A System Dynamics Approach to Managing Material Cost Overruns in Industrial Building Projects

ABSTRACT

Material-related cost overruns are a significant challenge in industrial construction, arising from various dynamic and interdependent risks such as price instability, supply chain delays, and specification adjustments. Traditional risk assessment models often fall short in addressing the complex interactions between these risks, resulting in suboptimal risk management. This study utilizes a system dynamics approach to capture and analyze the feedback structures between critical risk factors that influence project costs. Nine essential risk drivers were identified through literature synthesis and expert insights. These drivers were incorporated into a dynamic, quantitative simulation model, structured into sub-models representing risks such as material price variability, distribution inefficiencies, and rework. The simulation demonstrates that applying targeted preventive and corrective actions effectively limits cost deviations and improves cost performance. Additionally, the model highlights how the interrelationship among various risks can intensify cost overruns if left unaddressed. The system dynamics model serves as a strategic decision-making tool, offering project stakeholders a comprehensive means to forecast and control cost deviations. Further research is recommended to integrate real-time project data and artificial intelligence to enhance the model's adaptability and extend its relevance across broader construction domains.

Keywords: System dynamics, cost overrun, construction risk management, material cost deviation, industrial building projects

INTRODUCTION

Organizations operating within the construction industry are invariably exposed to a wide spectrum of risks. Consequently, risk management plays a pivotal role in ensuring that both organizational and project-level objectives are achieved (Zhao, 2023). This becomes even more pressing given the growing uncertainty and complexity associated with future project demands (Nyqvist et al., 2023). The successful delivery of construction projects is contingent upon the effective and comprehensive management of this complexity (Yadav & Paul, 2023).

Risks are embedded in every phase of a construction project, from the initial conceptualization, through feasibility assessments and design development, to the actual execution. This omnipresent risk exposure often hinders projects from achieving their intended targets related to schedule, budget, and quality standards (Nazirzadeh et al., 2008). Put simply, unmanaged risks significantly impair the overall performance and success of construction projects (Wideman, 1992).

Among the most common consequences of unmanaged risks are cost deviations, which often escalate project expenditures beyond initial budgets. For example, Flyvbjerg et al. (2003) revealed that 86 percent of large-scale infrastructure projects globally experienced an average cost overrun of 28 percent. Supporting this trend, Love et al. (2011) identified that infrastructure projects in Australia typically encounter cost overruns averaging 13.55 percent. Similarly, Jackson (2002) found that more than half (55 percent) of construction projects in the United Kingdom exceeded their planned budgets, with overruns in some cases reaching 30 percent or more, and in extreme cases surpassing 100 percent.

Given the significant financial resources committed to construction activities, cost management emerges as a vital concern to mitigate the risk of financial failure (Dipohusodo, 1996). Contractors often seek to counterbalance this uncertainty by incorporating anticipated risk costs into their tender pricing as contingency reserves (Al Bahar, 1988). However, Hartman (2000) contends that such practices, when lacking scientific rigor, can paradoxically contribute to cost overruns instead of preventing them.

In reality, cost overruns in construction are frequently triggered by both unanticipated (unforeseen) and foreseeable (foreseen) events where uncertainty has not been sufficiently accounted for (Andi, 2004). This highlights the necessity for contractors to identify and manage the primary risk drivers that elevate project costs (Akinci & Fischer, 1998). According to Wideman (1992), effective risk management should integrate risk factors with potential impact scenarios, while addressing the cascading consequences of these impacts. Such an approach requires a systematic framework involving risk planning, identification, assessment, mitigation strategies, and continuous monitoring and control (Kerzner, 2002).

Scholarly evidence shows that the drivers of cost overruns differ across projects, depending on factors such as project typology, geographic context, and regional characteristics (Sharma & Goyal, 2014). This variability accounts for the inconsistency often found in cost overrun estimates. A key underlying issue is the absence of universally accepted standards or formalized cost estimation procedures (Boukendour, 2005).

In response to this challenge, the field has seen the development of various risk assessment methodologies aimed at supporting cost estimation processes. These include widely adopted techniques such as decision tree analysis, Monte Carlo Simulation (MCS), factor rating, regression models, fuzzy logic, the Delphi method, range estimating, and the Analytical Hierarchy Process (AHP) (Flanagan, 1993; Wideman, 1992; Wan & Liu, 2014).

Nevertheless, Wan (2014) notes that these traditional methods, being largely probabilistic and mathematical in nature, often fail to capture the dynamic and interactive nature of risks within construction environments. The intrinsic complexity of construction projects, characterized by interdependent processes and shifting variables, often exceeds the capabilities of static models to fully represent or quantify risk impacts. Moreover, such models tend to overlook indirect or second-order risk effects.

To address these shortcomings, Nasirzadeh et al. (2008) advocate for the application of system dynamics modeling, which is better suited to the inherently dynamic character of project risks. System dynamics models provide a holistic view by representing feedback loops, enabling project teams to simulate evolving project scenarios and their associated risks over the entire project life cycle.

Indeed, system dynamics frameworks have been extensively employed to examine interactions among risk variables and to model the cascading effects of risk factors in real-time project conditions (Xu & Zou, 2006). Over time, specialized system dynamics models have been developed to address diverse topics such as delays, procurement bottlenecks, adverse weather conditions, rework incidents, safety concerns, quality control, workforce availability, and outsourcing, or even combinations of these factors (Nasirzadeh et al., 2008).

While conventional risk assessment models tend to assume static and linear relationships, actual project environments are characterized by dynamic, interwoven risks that fluctuate over time. In this regard, system dynamics modeling more accurately mirrors real-world project dynamics and offers greater adaptability to changing conditions. This makes it a powerful tool for identifying the limitations of traditional mathematical approaches to risk assessment.

Given the ability of system dynamics to incorporate and simulate the behavior of linear models under dynamic conditions, there is growing interest in investigating the extent to which this approach can help reduce cost overruns in industrial construction projects.

LITERATURE REVIEW

A project is defined as a unique, temporary, and structured initiative that mobilizes multidisciplinary resources to achieve predefined deliverables within specified constraints and requirements (IPMA, 2023). Fundamentally, a project comprises a sequence of coordinated activities designed to achieve a specific objective that adds business value. These activities are characterized by distinct start and end dates, resource limitations (both financial and non-financial), and typically require contributions across multiple functional areas (Kerzner, 2017).

Within the construction industry, projects are generally categorized into three main sectors: building, infrastructure, and industrial construction. The building sector is further subdivided into residential (real estate) and non-residential (commercial) projects. Infrastructure projects encompass heavy civil or engineering works such as public utilities, highways, bridges, dams, railways, and water or waste-water systems. Meanwhile, the industrial sector focuses on specialized facilities including refineries, power plants, chemical processing plants, mills, and manufacturing facilities (Edison & Singla, 2020).

The combination and effective utilization of construction resources—namely labor, materials, equipment, and energy—are critical determinants of project performance. These factors collectively influence key project metrics such as time, cost, and energy efficiency (He & Li, 2021; Ghafoori & Abdallah, 2024; Rouhparvar et al., 2024). Consequently, resource planning and integration play an essential role in achieving project success.

Risk and opportunity management is a core component of project governance, encompassing risk identification, assessment, response formulation, implementation, and ongoing control throughout the project's life cycle (IPMA, 2017). This process enables project managers and stakeholders to make informed decisions, prioritize actions, and select between alternative strategies while balancing threats and opportunities.

Importantly, definitions of risk probability and impact are tailored to the specific context of each project, reflecting the organization's risk appetite and the tolerances of key stakeholders. Projects may adopt custom definitions or leverage standard frameworks provided by their parent organizations. The granularity of risk classification—ranging typically from three to five levels—depends on the complexity of the project and the detail required in the risk management process (PMI, 2017).

To systematically assess both positive (opportunities) and negative (threats) impacts, risks are often mapped onto a unified probability-impact matrix. This matrix may use qualitative descriptors (e.g., very high, high, medium, low, very low) or quantitative scales to rate risks. Numeric scales enable calculation of risk scores by multiplying probability and impact values, thereby facilitating prioritization of individual risks within their respective categories. An illustrative example of such a matrix is provided in Figure 1, which demonstrates a potential scoring methodology.

Probability	Threats					Opportunities					Probability
Very High 0.90	0.05	0.09	0.18	0.36	0.72	0.72	0.36	0.18	0.09	0.05	Very High 0.90
High 0.70	0.04	0.07	0.14	0.28	0.56	0.56	0.28	0.14	0.07	0.04	High 0.70
Medium 0.50	0.03	0.05	0.10	0.20	0.40	0.40	0.20	0.10	0.05	0.03	Medium 0.50
Low 0.30	0.02	0.03	0.06	0.12	0.24	0.24	0.12	0.06	0.03	0.02	Low 0.30
Very Low 0.10	0.01	0.01	0.02	0.04	0.08	0.08	0.04	0.02	0.01	0.01	Very Low 0.10
	Very Low 0.05	Low 0.10	Moderate 0.20	High 0.40	Very High 0.80	Very High 0.80	High 0.40	Moderate 0.20	Low 0.10	Very Low 0.05	
	Negative Impact					Positive Impact					

Figure 1. Probability and Impact Matrix with Scoring Scheme

In parallel, cost engineering provides essential support to project and portfolio management by applying scientific and analytical techniques across several domains, including business planning, profitability analysis, cost estimation, scheduling, risk management, and dispute resolution (AACE, 2024).

Within this context, contractors rely on cost control systems for several critical functions. First, these systems compare actual expenditures against budgeted costs, providing early warning of financial deviations. Second, they serve as repositories for productivity and cost performance data, which inform the estimation processes for future projects. Lastly, they support the accurate valuation of contract variations and claims related to additional payments (Potts & Ankrah, 2013).

