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Causal loop analysis for smart production precast: Balancing productivity and sustainability with digital technologies

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Abstract

Indonesia's precast concrete industry plays a crucial role in infrastructure development. National capacity reached 41 million tons in 2019 and stabilized at around 26 million tons annually in the post-pandemic period, while the Ministry of Public Works and Housing projects growing demand for precast to support National Strategic Projects (RPJMN), including the Indonesia New Capital City and major housing programs. This study uses causal loop analysis to examine interactions among six domains: technology adoption, productivity, cost, quality, human resources, and sustainability in smart precast production. Data were collected from three precast companies and interviews with 25 industry professionals. The causal loop diagram identifies two reinforcing and three balancing loops. BIM and IoT adoption increased productivity by 18% and profit margins by 12%, encouraging further digital investment. Digital Twin implementation reduced defect rates from 8% to 5%, improving client satisfaction and generating 10–15% demand growth. However, balancing loops emerge from high upfront investment (IDR 15–20 billion per plant), limited digital proficiency (40% of the workforce), and a 12% rise in energy-related carbon emissions. These results indicate key leverage points in phased adoption, workforce upskilling, and AI-enabled energy monitoring.

Keywords

Smart production precast, Causal loop analysis, Sustainable construction

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Introduction

Precast concrete industry in Indonesia

The precast concrete industry in Indonesia is vital for infrastructure. AP3I (2020) reported 41 million tons capacity in 2019, stabilizing at ~26 million tons post-pandemic, with 35% supporting NSPs under RPJMN 2020–2024 [1]. Precast systems offer efficiency, reliability, and sustainability; projects like Jabodebek LRT improved U-Shape beam productivity [2], and BIM enhanced seismic evaluation [3].

Innovations like RFID-IoT integration aid material tracking and automation [4], while sustainable solutions, including earthquake-resistant systems [5] and bamboo reinforcement [6], reduce environmental impact. Technical challenges persist, such as panel connection failures [7] and fabrication risks like machine defects [8], yet precast and prestressed systems remain advantageous over cast-in-place methods, especially for remote or rapid projects [5] [9].

Digital technologies for smart production

Digital transformation is reshaping construction through technologies such as Building Information Modeling (BIM), Digital Twin (DT), the Industrial Internet of Things (IIoT), Big Data, Artificial Intelligence (AI), and Geographic Information System (GIS) [10]. BIM serves as a core tool, improving facility coordination and enabling comprehensive lifecycle management, which helps reduce design errors and rework [11]. BIM facilitates virtual modeling and simulation, enhancing efficiency throughout design and construction stages [11]. It also supports collaboration and decision-making across multiple project phases [12], and its implementation in mid-sized engineering firms has been shown to reduce errors and improve overall productivity [13].

IoT plays a strategic role by connecting construction equipment and systems, allowing real-time data collection and predictive maintenance [14]. In addition, Big Data and AI process large volumes of information to support decision-making and risk management, enhancing construction efficiency and sustainability [15] [16]. AI-based tools can also forecast project outcomes and optimize resource allocation, enabling smarter and more sustainable construction practices [17] [18].

Digital Twin enables lifecycle monitoring and predictive control, reducing resource consumption and improving sustainability performance [12]. Frontiers in Built Environment (2022) demonstrated that industry 4.0-integrated DT supports real-time quality control in serial precast production [19] [20]. In precast projects, BIM with 3D printing has cut production time by 24–53% [21]. Challenges remain in data integration and implementation readiness [15].

Sustainability

Sustainability is central to modern construction. Material efficiency, energy reduction, and waste minimization are essential for aligning precast production with sustainable development goals [22].

Workforce readiness is equally critical. Nofianti and Sutopo (2025) identified limited digital skills as a major barrier in Indonesian firms [23]. Integrating sustainability into Human Resource Management (HRM) aligns recruitment, training, and performance evaluation with ESG principles [24]. Sustainability-oriented training improves awareness and practical capability [25] [26].

Organizational culture also influences environmental performance [27]. Aligning HRM strategies with SDGs requires capacity building and technical skill development [28].

Thus, digital transformation and sustainability depend not only on technology but also on human capital [29].

Despite advances in digital technologies and sustainability, the interactions among productivity, cost, quality, workforce readiness, and environmental impact in Indonesian precast production remain unclear, motivating this study's use of causal loop analysis to reveal systemic dynamics unique to smart precast production.

Methods

This study employed a system dynamics approach to analyze interdependencies among six key domains; productivity, cost efficiency, quality, sustainability, human resources, and digital technology adoption which selected based on literature review and industry relevance to capture critical factors in smart precast production.

Quantitative data were obtained from AP3I reports (2019–2023) and Ministry of Public Works and Housing projections indicating annual NSP demand of approximately 12 million m³ of precast components by 2025.

