Process Evaluation of Construction Methods to Quantify Safety

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ABSTRACT

The use of off-site construction methods is increasing within the construction industry. While this method has been captured by a variety of terms, they all refer to the process of producing project components in a manufacturing-like facility off-site and transporting completed units to site to be assembled to achieve the desired end-product. To support the quantification of safety performance in off-site construction versus conventional on-site methods, the research has developed a generalized model for capturing and evaluating construction methods. The methodology was developed in partnership with local practitioners to define, assess and compare on-site and off-site construction practices with a safety lens, and the methodology is partially validated in collaboration with various project owners to assess case study projects that employed off-site construction into their processes. The evaluation methodology takes a construction product-focused approach with emphasis on defining a complete material supply chain and capturing the data needed to support quantifiable safety evaluations of the process. As such, the approach takes a unique approach to establish an evaluation methodology for future comparisons.

KEYWORDS

Offsite construction, process analysis, offsite construction process, safety assessment

INTRODUCTION

Prefabricated construction involves both off-site and on-site aspects in its processes (Fard et al., 2017), and while the concept of building in an off-site environment is not new (Sutrisna and Goulding, 2019), the effort to move towards an off-site approach is a growing facet of the construction industry (Goodier et al., 2019). There are many notable benefits that have been attributed to adopting off-site construction methods such as reduced schedule, reduced cost, improved quality, improved productivity, innovative competitiveness, sustainability and safety (Wuni and Shen, 2019).

When it comes to safety research in off-site construction, topics explored include an analysis of risks in off-site versus hypothetical on-site construction scenarios for the same building components (Ahn et al., 2020); off-site construction facilities to determine root causes of safety incidents (Fard et al., 2017); and behaviours in off-site environments to predict safety outcomes (Liu et al., 2019). Additionally, much of the research surrounding safety risk assessments in off-site construction is qualitative and summarizes findings from expert opinions (Killingsworth et al., 2020) about the perceived benefits of the off-site approach.

While research suggests many of the aforementioned benefits of off-site, what can still be observed within the construction industry is heuristic biases (Mather and White, 2020) in decision makers, especially those who are most familiar with traditional on-site construction methods and know-how to execute projects with this approach. In order for off-site methods to be viable construction options, processes must be well-understood by all parties and coordination of potential off-site opportunities must be planned in the early stages of the project (Sutrisna at al., 2018). To ensure these processes and opportunities are well-understood, the research has developed a generalized model for analyzing construction methods producing the same end-product to enable comparisons from a safety perspective. The process analysis takes a product-focused approach, and requires a definition of the complete supply chain to define all work activities and potential sources of injury within the scope of work. The research leverages two case study construction projects employing a range of construction methods, covering both on-site and off-site panel and volumetric approaches to evaluate, compare and partially validate the research.

METHODS

Research Design

The proposed framework includes the development of a defined process at an activity level, with emphasis placed on the assessment of the complete supply chain to deliver the end-product. The development of the process analysis methodology uses a non-probability sampling model through various case studies executing projects that apply off-site construction methodologies. The research has taken an exploratory approach to develop this process analysis model. This allows for the analysis of non-hypothetical scenarios, all while investigating the feasibility and effectiveness of capturing the data with the proposed methodology.

Data Collection

To complete the process evaluation of construction methods, the data required includes: sequence of construction activities, allocated resources by activity, construction activity durations (ie. risk exposure durations) and identification of potential sources of injury. The application of this process analysis methodology is intended for the project initiation and design phases; therefore, the data would be collected through estimation of resource requirements based on a pre-defined sequence of events. In the scenario of the case studies, the process definition and analysis happened after the fact, so the data was collected form the observed processes.

Data Analysis

The process evaluation of methods has three stages: identifying the end project, defining the process and analyzing the process. A summary of the complete process evaluation methodology is presented in **Figure 1**.

Identify End-Product

The identification of the desired construction end-product is required to complete an analysis of the potential construction methods to be used to deliver the product. This would occur at the project initiation and design phases. The process analysis methodology has taken a construction product-focused approach with emphasis on defining a complete material supply chain to promote a comprehensive analysis for all resources, activities and process steps as defined by the respective processes.