Contractor success is intrinsically linked to innovation and continuous improvement, leading to projects that are more likely to be delivered on time, within budget, and to a higher standard of quality and safety. Projects driven by innovation also tend to exhibit fewer defects and workplace incidents (Langston, 2023).

Additionally, price forecasting mechanisms, when embedded into contracts or contract amendments, offer contractors and clients a valuable tool for adjusting prices in response to market fluctuations. Such mechanisms are particularly useful during phased construction projects where long durations may expose stakeholders to significant price variability (Lederer et al., 2024).

Despite the availability of sophisticated forecasting and risk management tools, cost overrun remains a pervasive issue in construction management. This challenge is largely attributed to limited data availability during project initiation phases and the high financial costs associated with correcting errors during execution. Globally, cost overruns continue to exert a detrimental impact on project outcomes, frequently leading to budget and schedule failures (Ghazal & Hammad, 2020).

The following, as in Table 1, is previous literature regarding the causes of cost overrun.

Table1 Causes of Cost Overrun

Author(s)	Country	Causes of *Cost Overrun*	Type of Project
Okpala and Aniekwu, (1988)	Nigeria	- Fluctuation in price material - Time delays - Fraudulent practices - Additional work - Shortening of contract period	Construction project
Elinwa and Buba (1994)	Nigeria	- Shortage of material - fluctuations in price material - Financing and payment of completed goods - Time delays - Additional work	Construction project
Kaming, et al. (1997)	Indonesia	- Inaccurate material takeoff - fluctuations in price material - Increase in Labour cost - Lack of experience of location - Lack of experience of project type	High-rise project
Frimpong, et al. (2003)	Ghana	- Monthly payment difficulties contract - Management - Material procurement - Inflation - Contractor's financial difficulties	Groundwater

(Koushki, 2005)	Kuwait	- Change orders - Financial Constraints - Owner's lack of Experience - Materials - Weather	Private residential projects
(Long et al, 2008)	Vietnam	- Poor site management and supervision - Poor project management assistance - Financial difficulties of owner - Financial difficulties of contractor - Design changes	Large Construction Projects
(Azhar et al, 2008)	Pakistan	- Fluctuations in price material - Unstable cost of manufactured material - High cost of machineries - Lowest bidding procurement - Method Poor project(site) management/poor cost control	Construction project
(Olawale, 2010)	U.K	- Design changes - Risk and uncertainty associated with projects - Inaccurate evaluation of project's time/OR duration - Non-performance of subcontractors and nominated suppliers - Complexity of works	Construction projects
(Memon, A.H,2011)	Malaysia	- Poor design and delay in design - Unrealistic contract duration and requirements imposed - Lack of experience - Late delivery of material and equipment - Relationship between management	
(Rahman, 2013)	Malaysia	- Fluctuations in price material - Cash flow and financial difficulties faced by contractors - Shortages of materials - Shortage of site workers - Financial difficulties of owner	Construction projects
(Aziz, 2013)	Egypt	- Lowest bidding procurement method - Additional work. - Bureaucracy in bidding/tendering Method - Wrong method of cost estimation - Funding problem	Waste water projects

System Dynamics, originally introduced by J.W. Forrester in 1961, is a methodology designed to describe, analyze, and forecast the behavior of real-world systems that are large-scale and complex in nature. This method offers a powerful framework for understanding the intricate dynamics within systems that exhibit interrelated components and feedback mechanisms.

The system dynamics approach is founded on a holistic perspective of projects, emphasizing the feedback loops that operate within the project environment. By focusing on these interactions, system dynamics provides a robust and structured means to model, trace, and analyze the complexity inherent in project systems. These systems typically encompass elements such as organizational structures, scopes of work, and the influence of external environmental factors (Sterman, 1992).

One such application of system dynamics within construction management is presented by Jang (2011), as seen in Figure 2, who developed a model identifying key causal factors contributing to cost overruns in construction projects. The model highlights several direct contributors to cost deviations, including project delays, fluctuations in interest rates, price escalation, rising insurance costs, and the adverse financial consequences stemming from liquidity shortages. These interdependencies are graphically represented in the following system dynamics model.

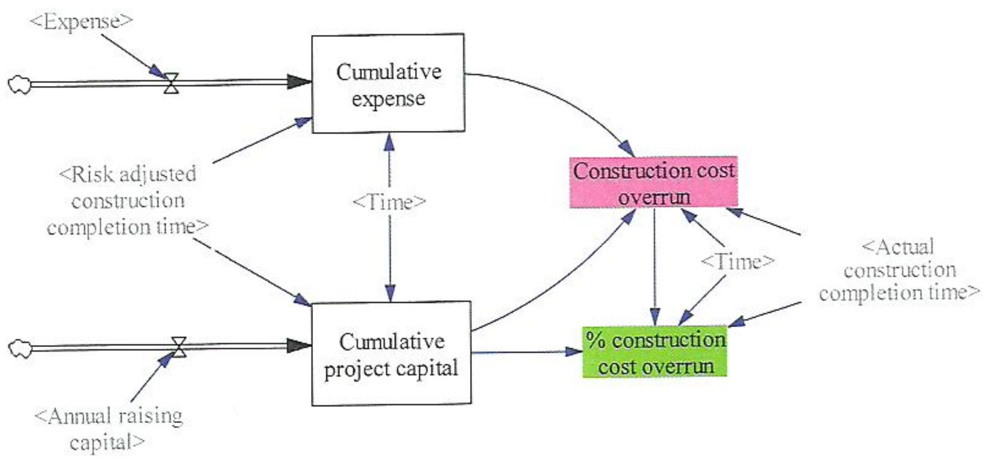


Figure 2 System Dynamics Model of Risk Impacts on Construction Cost Overruns, adapted from Jang (2011)

The following is as shown in Table 2, previous literature on the Application of System Dynamics in Research on Construction Project Management.

Tabel 2 the Application of System Dynamics in Research on Construction Project Management

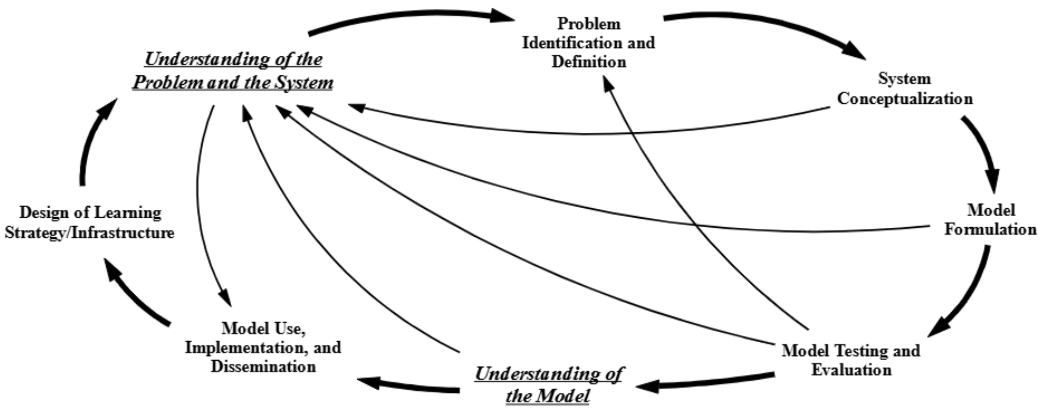
Author (s)	Year	Research Theme	Research Subjects	Project Type
Williams, TM, Eden C.L, Ackermann, F.R., and Tait, A	1995	The effects of design changes and delays on project costs	Design changes and delays	Major engineering project
Love, P.E.D. Holt, G.D. Shen, L.Y. Li, H. and Irani, Z.	2000	Using systems dynamics to better understand change and rework in construction project management systems	Change & rework	Constructio n project
Park, M.	2002	Dinamic change management for fast-tracking construction projects	Change management	Constructio n project
Howick, S.	2003	Disruption and delay in complex project for ligitation	Ligitation	Complex project
Ogunlana, S., Li, H., Sukhera, F.	2003	Performance enhancement in a construction organization	Enhancement organization	Constructio n project
Khamooshi, H.	2004	A dynamic and practical approach to project risk analysis and management	Dynamic & practical approach	Project
Minami, N.A. Madnick, S. and Rhodes, D.	2008	A system approach to risk management	Taskflow, financial impact, vechile safety	Engineerin g project
Nasirzadeh, F. Afshar, A. and Khanzadi, M.	2008	An approach for construction risk analysis	Time & cost quality based on fuzzy set	Project constructio n
Marco, A. D. and Rafele, C	2009	Using system dynamics to understand project performance	Montly revision, schedule pressure, productivity	Constructio n project
Hossen, F.A	2010	Project cost risk assessment : an application of project risk management process in Libyan construction projects	Delay	Constructio n project
Lisse, S.D.	2013	System dynamic applied to outsourcing engineering services in design build-Project	Outsourcing engineering services	Design build-Project

