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System Dynamics Modeling for Time and Cost Control in Tukad Badung River Infrastructure

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ABSTRACT

Water infrastructure construction in dense urban environments like Tukad Badung, Denpasar, faces severe operational uncertainty due to weather anomalies. Nonlinear interactions between rainfall, machinery productivity, and labor performance frequently cause schedule delays and cost overruns. This study develops a system dynamics model for adaptive time and cost control in river flood infrastructure projects. Using an exploratory sequential mixed-method design, qualitative expert interviews were transformed into Causal Loop Diagrams (CLD) and quantitative Stock and Flow Diagrams (SFD). Model validation against historical progress data yielded a Mean Absolute Percentage Error (MAPE) of 4.85%, supported by dimensional consistency, extreme-condition, and behavior reproduction tests. Baseline simulations under projected 2026 rainfall indicated a 12-day project delay and a 5.2% cost variance. Policy scenario analysis revealed that the "Scheduled Working Hour Optimization" strategy performed best among tested options, achieving timely completion (SPI = 1.00) with a minimal cost variance of 2.1% (final CPI = 0.98). Conversely, reactive workforce addition caused severe cost overruns of 8.0% (final CPI = 0.92) due to site crowding. System dynamics modeling provides project managers with a robust, proactive framework to mitigate climate-induced operational risks in riverine construction environments.

Keywords: System Dynamics Modeling; Project Management; Flood Control; Time Performance; River Infrastructure

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1. INTRODUCTION

Rapid urbanization in Denpasar City has accelerated land-use conversion from permeable surfaces to built environments, directly increasing surface runoff and escalating the demand for macro-drainage infrastructure. Tukad Badung, as a central hydrological artery, plays a vital role in draining urban runoff and mitigating flood risk across Bali's primary commercial and administrative zone. Maintaining the capacity and structural integrity of Tukad Badung through flood control infrastructure requires continuous project execution despite severe hydrological constraints.

Executing construction projects in a riverine construction environment entails significantly higher operational complexity and risk than inland civil works. Direct exposure to erratic natural variables requires dynamic resource allocation to preserve structural stability [1]. The unpredictability of riverbank site conditions represents a major obstacle for construction management in meeting safety and technical performance standards.

Hydrological factors and weather anomalies in Denpasar are primary drivers of productivity loss in river infrastructure projects. Heavy rainfall rapidly elevates river discharge, endangering workforce safety and drastically curtailing heavy equipment operations [2]. These disruptions create cascading delays across supply chains and physical execution, making contract schedule compliance difficult under traditional static planning tools.

Conventional project control methods, such as the Critical Path Method (CPM) and S-Curves, rely on linear assumptions and fail to capture feedback mechanisms and dynamic time delays [3]. Accelerating a delayed project by adding unplanned overtime or extra labor often triggers secondary disruptions such as worker fatigue and physical crowding which reduce marginal productivity and amplify cost overruns.

To address these limitations, system dynamics modeling offers a holistic framework to simulate complex feedback interactions between weather variables, managerial interventions, and project performance over time [4]. System dynamics enables decision-makers to evaluate policy intervention scenarios virtually prior to field execution.

Recent studies highlight the necessity of adaptive scheduling in climate-vulnerable construction [5], [6]. While traditional Earned Value Management (EVM) measures past performance, it lacks forward-looking predictive capability for dynamic delays [7]. System dynamics applications in urban flood control demonstrate superior accuracy in modeling nonlinear field disruptions [8], [9]. This study fills this gap by integrating weather forecasting parameters into a system dynamics model tailored to river infrastructure control in Bali.

This study formulates two main objectives: (1) to evaluate the predictive accuracy of a system dynamics model in estimating time deviations and cost variances in the Tukad Badung river infrastructure project, and (2) to identify the best-performing managerial intervention scenario among tested strategies to mitigate weather-induced schedule delays under 2026 hydrological projections.

1.1 The Comprehensive Theoretical Basis

1.1.1 Construction Project Management and Earned Value Management

A construction project is a temporary effort constrained by scope, cost, and duration [10]. Project success depends on balancing the "Triple Constraint" (Scope, Time, and Cost) through effective resource management [1] [11].

