Proceedings of the 2022 Winter Simulation Conference
B. Feng, G. Pedrielli, Y. Peng, S. Shashaani, E. Song, C.G. Corlu, L.H. Lee, E.P. Chew, T. Roeder, and P. Lendermann, eds.

SYSTEM DYNAMICS MODELING OF THE CONSTRUCTION SUPPLY CHAIN IN INDUSTRIAL MODULARIZED CONSTRUCTION PROJECTS

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ABSTRACT

Modeling the construction supply chain has been a challenge as the construction supply chain is a complex and dynamic ecosystem. To understand the variable and volatile nature of construction, this study developed a system dynamic model to simulate the influences of three key factors, scope changes, requests for information, and rework, on project duration. This study reviewed the latest literature, examined the typical modularized heavy industrial construction projects, sketched a causal loop diagram, developed a system dynamics model, and performed model verification and validation. The simulation results for a simple construction project with artificial input revealed that the three identified factors significantly influenced the project duration against the initial planned project duration. The proposed system dynamics model (1) simulates the multi-stakeholder construction supply chain as a holistic ecosystem; (2) quantifies the impact resulting from inefficient information flows on project duration; and (3) forecasts the project duration given these factors.

1 INTRODUCTION

Supply chain management is a concept that originated and flourished in the manufacturing industry (Vrijhoef and Koskela 2000). Christopher (2016) defined the supply chain in general terms as "the network of organizations that are involved, through upstream and downstream linkages, in the different processes and activities that produce value in the form of products and services in the hands of the ultimate customer." Christopher (2016) placed emphasis on material and resource management in the supply chain system. In comparison to the resource-focused supply chain in the manufacturing industry, the construction supply chain differs greatly in that it is a complex network involving multiple interactions (e.g., information exchanges) among stakeholders during the construction process (Winch 2001; Fellows and Liu 2012). Simply adopting the well-established supply chain management tools, techniques, and tactics from the manufacturing industry would fail to capture the essence of such a dynamic and complex system, and would therefore be unable to support critical decision-making during construction.

Despite its complexities, previous studies on construction supply chain management have mainly focused on material and resource supply chain management strategies (Fernie and Tennant 2013; Sundquist et al. 2018). The system dynamics of information flow in the construction supply chain and their impact on the project outcome, specifically in terms of project duration, have not been well studied. For example, a lack of collaboration among stakeholders in the construction information supply chain network causes delays, errors, and business process redundancy (Le et al. 2019). Such managerial and operational inefficiencies further negatively impact construction execution, resulting in rework, scope changes, issue of request for information (RFIs) and project delays. Few studies have studied or quantified the impact of the information flow inefficiency on construction project performance (e.g., project duration).

This study aims to address the above-identified research gap and advance the body of knowledge with respect to construction supply chain management in the context of information flow in a typical modularized industrial construction project setting. Particularly, the study quantified the systematic impact of information flow inefficiencies—RFIs, scope changes, and rework—on the final construction duration using a system dynamic model. The model developed in this study is capable of (1) simulating a multi-stakeholder information supply chain as a holistic ecosystem, (2) quantifying and investigating the impact of three identified factors on the project duration, and (3) forecasting project duration based on the identified factors.

2 BACKGROUND

The background section first reviews construction supply chain management, then describes its differences compared to supply chain management in the manufacturing sector, and also discusses its evolution. Next, a discussion is presented regarding the key non-material factors (i.e., information flow inefficiencies) within the construction supply chain that affect the construction project duration. Lastly, this section includes a review of system dynamics to demonstrate its suitability in modeling the complex and dynamic construction supply chain ecosystem.

2.1 Construction Supply Chain Management

Construction supply chain management is defined as the process of "strategic management of information flow, activities, tasks, and processes, involving various networks of organizations and linkages from up-stream to downstream, engaged in the delivery of quality construction products and services through the firms, and to the customer, efficiently" (Akintoye et al. 2000). Because construction processes are project-based and are provisional by their very nature, temporary supply chains are usually formed in construction projects, and a universal construction process system is hard to define (Bakker 2010).

