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Quantitative Impact of Delay Propagation in Interdependent Activities of Building Projects: A System Dynamics Approach

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Abstract- ***Complex projects operate in interdependent environments that create lengthy delays which spread throughout complete schedules. This research studies how delays in construction projects spread through project activities while highlighting how temporal task dependencies interact with increasing disruptions. The research employs System Dynamics (SD) modeling to represent delay propagation patterns through mathematical models and models nonlinear project behaviors with uncertainties. The historical development of delay analysis gets reviewed in depth through literature and researchers show why System Dynamics provides more value than existing theoretical approaches like CPM and DSM. The study evaluates the technical difficulties which exist when depicting interdependencies and handling uncertainties in addition to synchronizing SD with traditional project management platforms including MS Project and Primavera. Real-time monitoring integration with scenario simulation lets SD models actively work to prevent project delays. The study ends by suggesting what to do in future research which combines hybrid modeling techniques with artificial intelligence systems for project delay forecasting. The research outcomes serve as base knowledge for advancing time management approaches and choice-making procedures in construction projects.***

Indexed Terms- Delay propagation, System Dynamics, construction project management, interdependent activities, schedule delay, scenario analysis, uncertainty, hybrid modeling, real-time monitoring, AI integration.

I. INTRODUCTION

1.1 Overview of Delay Propagation in Interdependent Activities

Construction project delays originate from one particular job phase which extends to affect all subsequent dependent tasks throughout the project timeline. In the construction field it is frequent to encounter this dilemma because various tasks remain closely connected within a planned sequence. One delayed critical activity among procurement site preparation and foundation work will result in postponement of all associated tasks causing project cost and duration to escalate. Strategic issues create multiplying delays which prevent single-delay resolution while also affecting the complete project duration.

Structural projects feature complex systems because their numerous procedures require a consistent flow of operations that follows natural sequences. A network comprising finish-to-start and start-to-start and finish-to-finish relations operates as an easily disrupted structure that passes disturbances or changes in one node through to all components. Concrete curing delays cause two outcomes: both structural framing initiation and all subsequent works related to HVAC installation along with electrical activities simultaneously face postponement. These linked activities require complete progress of prior stages. The number of interlinked activities determines how easily delays spread across a project execution.

Several external elements increase the difficulty of scheduling construction activities including resource limitations together with the need to coordinate subcontractors and environmental conditions and regulatory clearance requirements. The factors create uncertain conditions which magnify the chance that delays will extend past their original location. Construction activities prove to be dynamic which makes it essential to develop analytical solutions that capture and handle feedback loops as well as sensitive time-dependent relations in project systems.

System Dynamics (SD) provides an effective method to analyze delay propagation patterns in such interdependent systems. The modeling approach based on systems thinking permits SD to support dynamic systems simulation through feedback mechanism analysis and accumulation calculations and delay modeling. Injection of System Dynamics into construction allows professionals to track resource restrictions and information flow and decision-making strategies which generate delays along with delay systemic spread across activity networks. The research of Das (2015) supports conceptual SD models because they enhance delay mechanism identification while testing systemic remedies against individual symptoms.

Wang and Yuan (2017) progressed this work by utilizing SD to determine how different risk elements affect project timelines in infrastructures. Project managers use SD to simulate different risk scenarios that affect project timelines because these findings enable predictive risk preparation. SD enables the simulation of delay ripples allowing managers to locate important critical nodes so they can pinpoint effective intervention points like resource shifting or schedule modifications to stop propagation.

SD modeling helps decision-makers during project planning and execution by creating a virtual testing space to evaluate various scheduling strategies as well as resource distribution strategies and backup plans. The ability to conduct scenario testing through SD establishes this approach as a crucial decision-support mechanism in complex construction conditions which experienced-based planning fails to identify systemic problems.

The performance of construction projects is substantially jeopardized by delay propagation effects that stem from processes linked by dependencies as well as external unpredictable elements. The systematic modeling approach of System Dynamics creates comprehensive analysis of these relationships to generate understanding needed for better project delay reduction methods. SD enables project managers to anticipate and understand construction system dynamics that cause delay propagation by simulating project interactions thereby enhancing project delivery resilience.

1.2 Importance of Studying Delay Propagation in Construction Projects

Project management and control require the study of delay propagation because construction projects advance in complexity and scale and networking between activities. The current construction sector uses many complex activities that need tight discipline-level coordination between trades while managing multiple project stages. Under these circumstances delays within one activity which may include permitting or material acquisition or subcontractor preparation will propagate through multiple subsequent processes. Delay propagation accelerates small problems into large-scale disruptions which threatens the complete project schedule and financial plan.

Delay propagation research gains its value from the cumulative effects the delays generate. When delays occur they create successive impacts which spread across all project scheduling elements. According to Soliman (2005) the Delay Hierarchy Propagation Model demonstrates that delay from the main source generates multiple levels of secondary and tertiary delays that create different time and cost changes. Delays in foundational work create effects that spread across multiple tasks and may lead to resource unutilization with accompanying higher costs as well as contractual penalties because of delayed milestone achievements.