Earned Value Management (EVM) integrates scope, schedule, and cost metrics to assess project performance [12]. Key indicators include the Schedule Performance Index (SPI) and Cost Performance Index (CPI):

$$SPI=\frac{EV}{PV} \quad (1)$$

$$CPI=\frac{EV}{AC} \quad (2)$$

Where EV is Earned Value, PV is Planned Value, and AC is Actual Cost. An SPI or CPI value equal to 1.0 represents performance on target, values >1.0 indicate favorable performance, and values <1.0 signify schedule delays or cost overruns [10].

1.1.2 System Dynamics Methodology

System dynamics (SD) is a rigorous simulation methodology for analyzing complex, feedback-driven systems over time [13], [14]. SD structures complex systems into feedback loops (reinforcing and balancing), stock variables (accumulations), flow variables (rates of change), and delays [15], [16].

In project management, system dynamics captures nonlinear behavior such as the "crowding effect" (declining labor productivity when worker density exceeds site capacity) and "workforce burnout" (productivity loss from sustained overtime) [19]. Modeling these feedback mechanisms enables explicit evaluation of how managerial decisions ripple through project time and cost outcomes.

1.1.3 Weather Impact on River Infrastructure

Precipitation represents a primary environmental risk factor in civil construction. High rainfall reduces labor efficiency and triggers safety protocols that halt heavy machinery operations [17]. Failing to model weather disruptions leads to dynamic schedule slippage and escalating site overhead costs [18].

1.1.4 Recent Applications of System Dynamics in Construction

System dynamics (SD) has gained traction for its ability to capture feedback loops, such as the 'crowding effect' when excessive labor is added to recover schedule delays [19]. Comprehensive reviews indicate that SD frameworks allow project managers to test various resource-allocation scenarios virtually before actual field implementation, effectively minimizing cost variances under extreme scenarios [20], [21].

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2. RESEARCH METHOD

2.1 Research Design

This study employs an exploratory sequential mixed-method research design [4]. The qualitative phase involved structured expert interviews with field managers and consultants to identify feedback structures and causal variables. In the quantitative phase, these insights were operationalized into Causal Loop Diagrams (CLD), transformed into Stock and Flow Diagrams (SFD), and simulated computationally using Stella Architect software.

2.2 Research Location and Context

The research site is the Tukad Badung Flood Control Infrastructure Project located in Denpasar City, Bali. The project scope encompasses riverbank revetment construction, channel dredging, and embankment reinforcement.

