: State of the art and future research directions. In *Energy and Buildings* (Vol. 301). https://doi.org/10.1016/j.enbuild.2023.113712
Madushika, U. G. D., & Lu, W. (2025a). Modelling the driving forces of green retrofitting adoption in developing nations: A data-driven approach. *Journal of Building Engineering*, *108*. https://doi.org/10.1016/j.jobe.2025.112921
Madushika, U. G. D., & Lu, W. (2025b). Policy strategies for green retrofitting adoption: a systematic review and future directions. *International Journal of Construction Management*. https://doi.org/10.1080/15623599.2025.2535752
Mughal, S., Khoso, A. R., Najeeb, H., Khan, M. S. N., Ali, T. H., & Khahro, S. H. (2024). Green Retrofitting of Building using BIM-based Sustainability Optimization. *Jurnal Kejuruteraan*, *36*(1). https://doi.org/10.17576/jkukm-2024-36(1)-17
Ojelabi, R. A., Mohammed, T. A., & Oladiran, O. J. (2024). Awareness and Implementation Challenges of the Green Retrofitting in Building Enclosure in the Nigerian Construction Industry. *IOP Conference Series: Earth and Environmental Science*, *1342*(1). https://doi.org/10.1088/1755-1315/1342/1/012023
Saroji, G., Berawi, M. A., Satyagama, D., Sari, M., & Woodhead, R. (2023). Land readjustment model for transit-oriented development (tod) projects: Generating optimal financial benefits. *Civil Engineering Journal*, *9*(10), 2535-2553. http://dx.doi.org/10.28991/CEJ-2023-09-10-012
Tanoz-Sargeant, T. (2019). The assessment of transit oriented developments using microsimulation models. In *Transit Oriented Development and Sustainable Cities* (pp. 172-185). Edward Elgar Publishing. https://doi.org/10.4337/9781788971713.00020
Tetteh, M. O., Darko, A., Chan, A. P. C., Jafari, A., Brilakis, I., Chen, W., Nani, G., & Kwame Yevu, S. (2022). Scientometric mapping of global research on green retrofitting of existing buildings (GREB): Pathway towards a holistic GREB framework. In *Energy and Buildings* (Vol. 277). https://doi.org/10.1016/j.enbuild.2022.112532
Yang, Y., Sun, R., Dai, J., Zhu, M., & Yang, Y. (2023). Evolutionary analysis of stakeholder behavior in green retrofitting of traditional residential buildings based on dissemination and game models. *PLoS ONE*, *18*(3 March). https://doi.org/10.1371/journal.pone.0282314
Zhang, M. (2025). Next-Gen TOD: Transforming Transit Oriented Development to Embrace New Challenges and Opportunities. *Urban Rail Transit,* 1-14. https://doi.org/10.1007/s40864-025-00242-y