Abdi, S. M., Zahedi, M. and Makui, A.	2011	A System dynamic model for measuring the construction quality of buildings' structures	Quality	Building structure
Aiyetan, A. Smallwood, J. and Shakantu, W.	2011	A systems thinking approach to eliminate delays on building contruction projects in South Africa	Delay	Building constructio n project
Jang, S.G	2011	A concessionaire selection decision model development and application for PPP project procurement	Net present value (NPV)	Project procuremen t
Boateng, P. Chen, Z. and Ogunlana, S.	2012	A conceptual system dynamic model to describe the impacts of critical weather conditions in megaproject construction	Weather	Megaprojec t constructio n
Boateng, P. Chen, Z. Ogunlana, S. and Ikediashi, D.	2012	A system dynamic approach to risk description in megaprojects development	Social and environmental risk	Megaprojec t
Li, C., Lu, G. and Li. P.	2012	Risk element transmission model of construction project chain based on system dynamic	Risk elemen transmission model	Multi constructio n project
Nasirzadeh, F. Khanzadi, M. and Rezaie, M.	2013	System dynamic approach for quantitative risk allocation	Quatitiative risk allocation	Pipeline project
Aiyetan, O.A. and Das, D.	2014	Using system dynamics principles for conceptual modeling to resolve causes of rework in construction project	Rework	Constructio n project
Li, C., Liu, Y. and Li, S.	2015	A dynamic model of procurement risk element transmission in construction project	Procurement	Constructio n project
Li, C., Liu, Y. and Li, S.	2015	Human resources risk element transmission model of construction project based on system dynamic	Human resources	Constructio n project
Ogano, N. and Pretorius, L.	2015	Managing project risk in electricity industry in Africa	Rework and work force	Electricity industry

METHODOLOGY

As noted by Martinez-Moyano and Richardson (2013), the system dynamics (SD) modeling approach, as illustrated in Figure 3, is characterized by two fundamental attributes. First, the SD modeling process is inherently cyclical and iterative, emphasizing the continuous refinement of the model. Second, SD modeling explicitly incorporates the creation of a key deliverable that is integral to the overall process—this element is typically highlighted in the diagram (in Figure 3, it is marked in italics and underlined). This indicates that SD modeling fosters not only the development of the model itself but also a deeper comprehension of both the underlying problem and the system it represents.

In system dynamics research, the model serves as both a means and an end to achieving understanding. As Richardson and Pugh (1981, p. 16) aptly describe, "The model is an understanding until to the end, and ends on the understanding." Thus, every system dynamics modeling endeavor should be anchored in the pursuit of clarifying the dynamics of the problem and enhancing the understanding of the system's behavior.



Source: Martinez-Moyano and Richardson (2013)

Figure 3 Process of System Dynamics Modeling

This study investigates the underlying factors contributing to cost overruns in major construction projects, particularly within the industrial building sector, which includes facilities such as power plants, chemical refineries, and cement factories. It highlights global data showing significant cost deviations, including a 13.55% average overrun in Australia and frequent occurrences exceeding 30% in the UK. A central focus of the research is material-related risk, which is amplified by accessibility challenges—such as remote sourcing locations, poor transportation infrastructure, heavy traffic, and logistical issues. Given that materials represent 50% to 70% of overall project costs, these challenges play a critical role in driving budget overruns. The research process, including problem identification, risk classification, and modeling, is illustrated in Figure 4. Research Process.

To assess and manage these risks, the researchers used a structured questionnaire that evaluates each risk by its likelihood and impact, while also exploring appropriate response strategies. The findings informed the identification of dominant risk events, which were then classified into strategic approaches: risk retention, reduction, transfer, and avoidance. Based on these insights, a System Dynamics Model was developed to simulate the behavior of cost-related risks over time. The model was built on a set of assumptions, such as stable project timelines, consistent material demand, and fixed transportation modes. A dynamic hypothesis was also formulated: if material risks, driven by accessibility constraints, are not mitigated early, they will amplify cost deviations non-linearly throughout the project lifecycle. The model was validated using case studies, confirming its practical relevance in improving cost management strategies for industrial construction projects (Figure 4. Research Process).

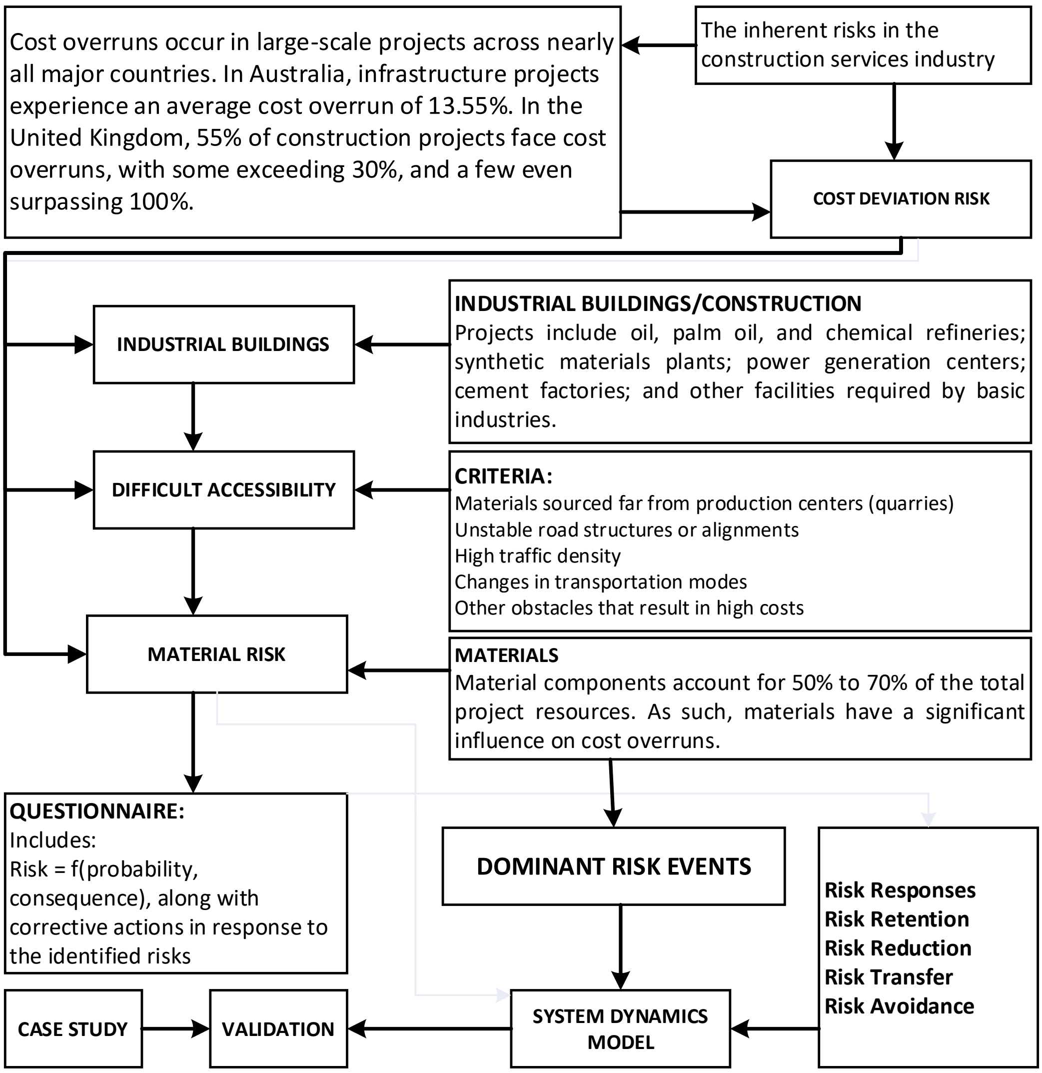


Figure 4. Research Process

RESULT AND DISCUSSION

Causal Loop Diagram

The structure of a system thinking model is typically presented in a graphical form, illustrating the feedback processes through a causal loop diagram. In this study, the system dynamics model has been developed based on a fundamental framework comprising four core variables, each of which contributes to the feedback mechanisms depicted in the causal loop diagram as shown in Figure 5.

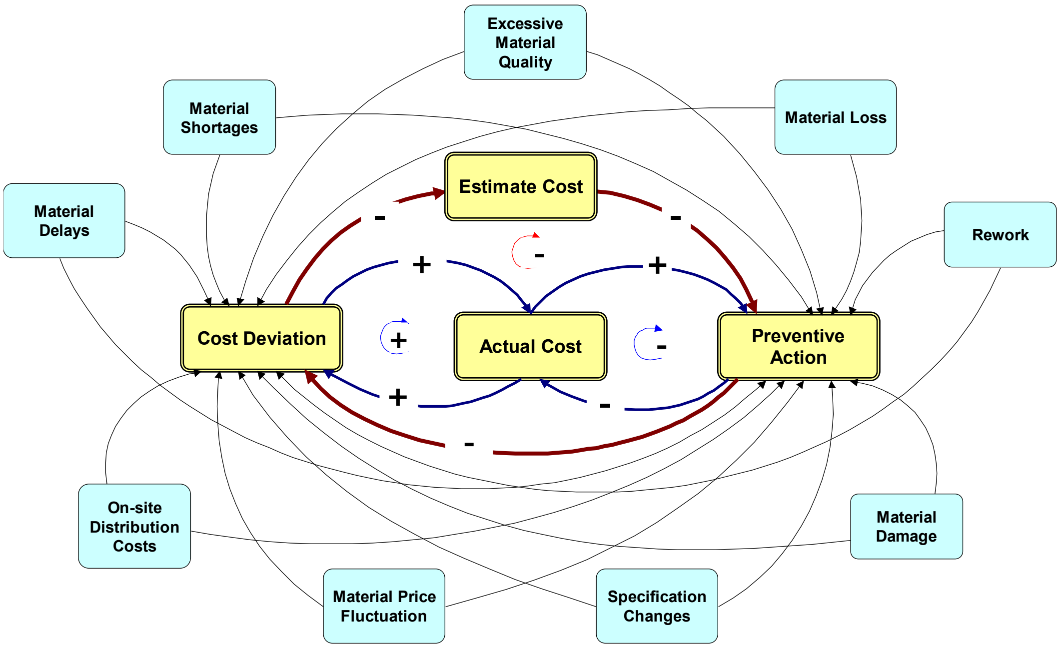


Figure 5 Causal Loop Diagram

The primary variables identified in this model are: estimated cost, cost overrun, preventive/mitigation actions, and actual cost. These cost overrun variables are influenced by nine distinct risk event variables. Initially, the literature review identified 13 potential risk events relevant to construction cost deviations. Through expert consultations, this number was refined to 10 key risk events. These variables collectively form the dynamic feedback system used to analyze project cost performance.