Qualitative data were collected through semi-structured interviews with 25 professionals from three precast companies and academia.

Variables were mapped into a Causal Loop Diagram (CLD) using Vensim PLE software to identify reinforcing and balancing feedback loops [30]. The model was validated through expert review and triangulation with empirical data and literature. Research method show in Figure 1.

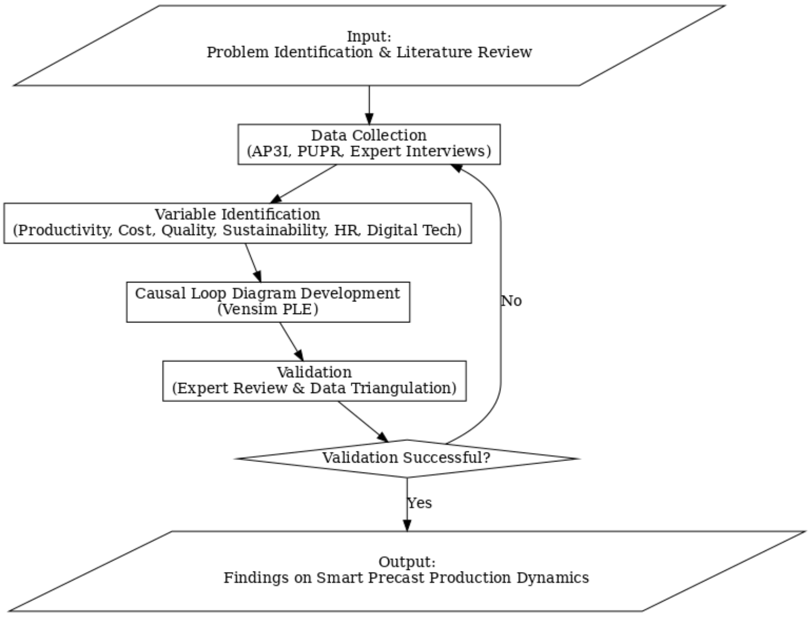

Figure 1. Research methods

Result

Data triangulation from company records, site observations, and 25 semi-structured interviews showed consistent interactions among technology adoption, productivity, cost, quality, human resources, and sustainability. BIM and IoT adoption increased production efficiency by 18%, reducing cycle time from 12.5 to 10.2 hours per precast element and raising profit margins by 12%, which supported further digital reinvestment. Managers noted that BIM improved coordination, reduced rework, and lowered overtime costs.

Digital Twin implementation reduced defect rates from 8% (2019–2020) to 5% (2022–2023), improving client satisfaction and contributing to 10–15% demand growth, particularly in government housing and IKN projects. A summary of these quantitative findings is presented in Table 1.

Tabel 1. Impact of digital technology on precast production performance

Variable	**Indicator/Metric**	**Baseline (Before Adoption)**	**After Adoption (2022–2023)**	**Change/ Impact**
Productivity	Output efficiency (m^3 per labor hour)	12.5 hrs per element	10.2 hrs per element	↑ 18% efficiency
Profitability	Average profit margin (%)	15%	27%	↑ 12 percentage points
Quality (Defect Rate)	% defective precast elements	8%	5%	↓ 3% defect rate
Client Demand	Annual demand growth (%)	–	+10% to +15%	↑ Increased order volume
Investment Cost	Upfront cost per plant (IDR)	–	15–20 billion	High barrier
Workforce Readiness	% digitally proficient employees	–	40%	Low adoption capacity
Carbon Emissions	Energy-related emissions (relative change)	100 (baseline index)	112 (index)	↑ 12% increase