The construction supply chain is formed via the construction processes and their execution, which takes place during multiple stages of a project's life cycle including conceptual, design, material procurement, fabrication, and construction (Akintoye et al. 2000). A construction supply chain typically involves a selection of stakeholders including but not limited to client/owners, designers, engineers, general contractors, subcontractors, specialized trades, suppliers, consultants, etc. Further, a construction supply chain is not only a chain of business-to-business relationships, but also a network of multiple organizations and relationships, which includes the flow of information, the flow of materials, services or products, and the flow of funds among the client, designer, contractor, and supplier (Xue et al. 2007). The construction project relies on smooth information exchange, on-time delivery of supplies, and adequate resources to achieve the required project deliverables (O'Brien et al. 2004).

Construction supply chain management integrates business processes in which all stakeholders are involved and focuses on how the integrated process utilizes material, information, technology, and capability to achieve success, with a goal "to improve construction performance and add client value at less cost." (Xue et al. 2007).

2.2 Difference between Construction Supply Chain and Manufacturing Supply Chain

A flowchart (as shown in Figure 1) was developed as part of the present study to demonstrate the differences between a typical construction supply chain for a modularized heavy industrial construction project and a typical manufacturing supply chain. In Figure 1, the material flow (solid line), cash flow (grey dashed line) and information flow (black dashed line) are identified in both settings. The blue two-way arrows between the two supply chains indicate the corresponding players from one supply chain to the other.

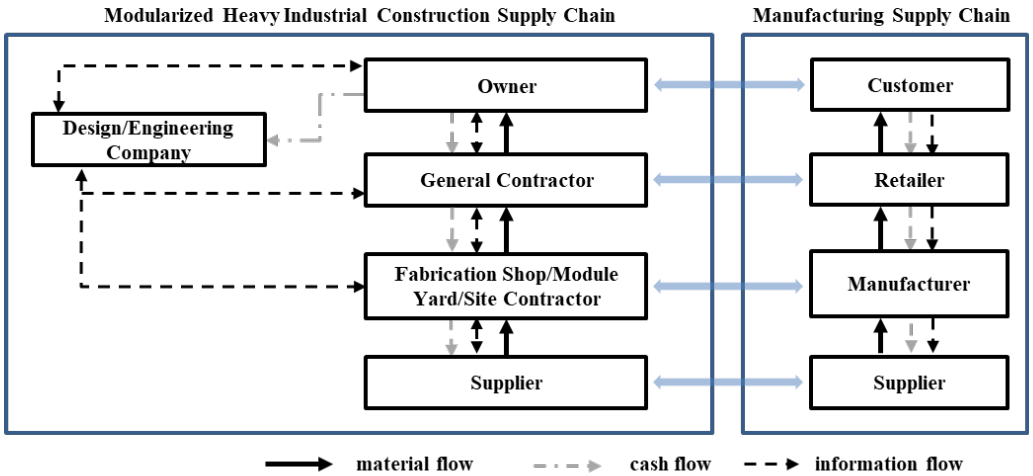

Figure 1: Comparison of a construction supply chain and a manufacturing supply chain (adapted from Liu et al. 2017).

First, information flow in a construction supply chain for a modularized heavy industrial construction project is far more complicated than that of a typical manufacturing supply chain. Information flows in both directions (as illustrated by black dashed lines) among the stakeholders in the construction supply chain (who are listed inside the black boxes), whereas the information flows in a single direction in the manufacturing supply chain. The complex information flow is due to the unique and customer-oriented deliverables in the construction industry. In the manufacturing supply chain, customers pick the products based on the market availability. Those products are "off-the-shelf" and not tailored to each customer's specific needs. In contrast, each construction project is unique and the owners define the project deliverables with assistance from the design and engineering teams. Therefore, a construction supply chain requires a large amount of information distribution and communication back and forth between various stakeholders to successfully deliver the project. Additionally, in a modularized heavy industrial construction project, the supply chain often involves additional stakeholders such as fabrication shops, module yards, and transportation.

Secondly, stakeholders' contributions to the value of products are different in the two supply chains. Within the manufacturing supply chain, the retailer distributes the products and increases the product's price to make non-value-added profits. However, in the construction supply chain, the majority of the stakeholders (e.g., suppliers, general contractors, fabrication facilities, and module yards) contribute to the final product and add value to the project deliverables.