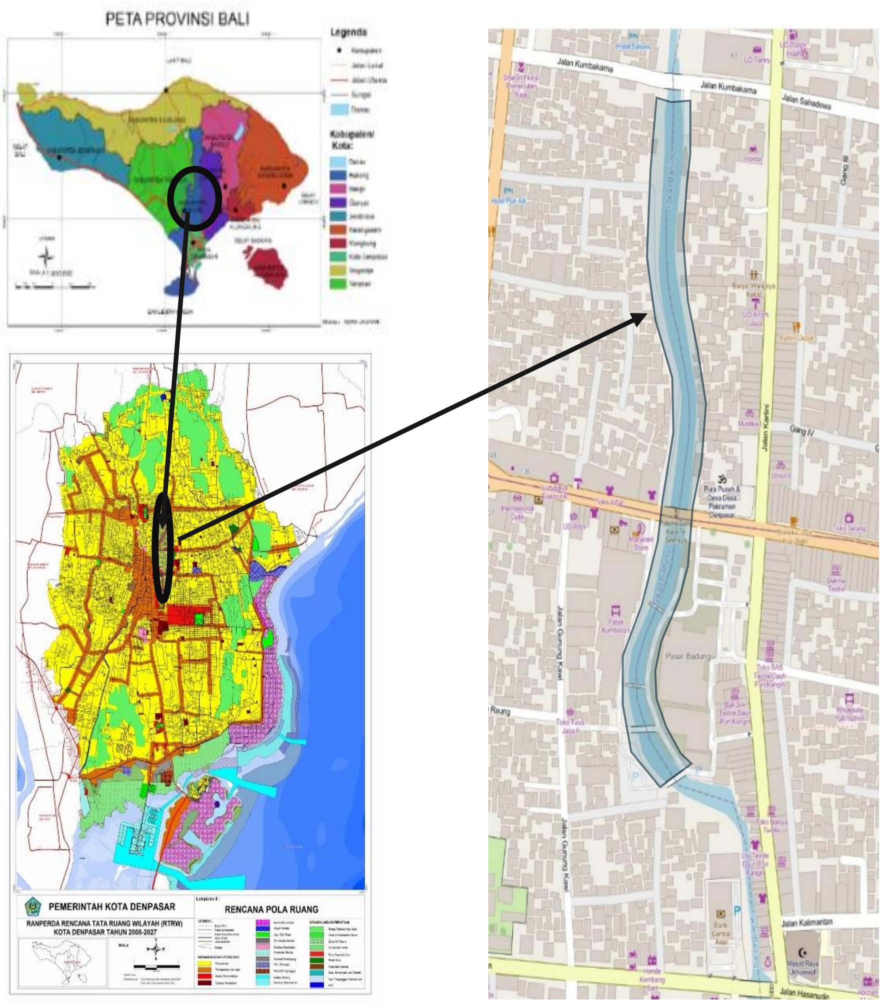

Figure 1. Research Location
Source: [22]

2.3 Data Collection and Baseline Parameters

Data collection incorporated primary and secondary sources:

1. Primary Data: Structured interviews with 8 key project personnel (site engineers, project managers, and supervisory consultants) to map causal relationships, crowding thresholds, and productivity loss factors [23].
2. Secondary Data: Approved Cost Budget Plans (RAB), master schedule S-Curves, weekly progress reports from the Bali-Penida River Basin Organization (BWS Bali-Penida), and 10-year historical rainfall data along with 2026 hydrological projections provided by the Meteorology, Climatology, and Geophysical Agency (BMKG Station Class I Ngurah Rai).

The baseline contract inputs for the reference project are detailed in Table 1.

Table 1. Baseline Project Input Parameters

Parameter	Value / Metric	Unit
Total Contract Value	Rp 12,500,000,000	IDR
Total Contract Duration	180	Days
Planned Daily Working Hours	8	Hours/Day
Baseline Workforce Size	50	Workers
Baseline Heavy Equipment Fleet	4 Excavators, 6 Dump Trucks	Units
Average Daily Overhead Cost	Rp 3,611,000	IDR/Day
Direct Daily Labor Wage Rate	Rp 175,000	IDR/Worker/Day
Normal Physical Progress Rate	0.556	% / Day

2.4 Model Formulation and Mathematical Equations

The conceptual CLD was converted into a Stock and Flow Diagram (SFD) governed by differential equations. The accumulated physical progress stock, $S_p(t)$, is defined as [24], [25]:

$$S_p(t)=S_p(t_0)+\int_{t_0}^{t} R_p(\tau)\, d\tau \qquad (3)$$

Where $R_p(t)$ is the daily physical progress rate (%/day), formulated as:

$$R_p(t)=R_{base}\times E_l(t)\times f(h) \qquad (4)$$

Where R_{base} is the planned progress rate, $E_l(t)$ is labor efficiency considering site crowding, and $f(h)$ is the continuous weather reduction function for daily rainfall h (mm/day):

$$f(h)=\begin{cases} 1.0, & h=0 \text{ mm/day} \\ 1.0-0.025h, & 0<h\leq 20 \text{ mm/day} \\ 0.0, & h>20 \text{ mm/day} \end{cases} \qquad (5)$$

The 20 mm/day threshold for total machinery stoppage ($f(h)=0$) reflects field safety regulations mandated by BWS Bali-Penida for in-stream excavator operations during high water levels.

Labor efficiency under crowding conditions, $E_l(t)$, is modeled as:

$$E_l(t)=\left(\frac{W(t)}{W_{base}}\right)^{-\alpha} \qquad (6)$$

Where $W(t)$ is active workforce, $W_{base}=50$, and $\alpha=0.35$ is the crowding sensitivity factor derived from empirical field observations in narrow riverbank work zones.

Accumulated Actual Cost, $AC(t)$, is calculated by integrating daily direct labor costs (C_{labor}), equipment costs (C_{equip}), material costs (C_{mat}), and overhead costs (C_{over}):

$$AC(t)=\int_{t_0}^{t}\left(C_{labor}(\tau)+C_{equip}(\tau)+C_{mat}(\tau)+C_{over}(\tau)\right) d\tau \qquad (7)$$

Overtime hourly wage multiplier is set at 1.5× base rate, and daily overhead continues until physical progress $S_p(t)$ reaches 100%.