The estimated cost represents the projected budget prepared prior to the commencement of a construction project. This estimation serves as a benchmark for evaluating project financial performance. Once the project is underway, deviations from this estimate—caused by the occurrence of risk events—typically lead to cost overruns, thereby increasing the actual project cost.

This relationship can be expressed as follows:

Actual Cost = Estimated Cost + Cost Overrun **…..** *(Eq. 1)*

To mitigate or minimize cost overruns, preventive, corrective, and mitigation actions must be implemented to address risk events that lead to such deviations. The relationship between these actions and cost overruns is inverse: the higher the quality and effectiveness of preventive, corrective, and mitigation measures, the lower the cost overrun will be. Conversely, poor or ineffective implementation of these measures results in larger cost deviations. While the application of preventive, corrective, and mitigation strategies incurs additional expenses—thereby influencing actual project costs—these interventions are critical in reducing the extent of cost overruns.

This can also be expressed mathematically as:

Actual Cost = Estimated Cost + Cost of Preventive/Corrective/Mitigation Actions *(Eq. 2)*

Stock and Flow Diagram

Following the risk analysis process, the subsequent step involves identifying which specific risks require treatment. Risk treatment is then executed in accordance with the pre-established risk action plan. In this context, beyond procedural and qualitative risk handling, the approach emphasizes risk management that is grounded in the efficient and practical allocation of both financial resources and project assets.

Building upon the foundational structure of the project cost overrun risk model, as previously outlined, the study further advances this into a quantitative system dynamics model aimed at simulating cost overrun risks in construction projects. This model, developed based on the research stages carried out, incorporates nine distinct risk events, each represented as a sub-model. A stock and flow diagram was subsequently developed, as illustrated in Figure 6.

In the core system dynamics model, the costs associated with risk mitigation actions are distributed between the estimated and actual project costs. The construction cost overrun risk model consists of several sub-models, each representing a specific risk factor contributing to cost deviations. The structure of these sub-models is described as follows.

The outputs generated by each sub-model, which reflect the associated costs of risk mitigation actions, are then integrated into the core model. This combined structure provides a comprehensive depiction of the dynamic interaction between risk events and cost deviation management, as illustrated in Figure 7.

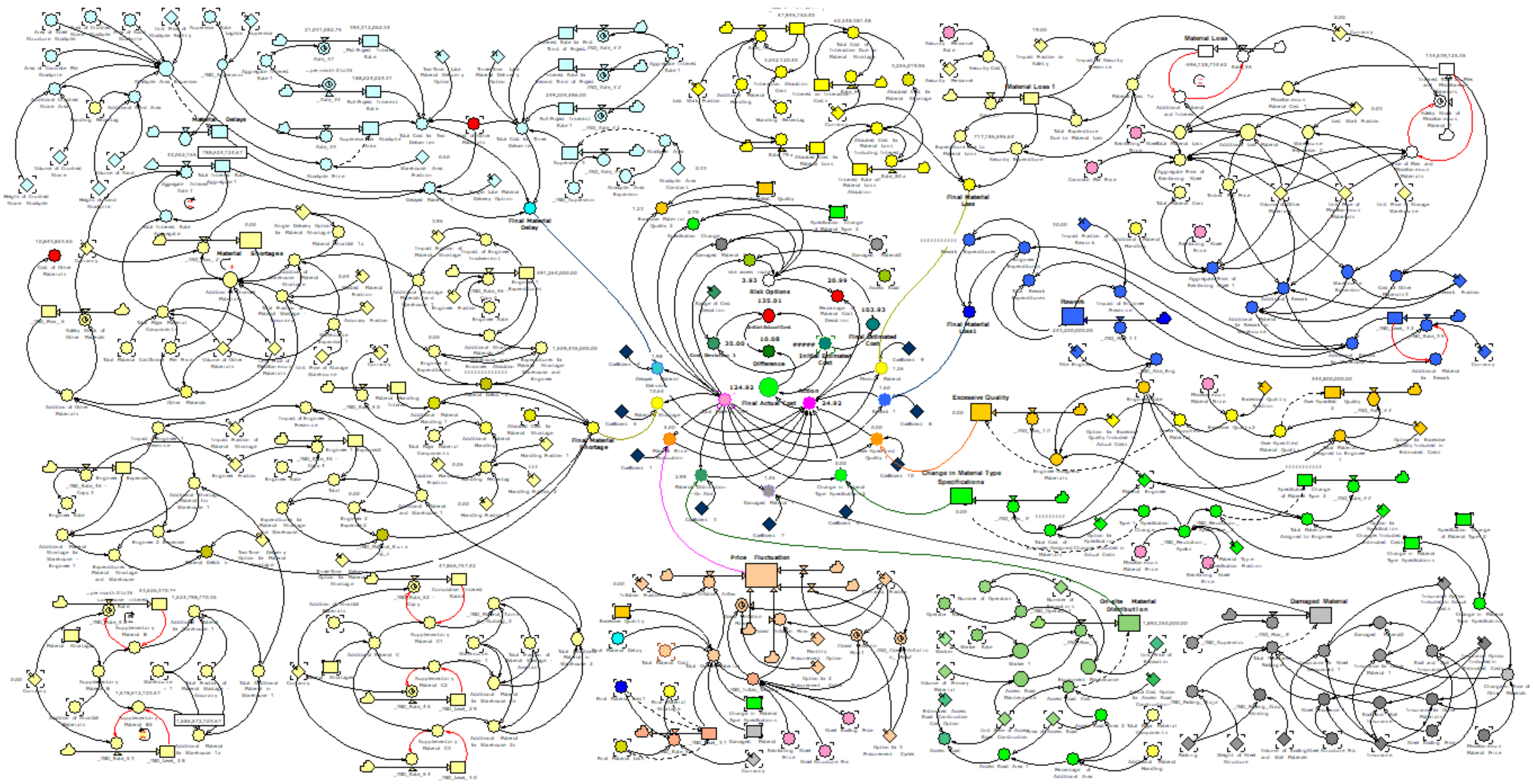
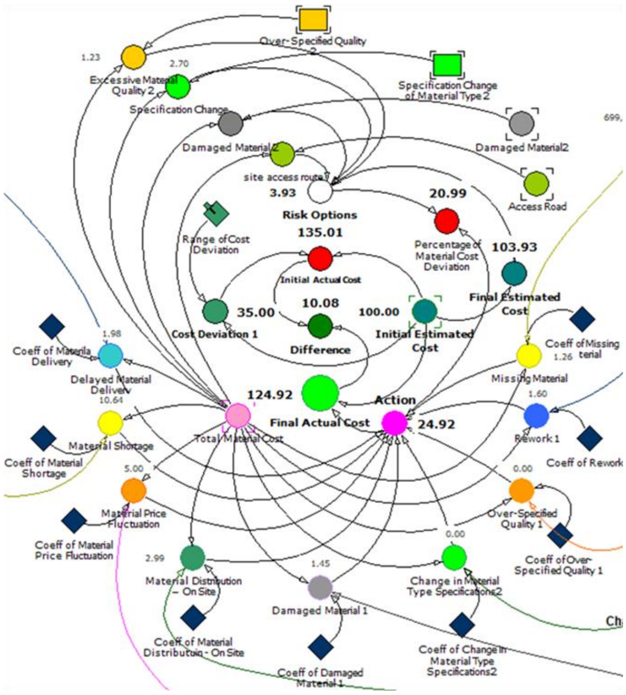
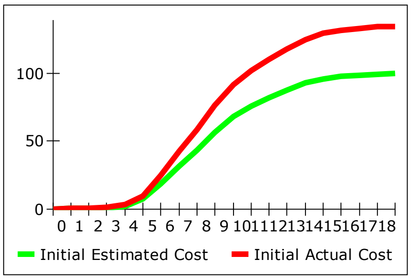


Figure 6 Stock and Flow Diagram of Material Cost Deviation for Industrial Building Construction Projects