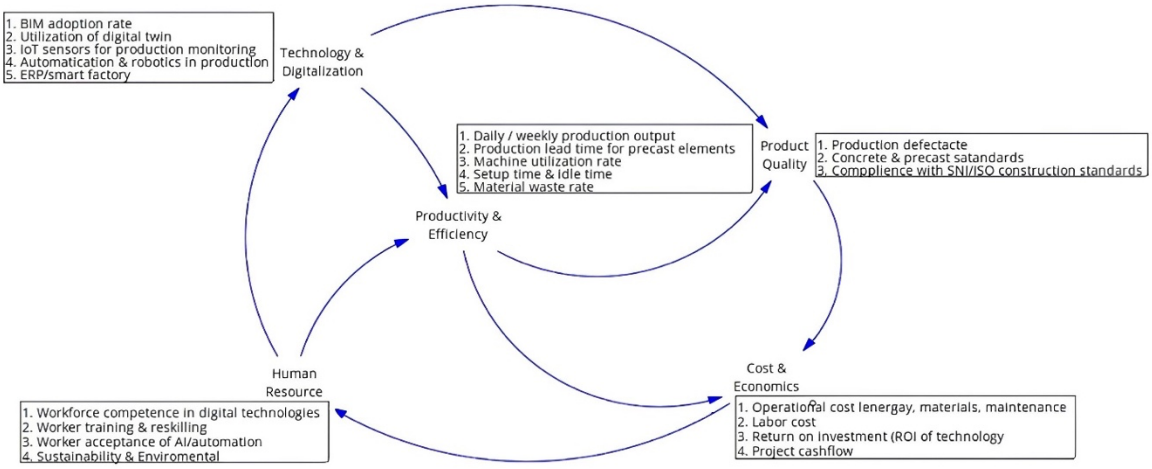

Figure 2. Causal loop diagram

However, several balancing factors emerged. High upfront investment (IDR 15–20 billion per plant) and long ROI periods (5–7 years) constrained adoption. Workforce readiness remained limited, with only 40% of operators digitally proficient, while sustainability analysis indicated a 12% increase in energy-related carbon emissions due to expanded automation and server loads. The systemic relationships among reinforcing and balancing feedback loops are illustrated in Figure 2, which presents the Causal Loop Diagram (CLD) of the model.

This model has several causal loops consisting of positive loops (reinforcing) and negative loops (balancing). Positive loops indicate a directly proportional relationship between variables, where an increase in one variable leads to an increase in the next. Conversely, negative loops indicate an inversely proportional relationship, where an increase in one variable reduces the value of another. The causal loop analysis in this study identifies five loops, the causal loops formed in the model (dynamic equations) include:

1. Technology Adoption, Equation(1)

$$\frac{dT}{dt} = \alpha_I \cdot \frac{I(t)}{I_0 + I(t)} \cdot HR(t) \; - \; \alpha_R \cdot R(t) \cdot T(t) \qquad (1)$$

2. Human Resource Readiness, Equation(2)

$$\frac{dHR}{dt} = \beta_T \cdot \frac{I(t)}{I_0 + I(t)} \cdot (1 - HR(t)) \; - \; \beta_L \cdot HR(t) \qquad (2)$$

3. Productivity, Equation(3)

$$\frac{dP}{dt} = \gamma_T \cdot T(t) \cdot HR(t) - \gamma_Q \cdot [1 - Q(t)] \cdot P(t) - \gamma_d \cdot P(t) \qquad (3)$$

4. Product Quality, Equation(4)

$$\frac{dQ}{dt} = \delta_{DT} \cdot T(t) - \delta_C \cdot \frac{C(t)}{C_0 + C(t)} \cdot Q(t) - \delta_d \cdot (1 - Q(t)) \qquad (4)$$

5. Sustainability Impact (emission load) , Equation(5)

$$\frac{dS}{dt} = \sigma_E \cdot E(t) - \sigma_M \cdot M(t) \qquad (5)$$

Variable Description:

$T(t)$ = *Technology & digitalization adoption level (BIM, IoT, DT, automation)*
$HR(t)$ = *Workforce competence and readiness (0–1 scale)*
$P(t)$ = *Production productivity/output*
$Q(t)$ = *Product quality (inverse defect rate, 0–1)*
$S(t)$ = *Sustainability impact (emissions/environmental burden)*
$I(t)$ = *Annual digital investment level*
$C(t)$ = *Operational production cost per unit*
$R(t)$ = *Perceived financial risk*
$E(t)$ = *Energy consumption*
$D(t)$ = *Market demand / order volume*
$\pi(t)$ = *Profit margin*

Discussion

Digital adoption creates reinforcing cycles between efficiency and profitability as well as quality and demand, leading to 18% higher productivity and 12% profit growth, while defect rates decrease through BIM, IoT, and Digital Twin technologies.

Structural constraints limit adoption because high capital requirements affect small- and medium-sized plants, and workforce readiness is critical since productivity gains may plateau without proper upskilling.

Environmental implications complicate digitalization as automation increased energy consumption by 12%, exemplifying the rebound effect (Jevons Paradox) as discussed in construction sustainability studies [16] [17] [31]. Without integrating renewable energy and AI-based optimization, smart production may increase carbon intensity. Digital transformation therefore requires coordinated attention to financial planning, workforce development, and sustainability management [32] [33].

Conclusion

This study indicates that digitalization in Indonesia's precast industry generates reinforcing benefits alongside balancing constraints. BIM, IoT, and Digital Twin adoption increased productivity by 18%, profit by 12%, and reduced defects by 3%, but these gains are limited by high upfront costs (IDR 15–20 billion), low workforce readiness (40% digitally proficient), and a 12% increase in carbon emissions.

Qualitative insights show adoption depends on culture, financing, and sustainability, with key leverage points being (1) phased investment, (2) workforce upskilling, and (3) smart production technology integration.

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