2.3 Development of Construction Supply Chain Management

Although the topic of construction supply chain management has garnered attention from researchers, the majority of the research has focused on material and resources supply chain management (Vaidyanathan 2009; Gan and Cheng 2015). Le et al. (2020) studied the evolution of supply chain management strategies and techniques and compared their adoption in general and in construction more specifically. As shown in Figure 2, the development of supply chain integration in the construction industry has been more limited and has occurred at a slower pace compared to its adoption more generally (Le et al. 2020). Due to the inherent characteristics of the construction industry—complexity, uniqueness, involvement of multiple stakeholders, and the highly risky environment—the benefits of simply adopting general supply chain management strategies are limited in the construction industry (Wu and AbouRizk 2023). Specifically, the dynamic and complex network of stakeholders requires a correspondingly complex and multidimensional information exchange infrastructure. Accurately simulating the ecosystem and the information flow structure will not only advance the knowledge areas in construction supply chain management but will also provide strategies that can benefit multiple stakeholders. Nevertheless, such a task remains a challenge in both the research community and in the construction industry (Le et al. 2020).

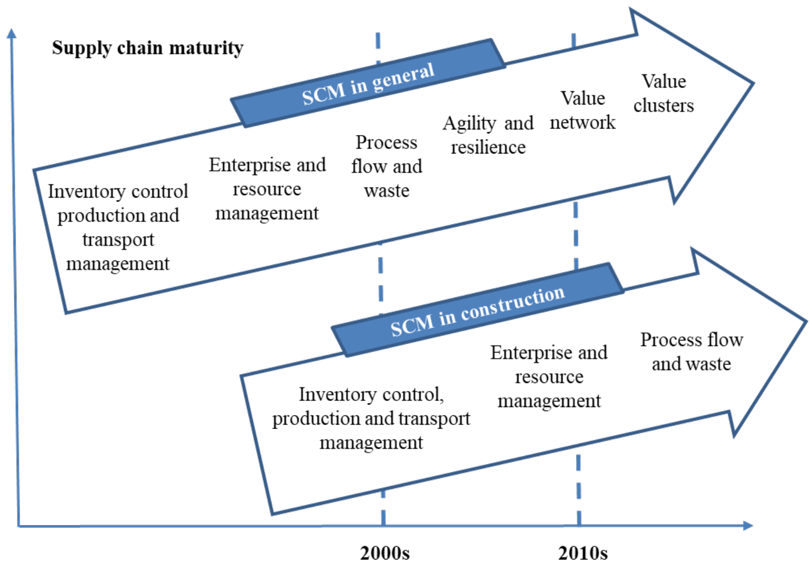

Figure 2: Evolution of supply chain management strategies and techniques in general and in construction (Le et al. 2020).

2.4 Factors Influencing Construction Project Duration

This study uses project duration as a measure to evaluate the impact of inefficiencies in information flow. The following subsections describe three main factors resulting from the inefficient information flow in the construction supply chain that subsequently affect the project duration.

2.4.1 Scope Changes

Construction projects are constantly changing for many reasons, such as unexpected site conditions, changes in owner requirements, recognizing ways to improve the design, adding new scopes, etc. Change orders are the official documentation used to capture those changes. Changes are a common issue in construction projects that may positively or negatively impact the construction project's duration, cost, and quality (Al-Kofahi et al. 2020). The frequency of changes and the contractual change order procedures drastically influence the productivities of the downstream stakeholders (e.g., general contractors and subcontractors), as certain construction activities have to be halted while waiting for change order approval (Loosemore 2014; Rompoti et al. 2020). An increase in scope changes from the upstream stakeholders leads to lower productivity for downstream stakeholders, increasing the likelihood the project will be delayed.

2.4.2 Request for Information (RFIs)

Modularized heavy industrial construction projects are commonly carried out in a fast-track fashion, where the construction phase overlaps significantly with the engineering and design phases (Wu et al. 2014). When construction starts based on an incomplete engineering package that has not yet been subjected to multiple rounds of checks, the errors in the drawings often result in conflicts in construction. The downstream stakeholders such as contractors rely on a formalized process, i.e., the request for information (RFIs) process, to obtain additional information to resolve such conflicts (Mohamed et al. 1999). The process of initiating RFIs and waiting for responses halts certain construction activities, and reduces productivity due to the breakdown of the workflow (Al-Kofahi et al. 2020). Thus, slow responses to RFIs from the upstream stakeholders might lead to severe project delays.