2.5 Validation Methods

Model validation followed standard system dynamics testing procedures [14], [16]:

1. Structural and Dimensional Verification: Equation units and causal structures were audited for physical consistency.
2. Extreme-Condition Testing: Simulation behavior was evaluated under extreme inputs (e.g., zero workforce, extreme continuous rainfall of 100 mm/day).
3. Behavior Reproduction Test: Model outputs were compared against a historical dataset from the Tukad Badung Channel Normalization Phase 2 project (July–December 2023; 26 weekly progress observations). Data were split into a calibration set (weeks 1–16) and a validation set (weeks 17–26). Accuracy was evaluated using Mean Absolute Percentage Error (MAPE) [26]:

$$MAPE=\frac{1}{n}\sum_{t=1}^{n}\left|\frac{A_t-F_t}{A_t}\right|\times 100\% \qquad (8)$$

Where A_t is actual historical progress and F_t is simulated progress.

3. RESULTS AND DISCUSSION

3.1. Logic and Structure of the System Dynamics Model

The system dynamics model structure captures two primary feedback mechanisms:

1. Reinforcing Loop (R1 - Progress Acceleration): Increasing active workforce increases daily progress flow, accelerating physical progress accumulation. However, when labor density exceeds riverbank capacity, the crowding effect feedback reduces marginal productivity per worker.

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2. Balancing Loop (B1 - Weather Interruption): High rainfall reduces effective daily operating hours via f(h), decreasing daily progress rates and widening the schedule gap (SPI<1.00).