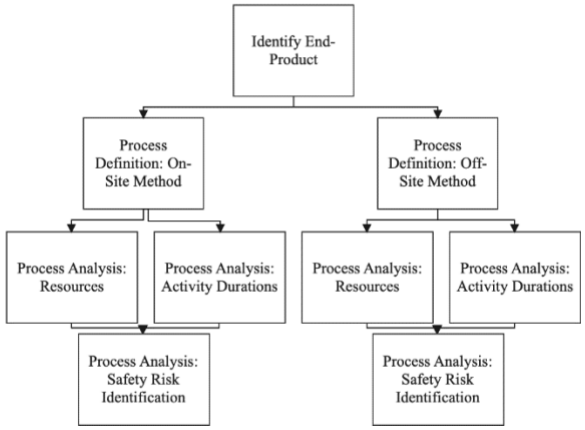

Figure 1: Process Evaluation Methodology

Define Process

The first input is a defined process map for the supply chain of the construction method. To develop a detailed process description of the expected process or what was observed on site, an activity diagram is developed.

Analyze Process

The process analysis is comprised of three analysis requirements: resource analysis, equipment analysis and risk exposure durations. If executing the process analysis during the planning stages of a project, the process analysis would be completed with estimated resources, equipment/tools and risk exposure durations. The process analysis stage is summarized as represented in **Table 1**.

Table 1: Process Analysis Table

Process Step	**Resources**	**Risk Exposure Durations**
Process Step 1	Resource 1 Resource 2	Duration 1 Duration 2
…	…	…
Process Step X	Resource 1 Resource 2 Resource X	Duration 1 Duration 2 Duration X
TOTAL RISK EXPOSURE	**SUM (Risk Exposure Durations)**	

Identify Safety Risks

The process steps should then be analyzed from a safety perspective by identifying potential sources of injury throughout the process that present risks to the resources involved. This analysis should be completed at a resource level, as each worker involved may be exposed to different risks based on their contribution to the process step. The sources of injury should consider conditions workers are exposed to, the nature of the task at hand and the methods of which the activity is completed. This provides the process inputs for a broader safety evaluation methodology (Odo and Rankin, 2022), as the identification of risks allows for extraction of risk likelihood and severity from historical jurisdictional safety incident claim data, which can then be used to quantify risk by the product of risk likelihood, severity and exposure duration. Examples of event exposure and source of injury combinations, and how they are linked to likelihood and severity data from a local jurisdictional health and safety authority's historical incident have been summarized in **Table 2**.

Table 2: Safety Risk Data

Event Exposure	Source of Injury	Risk Likelihood (Odo and Rankin, 2022)	Risk Severity (Odo and Rankin, 2022)
Fall on same level	Floor of building	0.014%	1.0
Struck by object	Nails, brads, tacks	0.042%	1.0
Overexertion in lifting	Wood, lumber	0.042%	1.0

RESULTS AND DISCUSSION

Two case study construction projects were selected to partially validate the process evaluation methodology and assess the feasibility of implementing it in practice. The first case study is a hotel construction project that leveraged both on-site and off-site methods to build the hotel rooms, and the second is a building development that used an off-site solution of pre-fabricated panels.