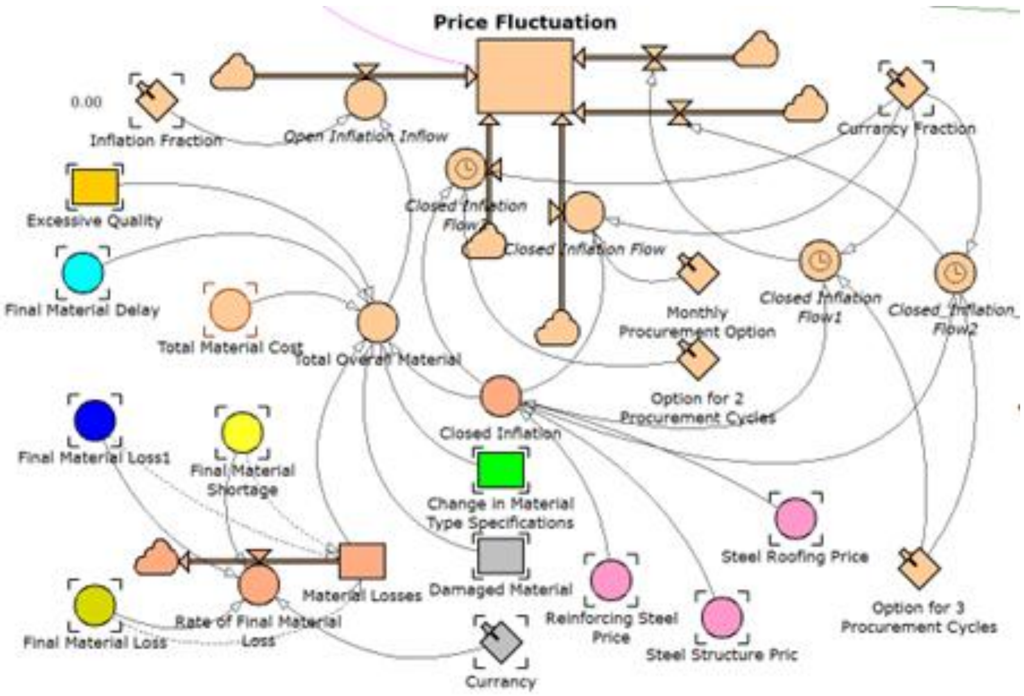


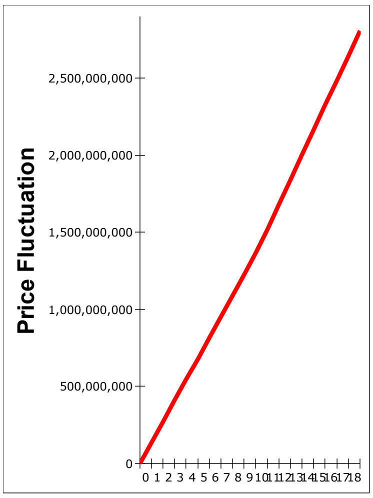
month 0 to 36	Initial Actual Cost	Initial Estimated Cost
0	0.00	0.00
1	0.10	0.08
2	0.31	0.23
3	0.90	0.66
4	2.78	2.06
5	9.57	7.09
6	24.66	18.27
7	42.67	31.61
8	58.80	43.55
9	76.52	56.68
10	91.86	68.05
11	102.52	75.94
12	110.84	82.10
13	118.62	87.86
14	125.57	93.02
15	129.97	96.27
16	132.13	97.87
17	133.51	98.90
18	134.68	99.76
19	135.01	100.00

Figure 7 Basic Model of Material Cost Deviation Risk for Industrial Building Construction Projects

Sub-model 1 of Material Price Fluctuation

The variable "Material Price Fluctuation" is influenced by factors such as inflation and exchange rate variability, both of which affect the total material costs. The proportion of inflation and exchange rate impacts is determined based on prevailing market conditions at the time of project execution. This sub-model is designed to anticipate risks related to material price volatility and is depicted in Figure 8.



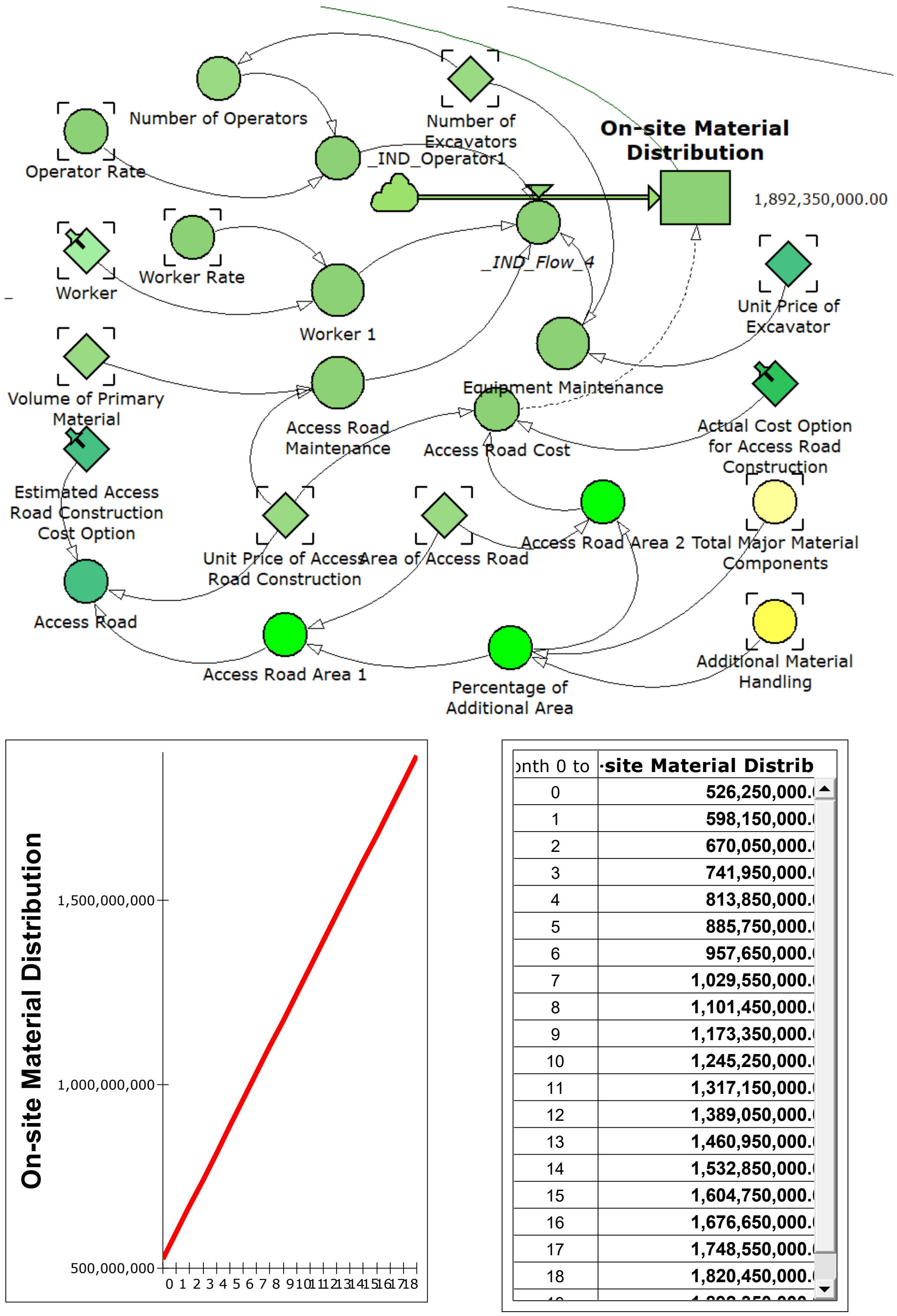


onth 0 to 3	Price Fluctuation
0	0.0
1	135,973,516.0
2	271,969,155.3
3	407,986,511.4
4	544,026,151.8
5	680,096,149.4
6	816,190,011.4
7	952,308,728.4
8	1,088,460,783.2
9	1,224,640,032.9
10	1,360,847,848.8
11	1,521,137,325.6
12	1,681,543,674.1
13	1,842,068,668.7
14	2,002,721,638.0
15	2,163,497,169.0
16	2,324,397,425.7
17	2,485,432,157.0
18	2,646,596,312.7

Figure 8 Sub Model of Price Fluctuation Variables.

Sub-model 2 of On-site Material Distribution Costs

The variable "On-site Material Distribution Costs" represents the cumulative costs associated with constructing and maintaining access roads within the project site. These costs include materials, equipment, and labor. Inadequate reinforcement or maintenance of these roads could disrupt the distribution of materials, potentially delaying project execution. This relationship is illustrated in Figure 9.

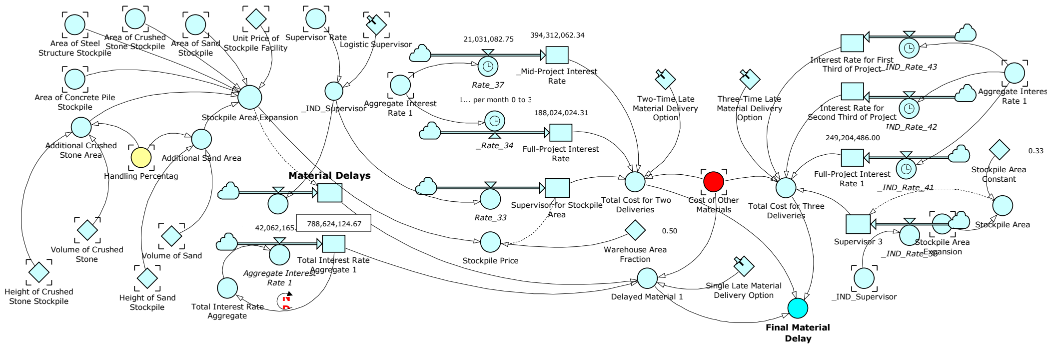


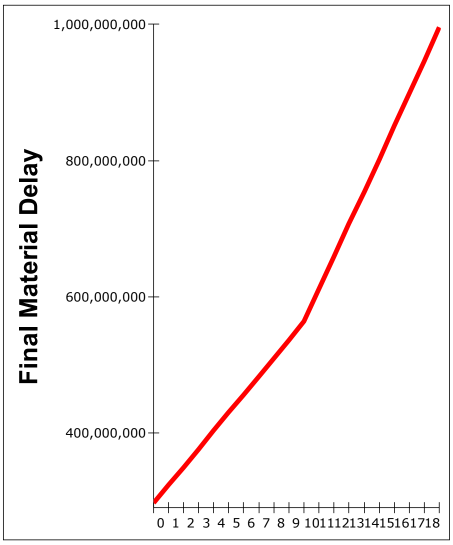
onth 0 to	-site Material Distrib
0	526,250,000.
1	598,150,000.
2	670,050,000.
3	741,950,000.
4	813,850,000.
5	885,750,000.
6	957,650,000.
7	1,029,550,000.
8	1,101,450,000.
9	1,173,350,000.
10	1,245,250,000.
11	1,317,150,000.
12	1,389,050,000.
13	1,460,950,000.
14	1,532,850,000.
15	1,604,750,000.
16	1,676,650,000.
17	1,748,550,000.
18	1,820,450,000.