The financial expenses that arise from delay propagation exceed the direct expense of the original disruption event. Welman, Williams and Hechtman (2010) evaluated this phenomenon by introducing delay propagation multipliers to determine the scope of single delay expansion. Delay propagation analysis needs to become integral within cost-benefit evaluations and contingency preparations due to new information from their study. Project managers who do not understand delay propagation risks end up underestimating the complete expenses and potential dangers that arise from limited schedule variations.

Delay propagation studies help identify the most vulnerable path sequences in projects and their points prone to timing sensitivities. Delays have their highest potential to spread across projects in these particular areas that exhibit insufficient time buffers. Project planners can effectively apply specific risk management strategies to high-risk zones through identification of these areas in order to control delay propagation.

Having command of delay propagation methods becomes essential during today's construction speed because contractors need it to meet deadline requirements while managing restricted budgets and performance-oriented contracts. Project stakeholders can move from handling issues after they occur to actively controlling risks and strengthen project resilience because of this understanding.

1.3 Objectives and Scope of the Study

The main goal of this research is to understand delay propagation patterns through interdependent construction activities using the System Dynamics approach for modeling. The research examines delay propagation through linked project schedules by analyzing initial interruption spread to gain deeper understanding about construction systems under delay conditions. The study seeks to answer key research questions: (1) What are the main drivers of delay propagation in construction projects? (2) How do interdependencies between activities influence the scale and severity of propagated delays? (3) How can System Dynamics modeling be applied to simulate and mitigate these effects?

The study investigates medium to large-scale building construction projects that include all types of residential, commercial and institutional developments which demonstrate high task interdependency needs. The study focuses on modeling time delays that occur during construction implementation period instead of pre-construction or post-construction procedures.

The study has two limitations: (1) it uses a conceptual modeling structure instead of empirical approaches and (2) it creates simulated scenarios through literature review and project case assumptions instead of actual project information. Traditional tools remain better suited to produce precise level scheduling details at the task level because the SD method provides limited specific information.

1.4 Significance of the Study

The research carries great importance because it attempts to resolve an essential long-standing problem in construction which affects project performance outcomes through delay propagation. Advanced construction techniques require better management of sequential delays because modern projects feature both complex networking between tasks and shortened deadlines. Standard project management solutions lack the ability to handle feedback-based delay dynamics which results in reacting with fragmented approaches for delay mitigation.

The implementation of System Dynamics for modeling delay propagation completes significant gaps within both academic books and practical industry knowledge. Previous studies investigated single delay causes yet few works have developed an integrated model demonstrating how delay elements communicate and intensify during project duration. The developed understandings can direct project managers and planners and policymakers toward constructing better scheduling techniques while performing superior risk evaluation to boost project reliability in the present high-stakes construction realm.

II. LITERATURE REVIEW

2.1 Historical Development of Delay Analysis in Construction

Modern construction delays face substantial transformation because of escalating project complexity together with escalating project scales along with evolving modern contractual requirements. At the beginning of project management practice delay analysis was primarily anecdotal while being unmethodical through subjective interpretations of project records and stakeholder testimonies. The initial procedures in delay analysis provided limited standardization and produced weak evidential value which was significant in legal disputes and claims response. The growing number of disputes and legal actions against construction projects proved the necessity to develop systematic methods for delay investigations and dispute resolution.

Early in the 1950s through 1960s the Critical Path Method (CPM) brought delay analysis to a more technical level. CPM helped planners see the order of project tasks while allowing them to find important paths which directly affected when the overall work would finish. The industry adopted two fundamental CPM-based delay analysis methods called "as-planned versus as-built" and "time impact analysis" (TIA). Such methods facilitated objective evaluation between original planning timelines and project implementation phases to determine delay lengths and identify responsible factors. The analytical approaches relied on linear task duration assumptions together with a limited understanding of feedback loops which impacted non-critical path activities.

The research by Braimah (2013) reviewed construction delay analysis approaches to recognize their technical advancement as well as ongoing performance limitations. The delay quantification techniques including "window analysis" and "collapsed as-built" became more precise but failed to sufficiently replicate the nonlinear and dynamic aspects of delay propagation. The combination of doubtful logic pathways and stringent schedule dependency and poor reaction to concurrent activity dependencies undermined the capabilities of these approaches in sophisticated projects. These methods provided little proactive risk mitigation support because they were typically used in a retrospective manner.

Researchers and practitioners started to promote careful planning coupled with preconstruction programming when managing project delays since existing approaches proved ineffective. Braimah (2014) explained that well-developed scheduling during preconstruction holds strategic value because identifying essential relationships and possible roadblocks helps minimize execution delays and their severity. Preventive delay management replaced outdated reactive methods which established the necessary basis for implementing detailed modeling approaches.

The traditional CPM-based tools fell short when project environments started using just-in-time delivery and concurrent task execution while working with multiple subcontractors because they failed to track the wide-ranging effects of related delays. Real-world project scenarios showed that delays do not occur independently because they tend to pass through interconnected networks of project activities. System Dynamics (SD) and other dynamic simulation models have become key areas of research due to their ability to model feedback and time-dependent along with non-linear phenomena in project systems.