2.4.3 Rework

Rework is another common cause of productivity loss and project delay (McDonald 2004). A high number of RFIs and frequent changes disturb the work plan and are among the many factors that cause rework. Rework adds substantial material cost and requires several tasks to be re-planned and re-sequenced (Al-Kofahi et al. 2020), which can result in schedule delays and material and equipment waste. If more tasks are required to be reworked, more time (i.e., delay) is expected.

2.4.4 Other Factors

Ibironke and Elamah (2011) summarized other factors influencing construction project duration from previous research; these factors include labor shortages, slow decision making, delays in work approval, organization deficiencies, lack of proper tools and equipment, shortage of construction material, late submission delivery, weather, physical site conditions, etc. The present study also considered the impact of the above-mentioned other factors on construction duration and reflected them in performance factors when developing the system dynamic model.

2.5 System Dynamics

System dynamics (SD) analytical modeling is derived from Jay Forrester's work on industrial dynamics at the Massachusetts Institute of Technology, which examines an identified problem both qualitatively and quantitatively (Forrester 1968). Using stocks, flows, internal feedback loops, table functions, and time delays, SD simulates a complex system's nonlinear behavior over time. SD models present a holistic view of the construction ecosystem in the project management context and provide a simulated environment in which various decision-making policies and their consequences are evaluated (Forrester 1968). This study developed a SD model using an industrial-strength simulation software called Vensim due to its rich feature set and flexibility.

3 MODEL DEVELOPMENT

An SD model that simulates information flow within the construction supply chain of a modularized heavy industrial construction project was developed according to the following five steps—conceptual modeling, model parameters setup, model development, verification, and validation.

3.1 Conceptual Modeling—Developing a Causal Loop Diagram

Through reviewing literature and interviewing senior project managers in modularized heavy industrial construction, this step defined the relationships among the three factors, namely (1) scope changes, (2) request for information, and (3) rework, and their impact on the project duration. The resulting causal loop diagram is shown in Figure 3. Project duration was measured using "Actual Project Labor-hours at Completion."

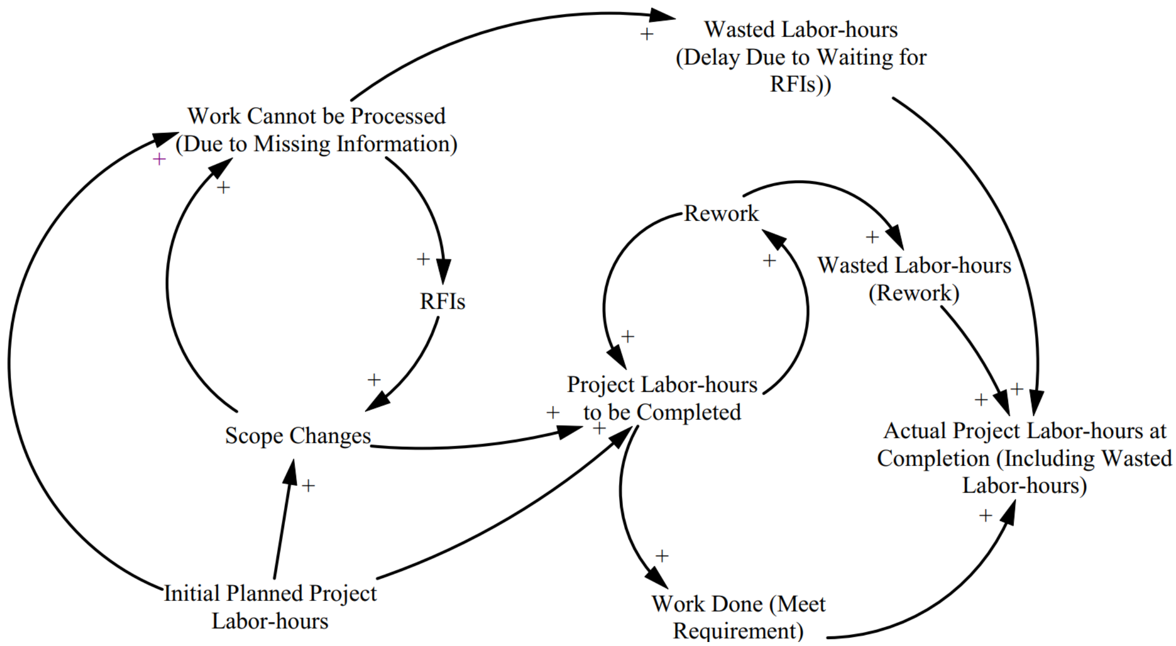

Figure 3: Causal loop diagram of actual project labor-hours at completion.