Process Definition

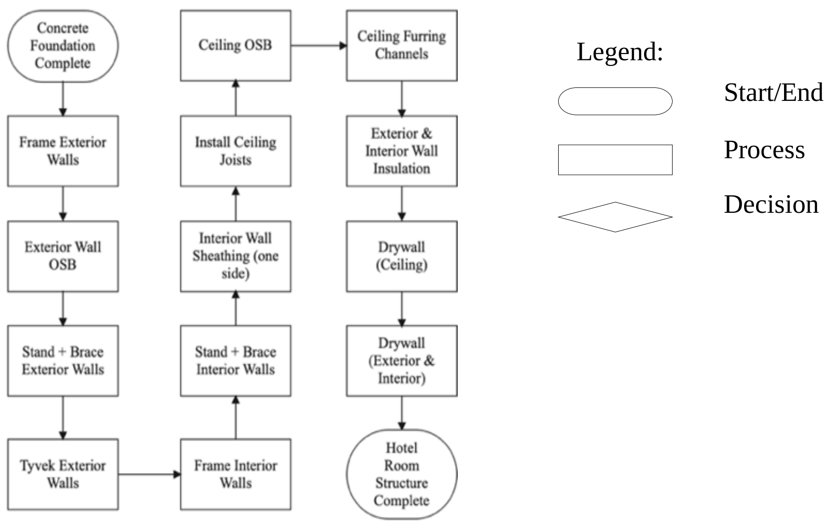

Figure 2: On-Site Construction Process Map

Case Study 1: Hotel Construction

The data for this analysis was obtained through various means as the construction of the ground level hotel rooms was already complete by the time this research was initiated. To develop the detailed process map, daily logs from the general contractor were reviewed in conjunction with site photos to determine the sequence of construction activities, as described by **Error! Reference source not found.**. To capture the work for the off-site construction methodologies, data was collected from observations at the module manufacturer and through on-site observations at the project site. There are 3 high-level process steps for the off-site construction method: module manufacturing, mobilization and on-site installation, which were defined and depicted in the same manner as the on-site construction process to complete the process definition stage.

Case Study 2: Pre-Fabricated Panels

The scope of work for the pre-fabricated panels was limited to the on-site installation of the modular components only. The data was collected through on-site observations and data collection of the construction process and was analysed to define the process map, as described by Figure 3.

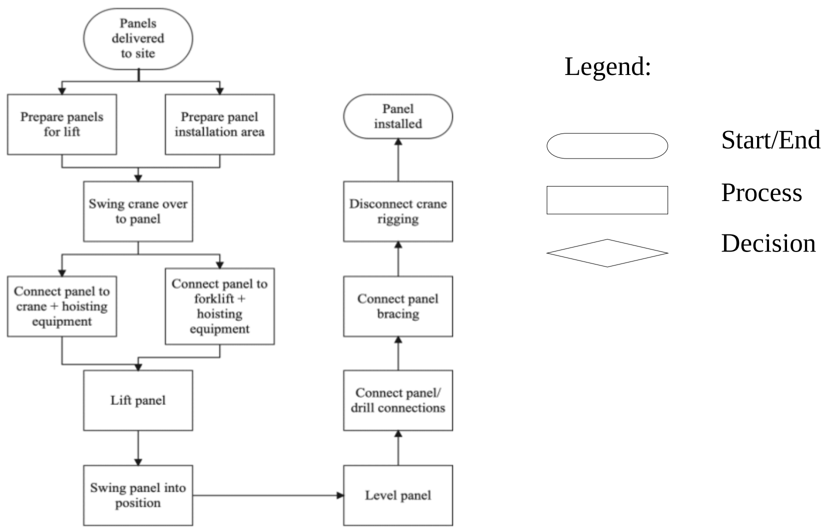

Figure 3: Pre-Fabricated Panel On-Site Installation

Process Analysis

To analyse the processes, the research leveraged four key sources of information (Table 3). The data was obtained through on-site observation, daily logs and video collection to observe the resources and determine the durations of construction activities, which is used as the risk exposure durations.

Table 3: Data Sources

Case Study 1: Hotel Construction			Case Study 2: Pre-Fabricated Panels
General Contractor	**RSMeans**	**Module Manufacturer**	**General Contractor**
Data Collected			
15 hours on-site observation 15 hours video records 159 site photos 2 months of daily logs	On-site construction resources Resource productivity	Productivity study data (van de Riet, 2021) 15 hours on-site observation 15 hours video records 159 site photos	8 hours on-site observation 8 hours video records
Data Obtained			
On-Site Construction Process	Process Resources Risk Exposure Durations	Off-Site Construction Process Off-Site Transportation Process On-Site Assembly Process	On-Site Assembly Process Process Resources Risk Exposure Durations

	Process Resources Risk Exposure Durations

From the data sources, each process was analysed to determine *total risk exposure hours* based on the durations by resource, as summarized by **Table 4**. These durations were also used as inputs into to a comprehensive safety evaluation methodology to determine the *total construction method safety score*. A detailed explanation of the total safety score findings can be found in Odo and Rankin, 2022.