Delay analysis has transformed historically into quantitative methods based on CPM from previous subjective methods focused on documents. The advancement of traditional methods faces challenges when attempting to model the sequential impact of delays among dependent construction tasks. System-based approaches emerged because of increasing construction project complexity to capture delay-related dynamics and represent a fresh stage in delay analysis methods.

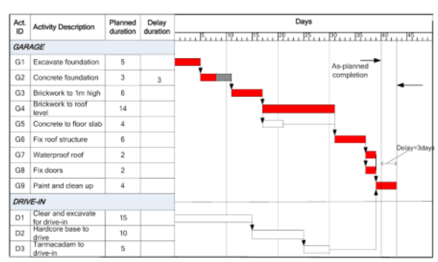

Figure 1. Overview of construction delay analysis techniques and their application issues.

Source: https://doi.org/10.3390/buildings3030506

2.2 Theories and Models of Delay Propagation and System Dynamics

Several theoretical concepts for studying and controlling delay spread in construction projects have been developed to enhance delay investigation efforts. The Critical Path Method (CPM) Dependency Structure Matrix (DSM) and System Dynamics (SD) stand as the three frequently used models which analyze delay propagation among interconnected project activities while presenting specific benefits along with constraints.

People have used the Critical Path Method (CPM) as the principal scheduling and delay analysis standard for construction since its inception. The goal of CPM is to identify critical path by finding the longest series of linked activities which determines the shortest possible project duration. Activities present on the critical path remain as fundamental elements for delay analysis because delaying them always affects the final completion deadline of the project. CPM delivers optimal results in simple projects featuring clear activities linked through defined dependencies. One key drawback of CPM is its inability to properly handle difficulties caused by task relationships in projects especially since delays from nonessential activities can ultimately affect the main critical path. The analysis framework of CPM fails to identify feedback loops and the delayed effects on dependent tasks that occur in dynamic systems according to Perera, Sutrisna, and Yiu (2016).

DSM offers project managers a superior system to track and manage their project dependencies. DSM presents project dependencies differently from CPM by showing all task relationships in a matrix because it reveals both direct and secondary connections. DSM stands as a powerful tool for projects with elaborate task graphs since it helps recognize constraints while tracing feedback effects. DSM improves delay propagation analysis compared to CPM because it allows project professionals to understand how delays in a single task create additional complications and delays that must be assessed at multiple levels. Vasilyeva-Lyulina together with Onishi and Kobayashi (2015) confirm that DSM delivers essential benefits in projects featuring intricate task interdependencies because it reveals delayed information paths and enhances scheduling adaptability.

System Dynamics (SD) provides the most comprehensive as well as sophisticated method to model delay propagation in construction projects. According to System Dynamics the model relies on systems thinking principles which explore feedback mechanisms together with time delays and continuous behavioral changes in complicated systems. SD outperforms CPM and DSM by enabling the simulation of delaying impacts on dependent tasks which extends to secondary activities linked through indirect correlations. SD allows stakeholders to create models that depict component operational relations including manpower supply and task progression and communication paths leading to a comprehensive understanding of development operations and unapparent feedback influences. SD enables managers to conduct scenario modeling and intervention simulation which assists in anticipatory delay mitigation planning since it helps identify and test potential strategies. According to Perera et al. (2016) system dynamics proves useful for complicated construction project management because it includes both resource constraints and nonlinear interaction dynamics.

System Dynamics emerges as the best option to manage delay propagation in complex systems because it outperforms CPM and DSM when working with projects that have linear dependencies. SD allows an improved emulation of real-world project conditions by simulating delay control elements which gives powerful delay propagation knowledge to decision-makers and helps them create resilient project schedules.

Each modeling system delivers essential perspectives about how delays spread through systems. The simple linear nature of projects makes CPM the best choice whereas DSM proves its worth for multiple interlocking tasks. System Dynamics proves to be the most efficient framework for complex construction projects containing multiple interdependent variables to track and handle delay propagation because it helps project managers optimize scheduling and reduce risks of delay cascades.

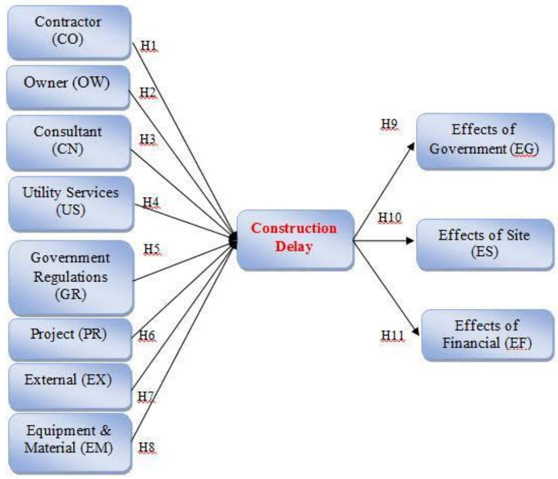

Figure 2. Theoretical model of construction delay (CD).