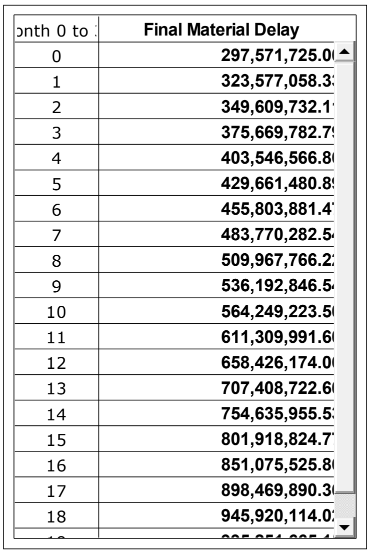
Figure 9 Material Distribution Variables on Site in Industrial Building Construction Projects

Sub-model 3 of Cost of Material Delays

The variable "Cost of Material Delays" can be mitigated by optimizing material procurement strategies, such as purchasing materials in bulk or in fewer batches. This approach helps reduce transportation frequency, particularly in projects with limited site accessibility, thereby ensuring material continuity. However, this also leads to increased stockpile requirements, higher interest rates, and additional logistical personnel. This sub-model also offers multiple procurement options (e.g., single, double, or triple batch purchases) depending on project-specific conditions, as shown in Figure 10.





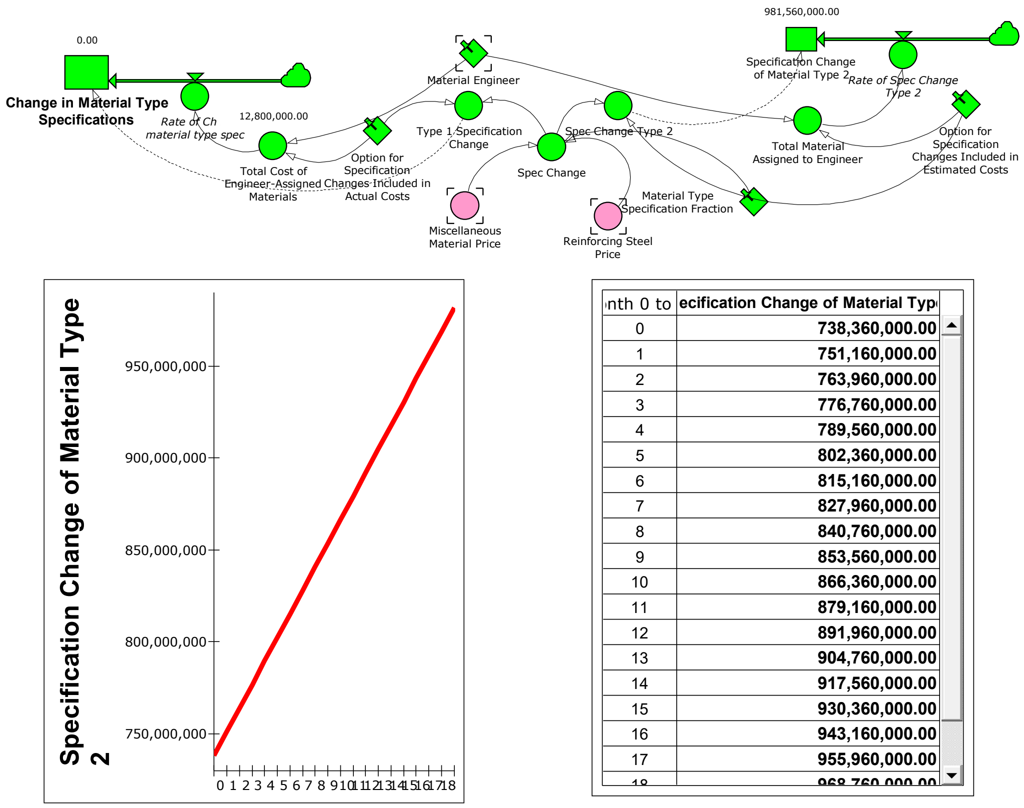


onth 0 to	Final Material Delay
0	297,571,725.0
1	323,577,058.3
2	349,609,732.1
3	375,669,782.7
4	403,546,566.8
5	429,661,480.8
6	455,803,881.4
7	483,770,282.5
8	509,967,766.2
9	536,192,846.5
10	564,249,223.5
11	611,309,991.6
12	658,426,174.0
13	707,408,722.6
14	754,635,955.5
15	801,918,824.7
16	851,075,525.8
17	898,469,890.3
18	945,920,114.0

Figure 10 Sub Model of Late Material Variables in Industrial Building Construction Projects

Sub-model 4 of Cost of Specification and Material Type Changes

The variable "Cost of Specification and Material Type Changes" is driven by the financial impact of such changes during the project lifecycle. Mitigating this risk requires expert supervision to ensure specification compliance. The sub-model provides flexibility in allocating these costs either to the actual or estimated project budget, depending on whether such changes are primarily attributed to the client or have been explicitly outlined in contractual agreements. This relationship is depicted in Figure 11.

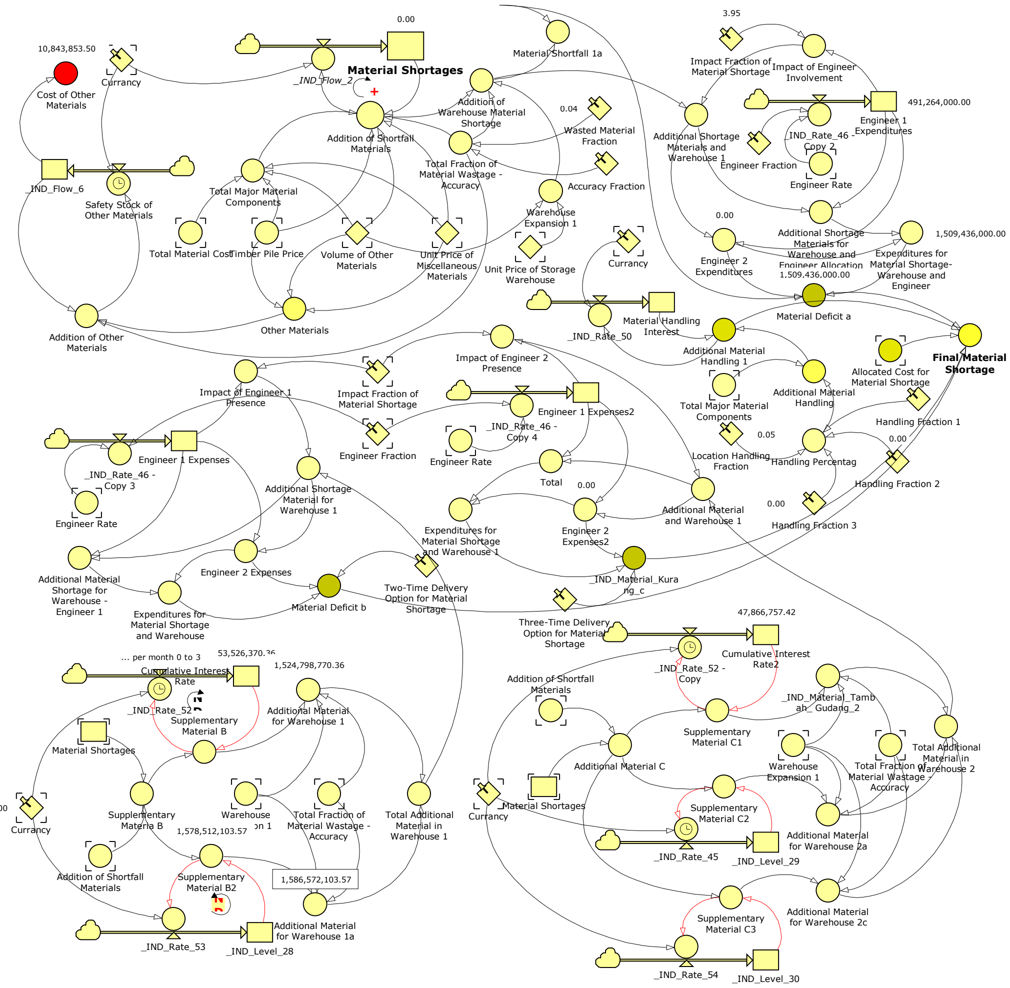


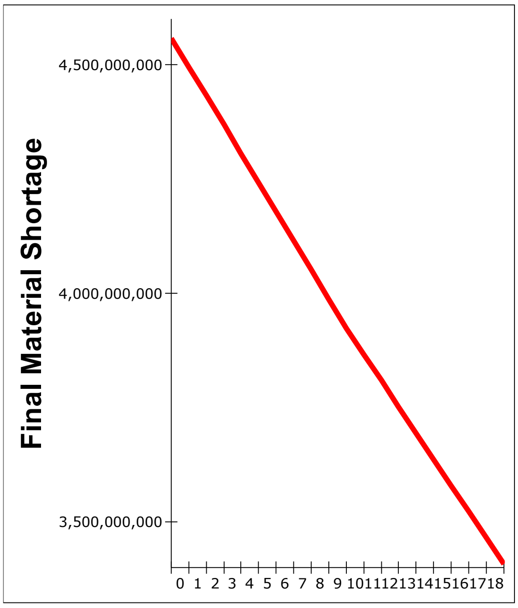
nth 0 to	ecification Change of Material Typ
0	738,360,000.00
1	751,160,000.00
2	763,960,000.00
3	776,760,000.00
4	789,560,000.00
5	802,360,000.00
6	815,160,000.00
7	827,960,000.00
8	840,760,000.00
9	853,560,000.00
10	866,360,000.00
11	879,160,000.00
12	891,960,000.00
13	904,760,000.00
14	917,560,000.00
15	930,360,000.00
16	943,160,000.00
17	955,960,000.00

Figure 11 Sub Model of Variable Changes in Specification and Material Type in Industrial Building Construction Projects

Sub-model 5 of Material Shortages

The variable "Material Shortages" is influenced by factors such as logistical challenges, inefficient material usage, and inaccurate quantity estimations. To reduce this risk, additional materials are procured, and expert personnel are deployed. These adjustments necessitate considerations for warehouse expansion and additional interest costs associated with the increased inventory. The sub-model offers three alternative procurement and delivery scenarios depending on project conditions and accounts for the role of experts in minimizing shortages. This sub-model is illustrated in Figure 12.