Within the casual loop diagram shown in Figure 3, fourteen reinforcing causal loops are identified and included below (a positive sign, +, indicates a reinforcing impact in the diagram). Note that "Project Labor-hours" is abbreviated as PLH in the fourteen reinforcing causal loops detailed below.

1) Initial Planned PLH → + PLH to be Completed → + Work Done (Meet Requirements) → + Actual PLH at Completion
2) Initial Planned PLH → + PLH to be Completed → + Rework → + PLH to be Completed → + Work Done (Meet Requirements) → + Actual PLH at Completion
3) Initial Planned PLH → + PLH to be Completed → + Rework → + Wasted Labor-hours (Rework) → + Actual PLH at Completion
4) Initial Planned PLH → + Scope Changes → + PLH to be Completed → + Work Done (Meet Requirements) → + Actual PLH at Completion
5) Initial Planned PLH → + Scope Changes → + PLH to be Completed → + Rework → + PLH to be Completed → + Work Done (Meet Requirements) → + Actual PLH at Completion
6) Initial Planned PLH → + Scope Changes → + PLH to be Completed → + Rework → + Wasted Labor-hours (Rework) → + Actual PLH at Completion
7) Initial Planned PLH → + Scope Changes → + Work Cannot be Processed (Due to Missing Information) → + RFIs → + Scope Changes → + PLH to be Completed → + Rework → + PLH to be Completed → + Work Done (Meet Requirements) → + Actual PLH at Completion
8) Initial Planned PLH → + Scope Changes → + Work Cannot be Processed (Due to Missing Information) → + RFIs → + Scope Changes → + PLH to be Completed → + Work Done (Meet Requirements) → + Actual PLH at Completion
9) Initial Planned PLH → + Scope Changes → + Work Cannot be Processed (Due to Missing Information) → + RFIs → + Scope Changes → + PLH to be Completed → + Rework → + Wasted Labor-hours (Rework) → + Actual PLH at Completion
10) Initial Planned PLH → + Scope Changes → + Work Cannot be Processed (Due to missing information) → + Wasted Labor-hours (Delay Due to Waiting for Information) → + Actual PLH at Completion

11) Initial Planned PLH → + Work Cannot be Processed (Due to Missing Information) → + RFIs → + Scope Changes → + PLH to be Completed → + Work Done (Meet Requirements) → + Actual PLH at Completion
12) Initial Planned PLH → + Work Cannot be Processed (Due to Missing Information) → + RFIs → + Scope Changes → + PLH to be Completed → + Rework → + PLH to be Completed → + Work Done (Meet Requirements) → + Actual PLH at Completion
13) Initial Planned PLH → + Work Cannot be Processed (Due to Missing Information) → + RFIs → + Scope Changes → + PLH to be Completed → + Rework → + Wasted Labor-hours (Rework) → + Actual PLH at Completion
14) Initial Planned PLH → + Work Cannot be Processed (Due to Missing Information) → + Wasted Labor-hours (Delay Due to Waiting for Information) → + Actual PLH at Completion

"Initial Planned Project Labor-hours" is estimated based on Request for Proposal documents issued by clients, and all of "Initial Planned Project Labor-hours" will flow to "Project Labor-hours to be Completed". "Project Labor-hours to be Completed" indicates work that is ready to be performed, without the need for clarifications or additional information. In the meantime, a certain portion of "Initial Planned Project Labor-hours" will result in changes, i.e., "Scope Changes", and will require RFIs, i.e., "Work Cannot be Processed". "Work Cannot be Processed" indicates work cannot be done due to missing information and RFIs are required for clarification. This process does not generate new labor-hours but causes project delays ("Wasted Labor-hours (Delay Due to Waiting for RFIs)"). Meanwhile, based on the RFIs types, a certain amount of RFIs become "Scope Changes", which increases labor-hours towards the "Project Labor-hours to be Completed". During construction, scope changes are issued from either 1) clients directly, or 2) RFIs. The former type of change might further require RFIs while the latter are assumed to be clear scope without the need for RFIs. All labor-hours that are stocked in "Project Labor-hours to be Completed" are subject to a certain percentage of rework. If the completed tasks do not meet requirements, additional labor-hours are generated and flow to "Project Labor-hours to be Completed" until all "Project Labor-hours to be Completed" meet requirements. "Wasted Labor-hours (Rework)" are increased during the same time when rework happens. Finally, all labor labor-hours including waste labor-hours are stocked in "Actual Project Labor-hours at Completion".