Source: https://doi.org/10.1080/15623599.2018.1484855

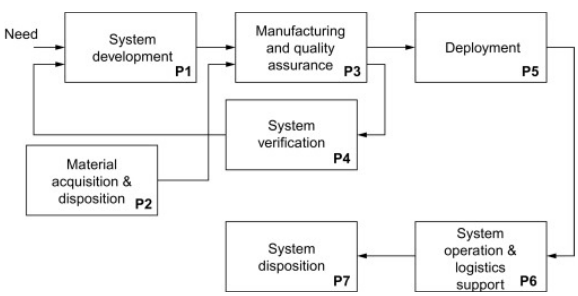

Figure 3. Illustration of the Critical Path Method (CPM) in construction project scheduling

Source: https://doi.org/10.1016/B978-0-12-814881-5.00003-X

2.3 Previous Research on Delay Propagation Modeling

Numerous analytical investigations have adopted System Dynamics (SD) and alternative methods to examine delay propagation through construction projects. SD-related studies demonstrate that delays in one task can spread across connected activities thus causing more extensive delays in project duration and project expenses.

Das (2015) executed some of the initial research that incorporated System Dynamics methods to study construction delay analysis. His SD conceptual model explored how project schedule delinquency propagates through projects with emphasis on the effects that miss-timed critical activities create on project continuity. Non-critical tasks experiencing even minor delays affect final project scheduling because of how activities link to each other according to his study findings. This research proved that proper resource management coupled with early identification of delays helps limit the extensive consequences of delays as they spread across projects.

Wang and Yuan (2017) developed these structural concepts through their research which studied the impact of risks on infrastructure project delays using the SD methodology. The authors investigated various risk elements including workforce deficiencies along with supply chain disruptions and climate fluctuations by developing models to monitor how these challenges would advance through time-based project sections. Researchers uncovered a compounding delay pattern through their study because initial delays in separate areas ended up causing further delays among connecting tasks which made the project delayed more extensively. SD demonstrated its capability to model non-linear project activity dependencies along with delivering dynamic real-time delay monitoring functions.

Braimah (2014) analyzed preconstruction programming from a different viewpoint in his effort to prevent delay propagation. The combination of System Dynamics with delay analysis techniques enabled preconstruction planning enhancement in his research. The analysis performed by Braimah showed that by detecting delays beforehand SD enables mitigation of multi-step delays by allowing pre-construction interventions to schedules and allocation of resources. The research showed that projects benefit from uniting System Dynamics with standard operational approaches to reach superior management results particularly in the planning stage.

Similar to Perera Sutrisna and Yiu (2016) investigated decision-making models which optimize the selection process for delay analysis methods in construction projects. Their research showcased how SD effectively handles construction project complexities which arise because of task interrelationships that cause delays to spread rapidly. The authors demonstrated SD to be more suitable than CPM for project delay management because it offers flexibility and full-spectrum capabilities for projects involving numerous interconnected activities.

Vasilyeva-Lyulina, Onishi, and Kobayashi (2015) conducted mathematical modeling to study delay analysis that confirmed SD provides exceptional benefits to complex transportation infrastructure projects. The research evaluated the impact of delayed activities on multiple project stages through their analysis. SD proved indispensable in delay forecasting because it efficiently tracked feedback loops while keeping track of tasks' non-linear connections according to the research findings.

These studies illustrate the growing recognition of System Dynamics as a powerful tool for modeling delay propagation in construction projects. By incorporating feedback loops, risk factors, and complex interdependencies, SD provides a more comprehensive understanding of how delays spread through project activities, enabling better decision-making and risk mitigation strategies.

2.4 Research Gaps and Emerging Issues

The application of System Dynamics (SD) models for delay propagation in construction has shown substantial advancement yet continuing gaps and new problems exist within current publications. The discovered gaps in existing models create new possibilities for researchers to improve their design alongside their practical use in actual construction settings.

SD models show an important shortcoming because they lack sufficient integration of real-time data. SD research mainly relies on Wang and Yuan (2017) and Das (2015) because their work examines conceptual modeling and performs data-driven simulations based on historical records. Current models deliver important findings but they usually cannot process dynamic project information including existing schedules and workforce profiles and delivery updates. The integration of real-time data in delay propagation predictions would enhance their accuracy so project managers could respond ahead of time to project changes.

Despite its ability to handle dependency assessments SD has limitations understanding human elements in construction projects including decision-related behaviors and workforce management issues which result in communication failures. Traditional SD models encounter challenges when quantifying human-related delays that lengthen project durations because such delays resist measurement precision. Future research should investigate methods to better include behavioral factors into SD analysis through integration with agent-based modeling and behavioral economics in order to enhance human behavior simulation in delay propagation.

Project delays are inadequately analyzed for their response to dynamic changes in external forces including economic conditions and regulatory modifications and environmental disturbances. Perera et al. (2016) join multiple research projects they conduct which focus solely on internal project dynamics while disregarding external environmental elements. Future researchers need to investigate how external variables link with internal project delays to build a complete model of delay propagation.

Finally, the scalability and complexity of SD models in large, multi-project environments remain an issue. While SD is well-suited for individual projects, applying it to large portfolios of projects or multi-site construction endeavors requires further development of scalable modeling techniques.

Addressing these gaps could lead to more robust, adaptable SD models that provide better insights into delay propagation and offer more effective solutions for managing delays in complex, real-world construction projects.