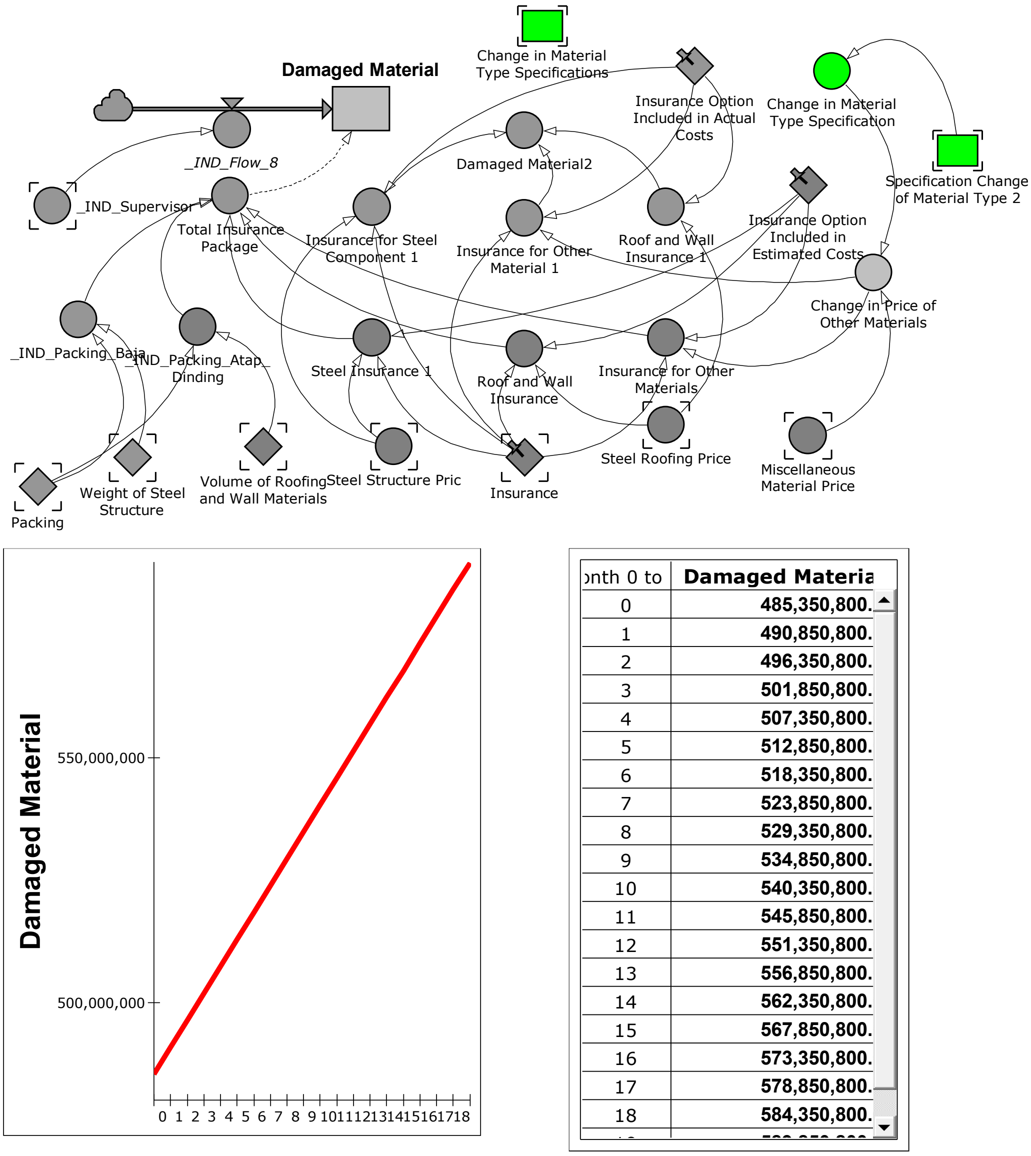


onth 0 to	Final Material Shortage
0	4,557,339,800.0
1	4,493,376,629.6
2	4,432,345,116.3
3	4,368,643,495.3
4	4,304,848,786.7
5	4,241,096,472.6
6	4,177,393,854.7
7	4,113,741,506.5
8	4,050,139,648.6
9	3,986,588,484.0
10	3,923,088,215.5
11	3,865,491,896.4
12	3,807,970,292.8
13	3,750,523,703.5
14	3,693,152,428.8
15	3,635,856,769.7
16	3,578,637,028.8
17	3,521,493,509.7
18	3,464,426,517.3

Figure 12 Sub Model of Material Shortage Variable in Industrial Building Construction Projects

Sub-model 6 of Material Damage Costs

The variable "Material Damage Costs" is mitigated by transferring risk through insurance coverage and ensuring that materials are adequately packaged and secured. Additionally, proper supervision of material handling activities, including loading and unloading, is critical. This sub-model also allows for flexible cost allocation between actual and estimated budgets, as shown in Figure 13.

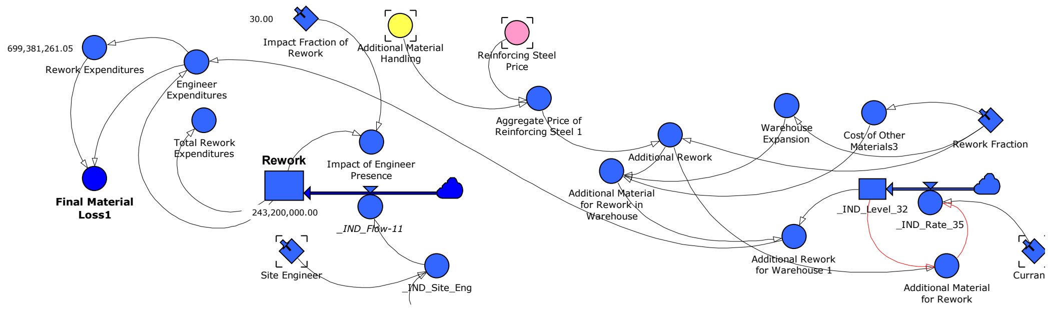


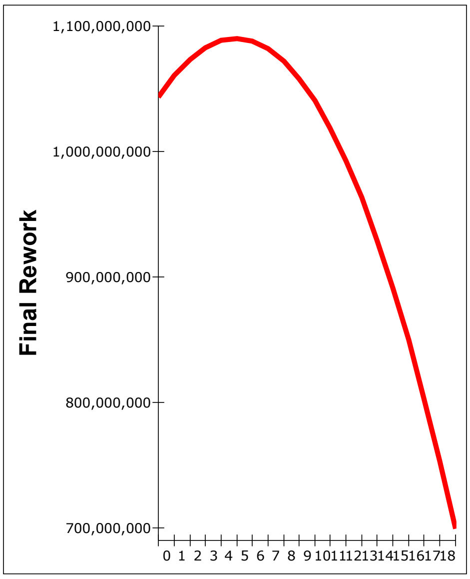
onth 0 to	Damaged Materia
0	485,350,800.
1	490,850,800.
2	496,350,800.
3	501,850,800.
4	507,350,800.
5	512,850,800.
6	518,350,800.
7	523,850,800.
8	529,350,800.
9	534,850,800.
10	540,350,800.
11	545,850,800.
12	551,350,800.
13	556,850,800.
14	562,350,800.
15	567,850,800.
16	573,350,800.
17	578,850,800.
18	584,350,800.

Figure 13 Sub Model of Material Damage Variables in Industrial Building Construction Projects

Sub-model 7 of Rework Costs

The variable "Rework Costs" is managed by procuring additional materials and hiring skilled workers and competent planners. These measures aim to reduce the likelihood of rework through improved planning and execution. This sub-model evaluates the positive impact of qualified personnel on minimizing rework and is represented in Figure 14.