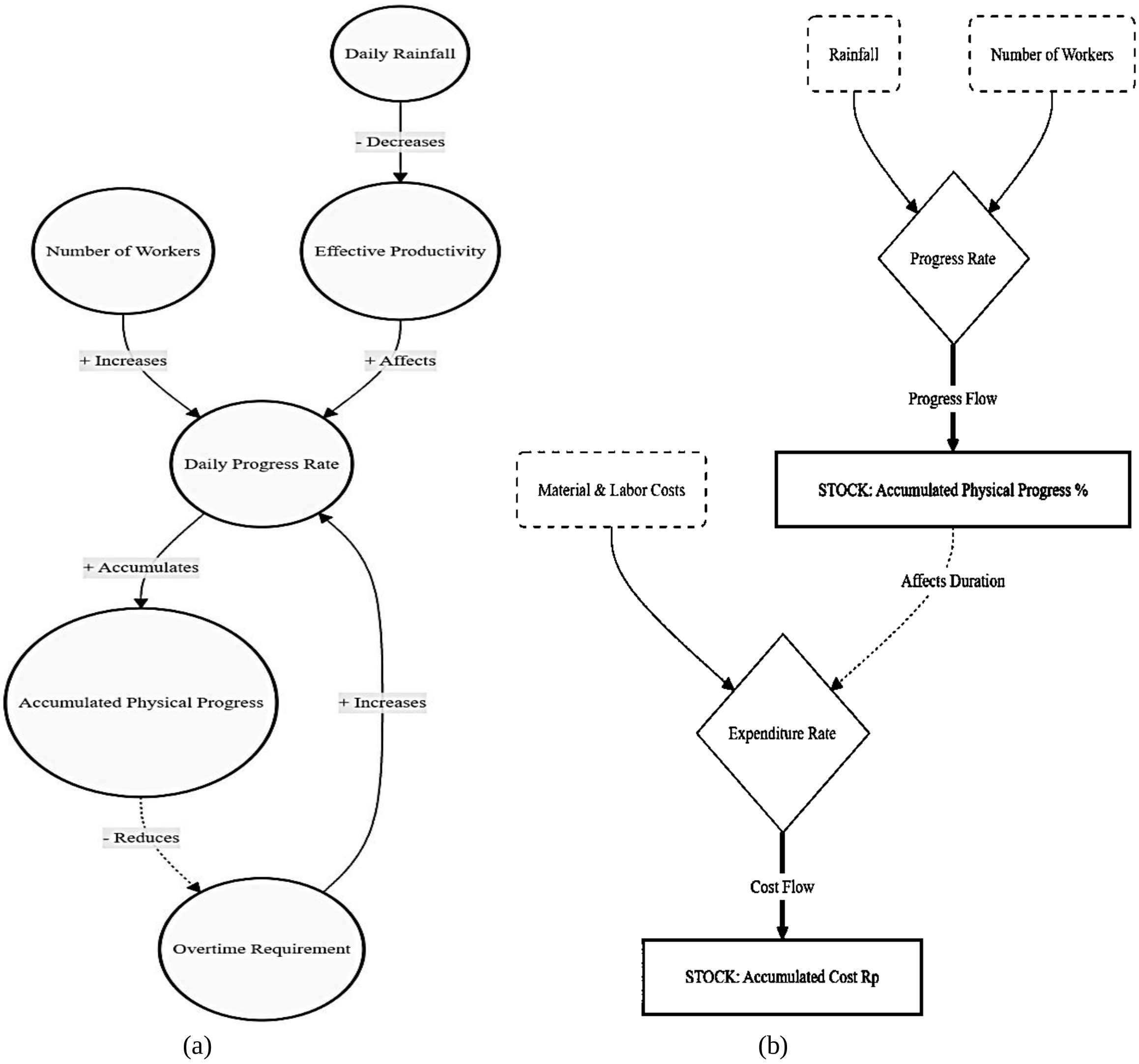


Figure 2. (a) Causal Loop Diagram (CLD) of Tukad Badung Project; (b) Stock and Flow Diagram (SFD) formulation

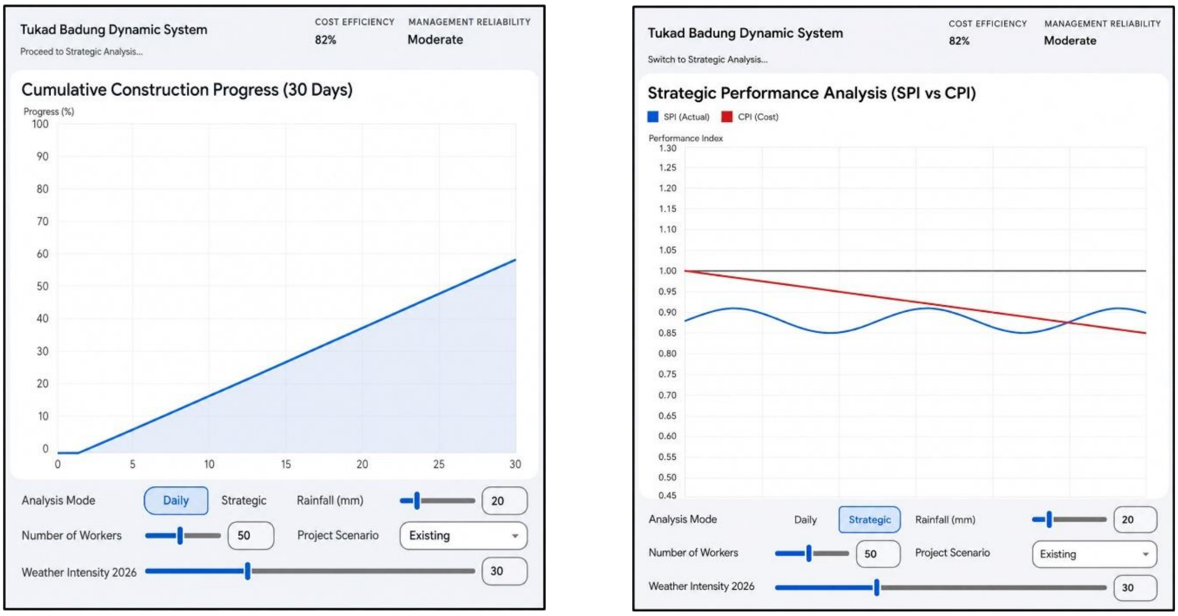
3.2. Model Validation Results

The model successfully passed structural and dimensional verification tests. Extreme-condition tests confirmed logical behavior: setting rainfall to 100 mm/day completely halted progress accumulation without mathematical divergence.

In the behavior reproduction test against the 2023 historical validation dataset, the simulated physical progress closely tracked actual field progress, yielding a MAPE of 4.85%. A MAPE below 10% confirms high predictive accuracy for dynamic simulation models.

3.3. Analysis of Baseline Existing Scenario (No Intervention)

The baseline simulation incorporated projected 2026 rainfall forecasts across the full 180-day contract duration. Figure 3 illustrates progress trajectories over a representative 30-day peak rainfall window during the construction horizon.



(a) (b)

Figure 3. (a) Progress accumulation over representative 30-day peak rainfall window; (b) Performance indices (SPI vs CPI) under Baseline Scenario

Without managerial intervention, rainfall disruptions reduced effective working hours significantly. Key baseline results across the 180-day project horizon include:

1. Time Performance: SPI dropped to a minimum of 0.82. The project experienced a cumulative delay of 12 days at contract end.
2. Cost Performance: Extended duration increased field overhead costs, resulting in a 5.2% cost variance above contract budget. CPI values were recorded as: Minimum CPI= 0.85, Average CPI = 0.91, and Final CPI = 0.95.