III. KEY CHALLENGES IN MODELING DELAY PROPAGATION

3.1 Complexity of Activity Interdependencies

Building accurate delay propagation models for construction projects remains difficult because activities in these projects have complex interconnecting requirements. The nature of construction projects creates complex networked activities which interrelate multiple tasks that depend on each other. Complex feedback loops form because of interdependent project activities which cause delay in one task to spread throughout the system and affect all other activities until delays accumulate resulting in project-wide delays.

The complex system emerges due to how activities interact in non-linear ways. A delayed material delivery will impact one task at first but because of interdependencies whole tasks will materialize further delays within the project. The effects remain hidden at first yet they can be shifted by how resources are used and how subcontractors work together and what sequence of tasks needs to be completed. The precise modeling of these interconnections demands complete comprehension of technical aspects with organizational elements of the project when numerous uncertain variables come into play.

According to Pryke et al. (2018) construction projects function as self-organizing network structures that adjust and transform their linked tasks because of continuous project interaction. Such networks display unpredictable complex behaviors which make their management and prediction challenging because alterations in one activity initialize unforeseen effects in other project regions. Chinowsky et al. (2011) explain how project interdependencies need alignment because poor alignment produces more project delays while damaging effectiveness. The strong emphasis belongs to professionals who argue that project success relies on effective network interdependency monitoring because it helps reduce delays during project execution.

The difficulty of modeling dependency network interrelations grows because of active feedback loops which operate within these networks. Several different feedback loops in complex networks lead to delayed effects that become easier to intensify than to reduce hence predicting final outcomes becomes difficult when analyzing the entire network structure. The Critical Path Method (CPM) along with other traditional methods struggles to evaluate feedback effects because their primary goal focuses on fixed sequential relationships between tasks. SD delivers a more comprehensive understanding of delay propagation through its models of system feedback loops with delays and their causal connections between different activities.

Given the complexity of these networks, it becomes clear that accurately capturing interdependencies and feedback loops is crucial for understanding and mitigating delay propagation. As construction projects continue to grow in scale and complexity, developing more sophisticated models that account for these dynamic relationships will be essential for improving project outcomes.

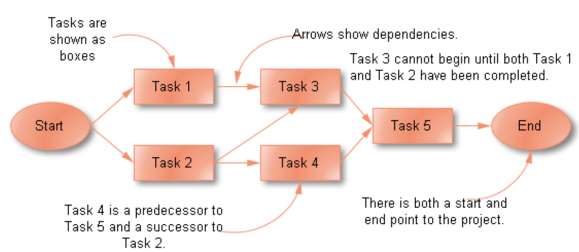

Figure 4. Activity network diagram illustrating the sequence of project tasks and their dependencies.

Source: https://www.edrawsoft.com/activity-network-diagram.html

3.2 Uncertainty and Dynamic Nature of Construction Environments

The prevailing factor of uncertainty affects project duration estimates and strained resources in construction environments. Construction sites remain unpredictable because they face weather and workers' strikes alongside material cost changes and unanticipated site conditions. Both planned and actual activity progression experience variable results due to environmental uncertainties which produces unreliable schedules and unpredictable time delays.

Wang and Yuan (2017) examine the influence of uncertainties involving labor availability and material supply as well as environmental conditions on schedule delays in major infrastructure projects. Project timelines become variable because of unpredictable factors according to their study which further grows due to interconnected project tasks. Unanticipated weather events can trigger delays in the completion of one activity leading to time changes that spread to following work assignments. Insufficient time prediction for unexpected occurrences results in project scheduling setbacks that spread throughout the entire project.

Through his research work Francis (2017) explores how chronographical scheduling logic helps simulate uncertainties that affect construction projects. The objective of his research investigates ways to embed the unpredictable nature of construction environments through combined factors of duration variability and resource availability into scheduling models. With chronographical scheduling users can create diverse simulation models to represent different time estimate uncertainties as well as resource availability variances which showcase their effects on delays. Project managers who consider uncertainty can improve delay prediction which helps them create mitigation strategies to decrease their effect on the total schedule.

Construction sites have a constantly changing environment which creates an additional difficulty in delay propagation. The project execution brings evolving uncertainties which combine with existing uncertainties to cause expanded time delays. Project schedules become unreliable because the constant modifications to project timelines remain difficult to predict. The traditional scheduling technique Critical Path Method (CPM) fails to incorporate the interactive tasks effects from variable factors because it doesn't handle such dynamic uncertainties well. SD uses a versatile modeling method which enables users to simulate unpredictable situations and find strategies to reduce project schedule disruptions.

Ultimately, understanding the role of uncertainty and its impact on delay propagation is critical for improving schedule reliability in construction projects. By incorporating uncertainty into delay analysis models, such as System Dynamics, project managers can better anticipate potential disruptions and devise more effective risk management strategies. This approach can help mitigate the cascading effects of delays, ensuring that projects are completed on time and within budget.

3.3 Data Collection and Model Validation Challenges

The main obstacle for applying System Dynamics (SD) modeling techniques to construction project delay simulations involves obtaining precise time-sensitive project data. The simulation abilities of SD models depend on accessing current data for representing the staying interactions and relationships between project activities. The construction industry experiences problems in data collection mainly because data varies unpredictably and time tracking produces errors and many stakeholders need help sharing detailed information. A comprehensive and reliable dataset for modeling becomes difficult to build because project management software and site reports join subcontractor input to fragment data across multiple sources.