3.2 Model Parameters Setup

The study made the following assumptions to facilitate simulating realistic construction situations:

1. The simulation model setup is summarized in Table 1.
2. The model stops when labor-hours stocked in "Project Labor-hours to be Completed" reaches 0.
3. RFIs, scope changes, and rework can happen throughout the entire construction process.
4. Although the scope changes could add or reduce project scope, this study only considers scope increase.
5. Due to the limited available resources during the current stage of the present study, the system dynamic model of the construction supply chain was run using a simplified construction project as described in Table 2.
6. The ineffective labor-hours due to RFIs (Wasted Labor-hours Due to RFIs) are assumed to equal the total labor-hours of the scope that cannot proceed thus requiring RFIs (i.e., labor-hours requiring RFIs).

Table 1: Model setup.

Initial Time	Final Time	Time Step	Unit
0	50	0.25	Week

Table 2: Project parameters.

Crew Size	Work Schedule	Planned Project Duration	Planned Labor-hours
15 Laborers	8 Labor-hours per day, 5 days per week	12 Weeks	7200 Labor-hours

The full list of model parameters, including 5 constants, 6 stocks (levels), 9 flows and 6 auxiliaries, together with their description, relationships to each other (i.e., equations), and unit of measure, is available online (Wu 2022). The model requires the six inputs defined below. Each input is modeled using triangular distribution due to its simplicity and its flexibility to incorporate subjective values (Chau 1995; Wu and AbouRizk 2021).

Performance Factor (PF) measures construction efficiency. In this study, PF excludes the influence caused by scope changes, RFIs, and rework, and is calculated as follows:

$$Performance\ Factor\ = \frac{Earned\ labor\text{-}hours}{Actual\ labor\text{-}hours}.$$

RFI Rate is the percentage of initial planned project labor hours (or scope changes based on initial planned project labor-hours) that are subject to the RFI process, shown below

$$RFI\ Rate\ = \frac{Labor\text{-}hours\ requiring\ RFI}{Initial\ planned\ project\ labor\text{-}hours} = \frac{Labor\text{-}hours\ requiring\ RFI}{Scope\ changes\ labor\text{-}hours\ (based\ on\ initial\ planned\ project\ labor\text{-}hours)}.$$

Scope Change Rate on the Initial Project Scope is labor-hours of scope changes as a percentage of the total labor-hours of the initial project scope, calculated as follows:

$$Scope\ Change\ Rate\ on\ the\ Initial\ Project\ Scope = \frac{Scope\ changes\ labor\text{-}hours}{Initial\ planned\ project\ labor\text{-}hours}.$$

% of RFI for Scope Change is the percentage of RFIs that lead to changes in project scope:

$$\%\ of\ RFI\ for\ Scope\ Change\ = \frac{Scope\ change\ labor\text{-}hours\ generated\ from\ RFI}{Labor\text{-}hours\ requiring\ RFI}.$$

Meet Requirements Rate states the percentage of the total labor-hours of the initial project scope are done without rework required, calculated as follows:

$$Meet\ Requirements\ Rate\ = 1 - \frac{Rework\ labor\text{-}hours}{Initial\ planned\ project\ labor\text{-}hours}.$$

Time to Discover Rework is the average time between the completion of a task and discovering it needs to be redone.

3.3 Model Development

Based on the fourteen causal loops defined in Figure 3, an SD model was developed as shown in the stock-flow diagram presented in Figure 4. Built upon the well-established and validated reinforcing loop for rework (Chang et al. 2007; Alvanchi et al. 2012; Han et al. 2013; Nasirzadeh and Nojedehi 2013; Al-Kofahi et al. 2020), the proposed model significantly expanded the original rework model to include compound impacts from RFIs and change orders. The “Initial Planned Project Labor-hours” was estimated by the general contractor using issued Request for Proposal documents. This “Initial Planned Project Labor-hours” will flow through “Project Labor-hours to be Completed” during the simulation toward the stockpile “Work Completed-Meet Requirement” at the rate of “Effective Labor Work Rate”. The “Effective Labor Work

Rate" considers the impact of PF, scope changes, and RFIs. Please refer to Wu (2022) for detailed descriptions and equations of all model parameters.