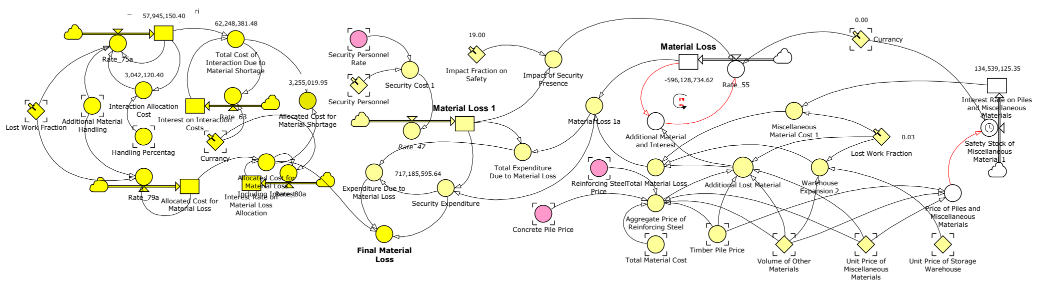


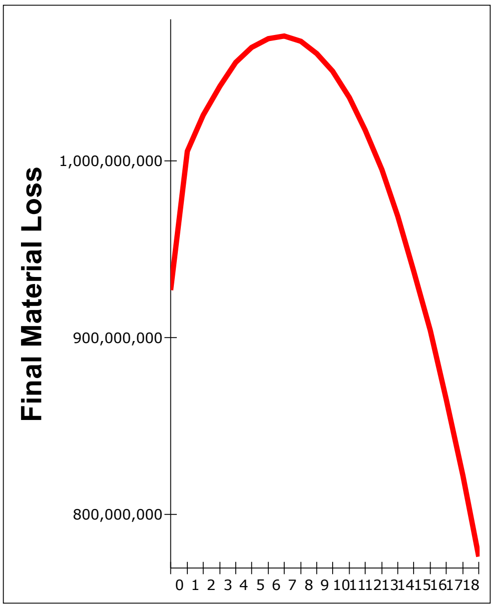
onth 0 to 3	Final Rework
0	1,043,169,875.0
1	1,060,102,554.5
2	1,073,211,764.7
3	1,082,482,211.7
4	1,088,453,540.6
5	1,090,000,334.7
6	1,087,662,116.1
7	1,081,980,564.5
8	1,071,825,637.9
9	1,057,738,891.6
10	1,040,264,047.2
11	1,018,266,416.7
12	992,289,595.7
13	962,879,354.0
14	928,896,338.0
15	890,886,190.0
16	849,396,734.7
17	803,283,932.5
18	753,095,479.1

Figure 14 Sub Model of Rework Variables in Industrial Building Construction Projects

Sub-model 8 of Material Loss Costs

The variable "Material Loss Costs" is reduced by assigning security personnel to protect inventory. This sub-model considers the relationship between material loss rates, warehouse expansion, and related interest costs. It also accounts for the potential increase in material losses as inventory levels rise due to stockpiling to mitigate shortages. This scenario is visualized in Figure 15.



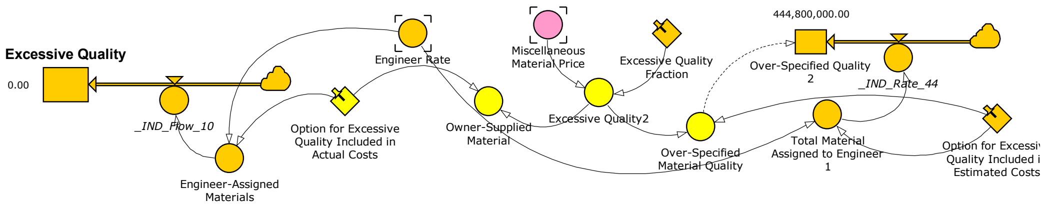


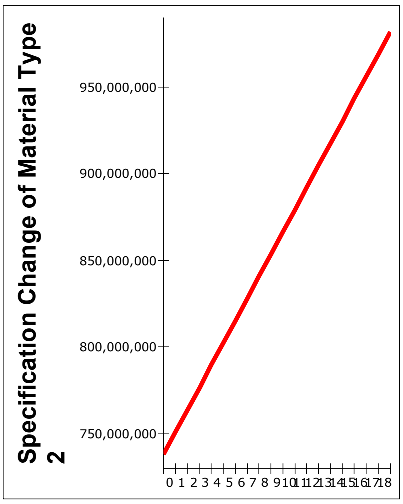
onth 0 to	Final Material Loss
0	926,840,000.0
1	1,005,495,990.0
2	1,025,664,173.9
3	1,042,013,630.6
4	1,055,283,885.1
5	1,063,950,001.5
6	1,068,751,382.3
7	1,070,430,387.8
8	1,067,455,858.9
9	1,060,570,031.8
10	1,050,518,112.0
11	1,035,762,690.5
12	1,017,048,847.4
13	995,124,642.8
14	968,446,391.9
15	937,762,028.0
16	903,822,476.2
17	865,077,748.8
18	822,278,642.6

Figure 15 Sub Model of Material Loss Variables in Industrial Building Construction Projects

Sub-model 9 of Excess Material Quality Costs

The variable "Excess Material Quality Costs" refers to expenses arising from purchasing materials of unnecessarily high specifications, often due to inaccurate specification interpretation or limited knowledge of material requirements. To address this issue, the deployment of expert personnel is essential. Similar to earlier sub-models, this framework offers flexibility in assigning these costs to either the actual or estimated project budgets, particularly in cases where responsibility lies with the client or where such costs are contractually defined. This sub-model is shown in Figure 16.





nth 0 to	ecification Change of Material Typ
2	763,960,000.00
3	776,760,000.00
4	789,560,000.00
5	802,360,000.00
6	815,160,000.00
7	827,960,000.00
8	840,760,000.00
9	853,560,000.00
10	866,360,000.00
11	879,160,000.00
12	891,960,000.00
13	904,760,000.00
14	917,560,000.00
15	930,360,000.00
16	943,160,000.00
17	955,960,000.00
18	968,760,000.00
19	981,560,000.00

Figure 16 Sub Model of Excessive Material Quality Variables in Industrial Building Construction Projects

Consolidated Simulation Results

The consolidated results of the system dynamics base model, which integrates outputs from all sub-model simulations, are presented in Figure 17 below.

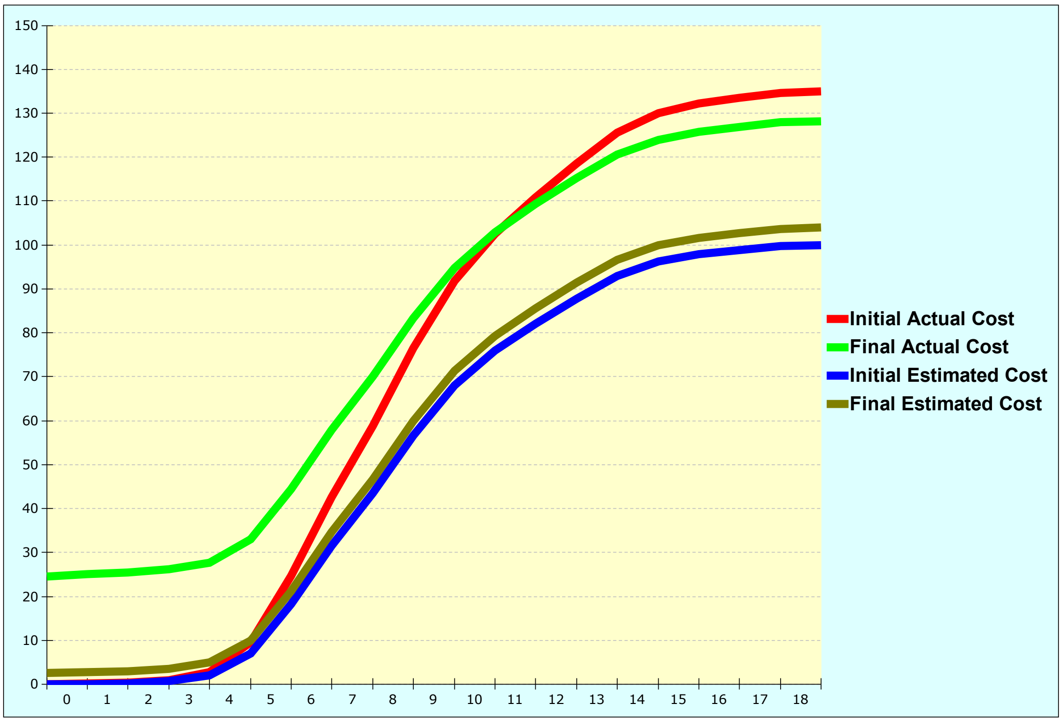


Figure 17 Overall Variable Simulation Graph

CONCLUSION

This research highlights the effectiveness of system dynamics modeling in addressing the persistent issue of material cost deviations in industrial construction projects. By integrating nine critical risk factors—such as material price volatility, distribution inefficiencies, and specification changes—into a dynamic feedback model, this study has illustrated the complex and interdependent nature of cost overrun mechanisms. The simulation results show that implementing preventive, corrective, and mitigation strategies significantly reduces actual project costs while balancing expenditure on risk management efforts. Furthermore, this approach offers a more nuanced understanding of cost overrun risks compared to conventional, static risk assessment methods. The developed model serves as a valuable decision-support tool for project managers and contractors, improving the accuracy of cost forecasting and enabling more effective risk control throughout the project lifecycle. Overall, this study underscores the relevance of system dynamics in modern construction risk management, particularly in industrial building projects where complexity and uncertainty are prevalent.

While this study provides critical insights, further research is recommended to enhance and expand the model's applicability. First, future studies could incorporate real-time project data and external macroeconomic factors, such as global commodity price trends and supply chain disruptions, to improve model precision. Additionally, integrating advanced technologies like artificial intelligence and machine learning could enable automated risk identification and dynamic model recalibration, fostering adaptive decision-making in volatile project environments. Expanding this model to cover other sectors, such as infrastructure or residential construction, would also provide comparative insights into sector-specific cost overrun dynamics. Finally, conducting empirical validation of this model across diverse case studies and regions could further strengthen its generalizability and practical utility for industry practitioners.

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