3.4. Policy Scenario Analysis

Two distinct policy intervention scenarios were simulated to mitigate the projected 12-day delay under 2026 weather conditions:

1. **Scenario 1: Workforce Addition (Reactive Strategy)**

   In response to delays, the workforce is increased by 20% (from 50 to 60 workers) during delayed periods.

   a. Time Impact: The additional labor successfully recovers lost time, restoring final SPI to 1.00 and achieving completion on target.

   b. Cost Impact: Physical space restrictions along the Tukad Badung riverbank trigger severe site crowding ($\alpha = 0.35$), reducing labor efficiency. Direct wage expenses surge without proportional progress gains. Cost variance reaches 8.0%. CPI metrics: Minimum CPI= 0.67, Average CPI = 0.78, and Final CPI = 0.92.

2. **Scenario 2: Scheduled Working Hour Optimization (Proactive Strategy)**

   Using short-term BMKG weather forecasts, working shifts are dynamically adjusted: regular hours are reduced during heavy rain days, and planned overtime (2–3 hours) is scheduled during predicted clear weather windows.

   a. Time Impact: Schedule gaps are offset during favorable weather, maintaining a stable SPI near 1.00 and completing the project on schedule.

   b. Cost Impact: Controlled overtime premiums are significantly lower than sustaining 10 extra daily worker wages. Prolonged overhead costs are avoided. Cost variance is minimized to 2.1%. CPI metrics: Minimum CPI = 0.94, Average CPI = 0.96, and Final CPI = 0.98.

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(a) (b)

Figure 4. (a) Performance indices for Scenario 1 (Workforce Addition); (b) Performance indices for Scenario 2 (Scheduled Working Hour Optimization)

A detailed comparison of simulation outputs across all scenarios is presented in Table 2.

Table 2. Simulation Performance Comparison Across Scenarios

Performance Metric	Baseline (Existing)	Scenario 1 (Workforce Addition)	Scenario 2 (Hour Optimization)
Managerial Approach	Static execution	Reactive 20% labor expansion	Weather-forecast adaptive shifts
Final Schedule Deviation	12 Days Late	0 Days (On Time)	0 Days (On Time)
Final Schedule Index (SPI)	0.82	1.00	1.00
Minimum Cost Index (CPImin)	0.85	0.67	0.94
Average Cost Index (CPIavg)	0.91	0.78	0.96
Final Cost Index (CPIfinal)	0.95	0.92	0.98
Total Cost Variance	+5.2% (Overhead)	+8.0% (Wage Overrun)	+2.1% (Controlled Overtime)

3.5 Synthesis and Discussion

The simulation results demonstrate that river infrastructure construction is highly sensitive to weather-induced productivity losses. Traditional reactive approaches, such as mass labor addition (Scenario 1), exacerbate cost overruns due to site crowding along narrow riverbanks.

Scenario 2 (Scheduled Working Hour Optimization) proved to be the best-performing option among the tested scenarios under the stated model assumptions. By dynamically aligning working hours with favorable weather forecasts, project managers preserve labor productivity and eliminate unnecessary overhead. These findings align with and extend prior work by Chen et al. [19] and Ballesteros et al. [20], confirming that predictive shift adjustment mitigates climate risks more cost-effectively than reactive labor inflation.

4. CONCLUSION

This study established a validated system dynamics model to simulate time and cost performance in the Tukad Badung river infrastructure project under rainfall uncertainty. The model achieved high empirical accuracy, recording a validation MAPE of 4.85% against historical project data.

Baseline simulations projected a 12-day completion delay and a 5.2% overhead cost variance under projected 2026 weather conditions. Among tested policy interventions, Scenario 2 (Scheduled Working Hour Optimization) was identified as the best-performing managerial strategy, maintaining timely completion (SPI = 1.00) while restricting cost variance to 2.1% (Final CPI = 0.98). In contrast, reactive labor additions caused severe cost escalation (8.0% overrun, Final CPI = 0.92) due to riverbank crowding effects. System dynamics modeling provides project managers with a practical, predictive tool for risk-informed scheduling in urban riverine environments.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

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