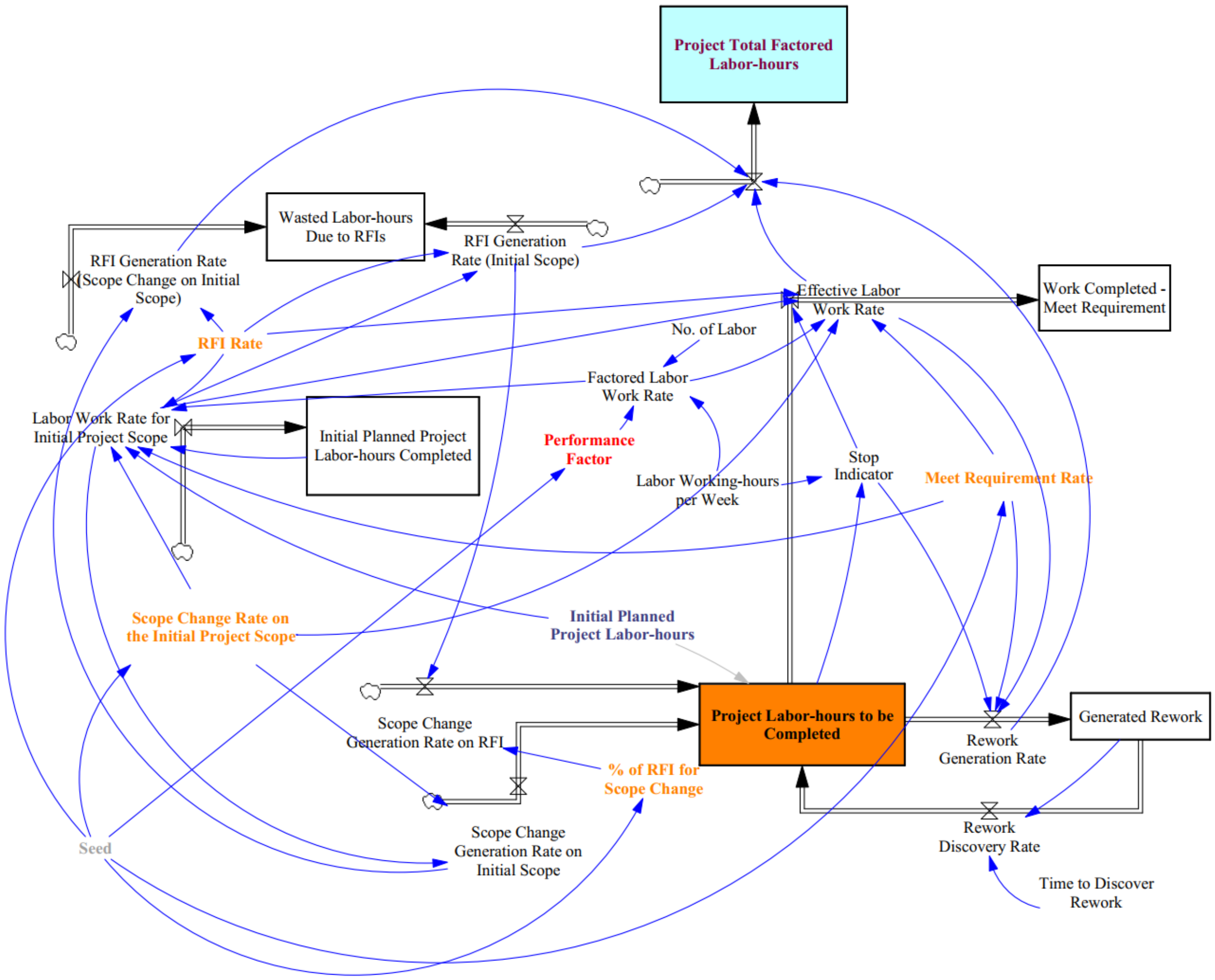

Figure 4: Stock and flow diagram.

3.4 Model Verification and Validation

The developed SD model was verified using boundary adequacy, structure verification, dimensional consistency, and parameter verification to "ensure that the computer program of the computerized model and its implementation are correct" (Sargent 2010). Using a verified model, an extreme condition test and comparison to manual calculation was conducted to validate the model "possesses a satisfactory range of accuracy consistent with the intended application of the model" (Schlesinger et al. 1979). Due to the page limitation, the details of the verification and validation are excluded from this manuscript.