Leite et al. (2016) show how advanced visualization as well as information modeling integration creates more accurate project data which also improves accessibility to address data collection difficulties. Advanced visualization and information modeling techniques support data collection but the project-wide data accuracy and consistency continue to pose substantial problems. Up-to-date data management for real-time modeling becomes unachievable when construction projects experience persistent modifications during their development process.

The validation process stands as a crucial obstacle in the SD modeling framework. Akhavian and Behzadan (2012) demonstrate how remote monitoring along with other technological data collection allows validation of SD models. The absence of both historical data and benchmark projects creates difficulties for validating SD model results according to Akhavian and Behzadan (2012). The validation of SD models depends on successful comparison between model simulations and project actual results while construction's dynamic nature and complexity pose difficulties during this process. Unforeseen situations causing prediction-reality differences frequently occur because weather conditions and labor availability changes are beyond the ability of predictive models to replicate accurately.

In light of these challenges, future research should focus on improving data collection techniques, ensuring data consistency, and developing more robust methods for validating SD models to enhance their applicability in construction project delay analysis.

Table 1: Data sources, challenges, and validation approaches for System Dynamics modeling in construction projects.

Data Source	Challenges	Validation Approaches
Project management software	Inconsistent or incomplete data, real-time tracking issues	Use historical data to compare simulated vs. actual performance
Site reports and logs	Fragmented data from different stakeholders	Cross-validation with case studies or benchmark projects
Remote monitoring tools (e.g., IoT)	Real-time data availability, sensor accuracy	Use remote monitoring data to track and validate model predictions
Subcontractor input	Variability in reporting standards and accuracy	Incorporate feedback loops to refine model predictions

IV. SOLUTIONS AND MITIGATION STRATEGIES

4.1 System Dynamics Modeling Approach

System Dynamics (SD) employs a complete procedure for modeling delay propagation throughout construction projects by understanding system dependencies while examining feedback loops alongside resource dynamics. SD model development for delay propagation demands multiple sequential steps which represent three major system elements including delays together with resources and feedback effects. The following guide demonstrates how to construct an SD model which analyzes delay propagation dynamics in construction scenarios.

1. Define the System Structure:

To establish SD modeling one must determine the specific system boundaries alongside identifying all essential components that affect delay spread. Taskwork and resources alongside delays and the connections among tasks must be identified at this stage. Each construction task acts as a stock element with completion rates making up its total value yet resource streams and work advancement data function as linked stock and flow units.

The development of an effective SD model requires complete knowledge about project structure and both dependency chains and resource limitations according to Boateng et al. (2012). Building the model requires identifying both feedback loops and delays that affect task execution as its fundamental basis.

2. Identify and Map Feedback Loops:

Attention should be given to finding feedback loops. The analysis of feedback loops helps to track how delays spread across the system that affect multiple tasks. The delivery delay of materials will postpone construction beginning until later which subsequently triggers delays in successive tasks. Project delays produce reinforcement feedback systems that grow continuously by passing through the project network.

The project model uses reinforcing feedback links for positive feedback patterns (such as delay cascades) and balancing feedback loops for countering these effects (resource reallocation happens to catch up on delays).

SD models require feedback loop representation according to Das (2015) foraccurate delay propagation simulation of construction projects. SD models analyze inter-tasks dependencies to forecast delay propagation while providing potential remedy solutions.

3. Construct Stock and Flow Diagrams:

Drawing feedback loops leads to the following step of stock-and-flow diagram development. Stock-and-flow diagrams use accumulating resources (work progress in percentages) as stocks together with time-dependent movements between these stocks known as flows (work progress rate and labor availability). The amount of work completion for a specific task can function as a stock while the work completion rate controlled by resources and task delays acts as a flow.

Sterman (1992) explains that stock-and-flow diagrams are essential for simulating the dynamic behavior of the system over time. By tracking the accumulation and flow of resources, the model can simulate how delays propagate and interact with resource constraints.

4. Define Delays and Time Lags:

The fundamental elements of SD modeling for project construction revolve around delays together with time-related controls. The timing of developments from cause to effect serves as a delay since the time elapses between a delayed task until it affects dependent tasks. The time interval between one task and another is organized into "delay" elements of SD modeling to show delay propogation duration.

A material delay initially impacts the construction start but its complete effects on subsequent process activities appear at a later time. The model needs accurate time lag definitions to understand multiple delay effects over time.

5. Model the System Dynamics:

The following step involves running system dynamic simulations after all elements have been mapped. The model execution over time helps track how time delays spread across the project. The SD model determines the effects of different delay situations through simulations that adjust resource availability and task completion rates and time lags as variables. Through simulation the model indicates specific points where interventions including resource increases or task schedule modifications will achieve the best results in reducing delay propagation.

6. Validate the Model:

To guarantee a proper real-world representation of the SD model designers must perform its validation. The assessment of the SD model accuracy occurs through comparison of its results against either project data and expert assessments. According to Boateng et al. (2012) validation processes confirm both the reliability and the capacity of models to supply useful information about delaying construction projects.