Table 4: Process Evaluation Results Summary

Case Study	High Level Process Step	Risk Exposure Hours	Total Risk Exposure Hours (by Case Study)	Safety Score (Odo and Rankin, 2022)	Total Construction Method Safety Score (Odo and Rankin, 2022)
Hotel Construction	On-Site Construction of Hotel Unit	171.84	171.84	2109.76	2109.76
Hotel Construction	Off-Site Module Manufacturing	81.72	97.82	388.23	433.86
	Module Mobilization (on-site)	12.29		30.80	
	Module Installation (on-site)	3.81		14.83	
Pre-Fabricated Panels	On-Site Installation	3.01	3.01	15.81	15.81

Once the risk exposure durations are determined, the potential sources of injury present in the process were analysed. The risk exposure duration (ie. activity duration) represents the length of time a worker is exposed to an identified safety risk, and determining these two variables are valuable inputs into a more comprehensive safety evaluation that also considers likelihood and severity of risks. A safety risk identification analysis was completed for all resources in each process step, and summarized into a table, as highlighted in Table 5, which shows a portion of results from the on-site construction process safety risk analysis.

Table 5: Safety Risk Analysis Results

Process Step	Resource	Event Exposure	Source of Injury
Frame Exterior Walls	Carpenter 1	Fall on same level	Floor of building Ground Ice, sleet, snow
	Carpenter 2	Fall on same level	Floor of building Ground Ice, sleet, snow

DISCUSSION

For the methods assessed, the notable difference between the on-site and off-site construction processes was the decreased duration of activities in the off-site environment. While the off-site construction processes have significantly more process steps due to the fact that components are constructed, then transported and installed on site, the individual construction tasks are more productive and shorter in duration. For example, a total of 97.82 cumulative labour hours are required for the off-site hotel room modules, in comparison to 171.84 cumulative labour hours for on-site construction, which is a 55% decrease. When comparing the pre-fabricated panel case study to the hotel construction case study, it was noted that the labour hours for the on-site module installation versus the on-site pre-fabricated panel installation are comparable in value at 3.81 and 3.01, respectively.

When analysing the observed processes from a safety perspective, the total labour hours represent the duration of time that an identified worker is exposed to risk throughout the process. This concept was explored in greater detail by Odo and Rankin (2022), where quantified safety scores were determined for the observed processes, as summarized in Table 4. In the hotel case study, the results show that the off-site construction methodology can be considered the safest approach of construction to deliver the desired end-product of a hotel room. The on-site construction process obtained a safety score almost 5 times greater than the comparable off-site construction process, 2109.76 versus 433.86, respectively. In the case of this evaluation methodology, the lower the score, the safer the process. The second case study, which analyzed the installation of the pre-fabricated panels, determined a total safety score of 15.81. This low score can be attributed to the relatively short risk exposure durations observed throughout the process. This case study was limited to the on-site installation portion of the work only, and is comparable to the results of 14.83 obtained for the on-site installation of the hotel modules.

This study demonstrated the feasibility of data collection and implementation in practice. It's recommended that future studies investigate the benefits of implementing digital technologies to simplify the evaluation and make it more likely to be adopted by industry. Recommendations include developing an interface that will automate the extraction of relevant Event Exposure and Sources of Injury information from the historical Provincial incident claim databases and implementing technology to track movement of resources the project site in the x, y and z directions to simplify the determination of risk exposure durations.

CONCLUSION

The objective of the research was to develop a generalized methodology to capture and analyze processes for the purpose of comparing construction methods from a safety perspective. To achieve this, the research standardized a way to define and analyze construction processes and provides a framework for capturing data for future comparisons. This is done by defining the process and resources, analyzing activity durations and identifying the safety risks for the complete supply chain of a defined end-product.

Throughout the research, there were lessons learned that have resulted in recommendations for future studies. Firstly, the data collection for this case study was completed in a variety of ways from different researchers. It’s recommended that all work be completed by the same researcher for consistency. Secondly, the study provided an understanding of which aspects of the methodology are labour intensive and time consuming, highlighting which areas are impractical for practitioners to adopt. The development of this evaluation model creates a foundation upon which additional construction processes can be evaluated in future.

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