3.5 Output Analysis

Due to the time limitation, the model was run using the artificial input data as described in Table 3. A survey of industry practitioners is planned to obtain real-world data for future study. After having been ran 50 times, the simulated final project durations are gathered and presented as the histogram shown in Figure 5.

Table 3: Model input.

Input	Low	Mode	High
Meet Requirement Rate	0.70	0.85	0.98
Performance Factor	0.75	1.00	1.20
RFI Rate	0.10	0.12	0.20
Scope Change Rate on the Initial Project Scope	0.06	0.23	0.50
% of RFI for Scope Change	0.20	0.50	0.30

The result indicates that the majority (36 out of 50) of the simulated project durations fall in a range from 23.75 to 26.65 weeks, which doubles its initial planned project duration (12 weeks). Moreover, 10% of the simulated project durations exceed 170% of the initial planned project duration. The drastic increase in project duration indicates how significant an impact the identified information inefficiencies within a construction supply chain have on project duration.

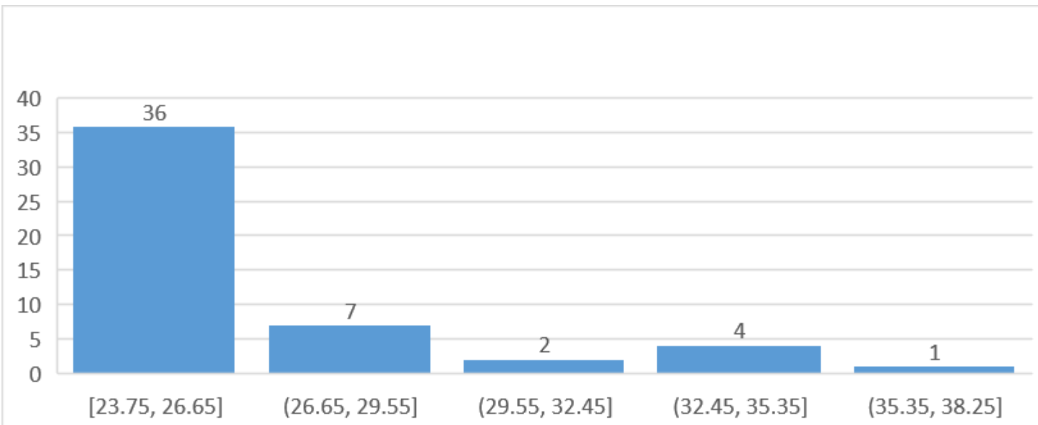

Figure 5: Histogram of the simulated project durations.

4 CONCLUSION

This study filled a research gap found in the domain of construction supply chain management—the need and challenge of modeling the impact of inefficient information flow on project duration in a typical modularized industrial construction project. Through reviewing literature and interviewing seasoned practitioners, this research identified fourteen causal loops that affect the project duration in a typical modularized industrial construction project. Based on the causal loop diagram, this study developed a SD model that is capable of (1) simulating a multi-stakeholder information supply chain as a holistic ecosystem, (2) quantifying and investigating the impact of the three identified factors on project duration, and (3) forecasting project duration based on the identified factors. The model has been verified and validated using a selection of recommended methods. The simulation results indicate the three identified factors significantly influence the project duration.

Nevertheless, the following limitations should be noted for consideration. First, the SD of the simulated construction supply chain only focuses on three information inefficiencies and their influences on project duration. To further advance the body of knowledge with respect to construction supply chain management, other information flow factors (inefficiencies) and other aspects of the construction supply chain (e.g., materials) should be considered in concert with each other. Second, the developed SD model applies to only modularized industrial construction projects. Third, due to the time limitation, the simulation results were based on artificial datasets. Fourth, the study applied system dynamics analytical modeling to analyze the dynamic behavior of the construction supply chain, but other methods that demonstrate valuable potentials, such as matrix representation (Respondek 2022), should also be considered in future studies.

ACKNOWLEDGMENTS

This project was supported by a Collaborative Research and Development Grant (CRDPJ 492657) from the Natural Sciences and Engineering Council of Canada. The authors would like to thank Dr. Catherine Pretzlaw and Kristin Berg for their assistance in editing the manuscript.

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