7. Intervention Strategies:

Once the model successfully passes the validation step it will become usable for testing various intervention methods. The model enables users to observe the consequences of labor force growth or expedited raw material delivery for delay minimization. Several planned interventions can undergo diverse simulations to evaluate how they minimize delay spread while enhancing project achievement levels.

In summary, the System Dynamics modeling approach provides a structured and comprehensive way to understand and simulate delay propagation in construction projects. By identifying feedback loops, constructing stock-and-flow diagrams, and defining delays and time lags, SD models can help project managers anticipate delays, test intervention strategies, and optimize project schedules. As construction projects become increasingly complex, the application of SD modeling will continue to be a valuable tool for managing the risks and uncertainties associated with delay propagation.

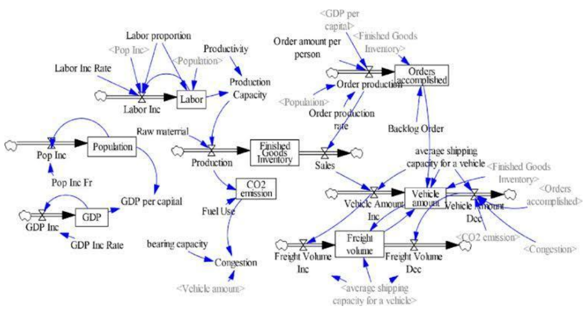

Figure 5. Stock and Flow Diagram of SD Model.

Source: https://doi.org/10.1080/13675567.2014.945400

4.2 Scenario Analysis and Simulation

Models of possible scenarios using simulation prove essential in measuring construction projects' sensitivity to different preventive actions. SD tools allow project managers to develop simulations that reveal potential effects that different delay mitigation techniques would have on project performance and delay duration.

Scenario testing provides project teams with an advantage to determine the complete impact of changes made in system components including resource allocation and task sequencing and schedule adjustments on overall projects. SD models assist project teams by testing added labor resources in critical tasks to determine their effects on project scheduling and risk mitigation capabilities. The SD model applies simulations to evaluate the effects that adjustments in supply chain management approaches such as material delivery timing have on propagation of delay patterns.

The analysis of schedule delay risks becomes more feasible through Koulinas et al. (2020) simulation-based expert system because it enables analysis of different intervention scenarios. Different scenarios of resource availability and task sequences are tested within the system through simulations which reveals their effects on delay probability and duration. The method allows managers to evaluate multiple strategies so they can select the best practices for minimizing project delays.

Similarly, Paz et al. (2018) show how a simulation-based scheduling methodology, incorporating potential delay risks, can help identify the impact of delays on the overall project timeline. By adjusting input variables and testing different scenarios, the simulation provides valuable data on how interventions, such as accelerating certain tasks or adding buffers, can prevent or mitigate delay propagation.

In conclusion, scenario analysis and simulation using SD models allow project managers to visualize the potential outcomes of different interventions. By testing a range of scenarios, these simulations provide critical insights into how to effectively manage and reduce delays in construction projects.

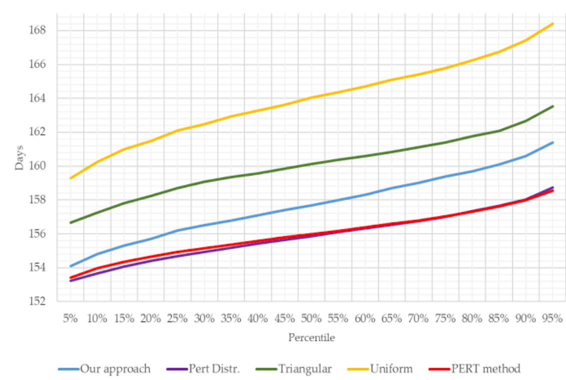

Figure 6. Schedule delay risk analysis framework using a simulation-based expert system.

Source: https://doi.org/10.3390/buildings10080134

4.3 Integration with Project Management Tools

The combination of System Dynamics models together with MS Project or Primavera increases project scheduling accuracy and effectiveness in complex delay propagation contexts. SD models outperform MS Project and Primavera since they incorporate feedback loops and system-level interactions together with uncertainty while these tools exclude this type of analysis.

Project management software integration with SD provides the capability to generate multiple simulations according to data received from scheduling tools. MS Project and Primavera examine linear task relationships and critical paths through their analysis models but SD models effectively show non-linear dependencies which cause delays to propagate throughout projects. MS Project provides an initial construction timeline through scheduling but team leaders gain additional simulation capabilities by adding SD modeling to determine how activity delays will spread among all tasks along with resource limitations and supply chain disruptions.

The research paper by Rodrigues and Williams (1997) shows how SD models can enhance traditional project management tools like Primavera and MS Project when used together for software project management. SD functions to identify project risks as well as delays but Primavera's Gantt chart provides a clear view of the complete timeline. Better decision-making becomes possible because the combination enables users to compare project data retrieved from real-time management systems against SD simulation predictions.

The integration typically involves linking the outputs of SD models (e.g., resource availability, task delays) with the input parameters of project management tools. Through this synergy, project managers can refine project schedules based on dynamic modeling results, improving project performance and reducing delays. Thus, combining SD models with traditional project management tools facilitates a more proactive and data-driven approach to managing construction project delays.

CONCLUSION

5.1 Summary of Key Findings

The research delivers critical findings regarding complex delay propagation patterns in construction projects and System Dynamics modeling as an effective method for delay examination and mitigation. Project delays normally spread beyond single points of origin since dependent activities enhance their overall impact on project duration. Different sources produce these delays which include shortages of resources as well as dependencies between tasks in addition to external factors that cause supply chain disruptions and weather effects. Multiple time delays join together to form a dynamic framework that makes initial time loss trigger numerous additional time delays which intensify total program delays.

System Dynamics modeling provides a successful means to create simulations of complex feedback systems that guide their analysis. When task interdependencies and resource flows trace into an SD model the system can anticipate delay propagation thus helping project managers understand risk factors better. Surveying the scenarios that matter through SD models enables users to conduct virtual tests using resource allocation changes and task re-sequencing sequences to analyze their effects on project durations. Uncertainty within construction environments together with dynamic changes becomes more manageable when software dependencies modeling represents it while traditional project management systems such as MS Project or Primavera lack this capability. These tools become more effective for decision-making when they integrate SD because it allows for better data-driven choices.

In conclusion, the application of SD in modeling delay propagation offers significant potential for improving project planning, risk management, and decision-making in construction projects, helping reduce delays and ensure projects are completed on time and within budget.

5.2 Implications for Stakeholders

The research outcomes create substantial implications which benefit project managers together with clients and policy makers and their contractors. This study demonstrates how System Dynamics modeling predicts delay propagation effectively while showing the complexity of delay processes to establish better dynamic project management methods.

For project managers, the adoption of SD models offers a more comprehensive toolset for understanding the cascading effects of delays. By incorporating SD into their decision-making processes, project managers can gain deeper insights into the interdependencies between tasks, resource availability, and external factors that contribute to delays. This allows them to make more informed decisions, identify potential risks early, and implement proactive interventions to minimize the impact of delays. Furthermore, by using SD for scenario testing, project managers can evaluate the outcomes of different strategies—such as adjusting task sequences, increasing resources, or rescheduling critical activities—before implementing them on the ground.

Contractors stand to benefit from the ability of SD models to improve resource management and scheduling. By simulating the impact of changes in task completion times, labor availability, or material delays, contractors can optimize their operations, allocate resources more effectively, and reduce the likelihood of costly overruns. This can lead to better adherence to timelines, which is crucial for maintaining client satisfaction and improving profitability.

For clients, the ability to model and mitigate delay propagation directly impacts project delivery. With a more accurate understanding of potential risks and delays, clients can engage in more realistic discussions with contractors, set more achievable timelines, and manage expectations. By using SD models to predict delays and their impacts, clients can minimize the financial repercussions of delayed projects and ensure that project objectives are met.

Policymakers can also use the insights from this study to advocate for the integration of advanced modeling techniques, like SD, into construction project management practices. This could inform the development of policies or guidelines that promote better risk management and delay mitigation strategies within the construction industry, ultimately improving the overall efficiency and effectiveness of the sector.

In conclusion, the integration of System Dynamics modeling in construction project management has broad implications for stakeholders across the industry. It offers the potential for more efficient project delivery, better risk management, and ultimately, improved outcomes for all parties involved.

5.3 Recommendations and Future Research

Based on the findings of this study, several key areas for future research and development emerge, particularly around the integration of hybrid models, real-time monitoring, and artificial intelligence (AI) in managing delay propagation in construction projects.

First, hybrid models combining System Dynamics (SD) with other modeling approaches, such as Critical Path Method (CPM) or Dependency Structure Matrix (DSM), hold significant potential for enhancing delay analysis. SD excels in capturing feedback loops and resource constraints, while CPM and DSM are strong in handling task sequencing and dependencies. Future research could explore how these models can be integrated to provide a more robust and comprehensive framework for understanding and mitigating delay propagation. Hybrid models could offer greater accuracy and flexibility in predicting delays under varying project conditions.

Secondly, real-time monitoring of project progress offers valuable opportunities to improve delay prediction and response. By incorporating real-time data from project management tools, sensors, or IoT devices into SD models, project managers can track task progress, resource availability, and environmental factors continuously. This would allow for dynamic adjustments to the model based on actual project performance, enabling more timely interventions and better forecasting of delays. Future research could focus on developing methods for integrating real-time project data with SD models to facilitate adaptive project management.

Lastly, the integration of artificial intelligence (AI) with SD models presents an exciting area for future research. AI can be used to analyze vast amounts of project data, identify patterns in delay propagation, and suggest optimization strategies. Machine learning algorithms could be incorporated into SD models to automatically refine predictions and recommend interventions based on historical project data and real-time inputs. Research into AI-driven SD models could lead to more intelligent, data-driven decision-making in construction project management.

In conclusion, advancing research in these areas will enhance the accuracy, efficiency, and adaptability of delay modeling in construction projects, ultimately improving project outcomes and reducing delays.

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