Systematic Investigation of Non-conformance Root Cause in Prefabrication: A Nuclear Case Study

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Abstract –

To help project managers better understand non-conformance in prefabrication projects, this research presents a probabilistic empirical study on non-conformance reports (NCRs), their root cause and frequency of occurrence, as well as their impact on the project cost and time. Data from a completed nuclear project were collected and analyzed, where 1,179 NCRs were raised during the three-year fabrication period, consisting of six distinct modules and a ring girder. Five broad categories are used to distinguish general liabilities of those NCRs (internal vs. external) as well as at which stage along the project the non-conformance occurred (material receipt vs. fabrication). A further breakdown of 33 defect codes from those broad categories reflect the specific root cause of each non-conformance. Probabilistic analysis show that geometric-related non-conformance amongst all defect codes represent over half of all analyzed NCRs. Furthermore, in the interest of understanding the impact of these geometric-related issues on the project, 84 NCRs were sampled for evaluation; they were reviewed and assessed individually by an industry expert who is familiar with the nuclear project in this study, to estimate the cost and time impact of the sampled non-conformance. Based on the estimate, the average cost and time impact per non-conformance are nearly $1,000 and 14.5 man-hours, respectively, accounting for additional resources required to rework, inspect again, and release the assembly. The findings provide project managers with useful implications to identify non-conformance root cause in prefabrication, reduce the risk and impact of these issues, and improve the performance of future projects.

Keywords –

Non-conformance; Nuclear; Prefabrication; Rework; Root cause; Quality control

1 Introduction

Construction is an integral industry of the Canadian economy, such that its $140 billion market contributes to 7.3% of GDP [1]. However, the worker productivity trend does not reflect growth experienced by the construction industry, which has nearly doubled since 1997. Construction labour productivity in Canada increased by less than 10% in the past two decades, while productivity in the manufacturing industry improved by almost 50% over the same time [2]. Efforts to improve construction productivity take advantage of the more established and mature manufacturing processes and techniques, such as modularization and off-site assembly. As civil industry work requirements become more demanding, and modular component tolerance continues to decrease for more complex projects, there exists a need to incorporate and utilize quality control technologies similar to what have been used in the manufacturing and automotive industries for years.

Project physical complexity may be affected by the component and module size dimensions, along with geometry of the overall module. Quality checks in the current modular fabrication sector may occur in the form of documented quality control by qualified staff, or undocumented self-checks by the craft workers themselves. To rework items that failed quality checks, the process includes taking the modules apart, realigning individual components, attaching the pieces together again, and conducting another quality check. This is a significant waste of resources, resulting in reduced overall productivity represented by additional time and manpower spent on correcting the errors.

To improve the productivity and continuous flow of prefabrication and construction, it is necessary to identify and better understand non-conformances along the project processes that would cause reworking. A number of studies have focused on developing real time monitoring technologies and software to detect defects of construction components [3,4]; however, less attention is received to examine the frequency of defects and non-conformances, as well as their impact on project performance such as cost and time. It is partly due to the lack of empirical project information available for analyzing the non-conformance issues and their impact. To address this gap, this paper collected data from a completed nuclear prefabrication project, and conducted probabilistic empirical study on non-conformances, their root cause and frequency of occurrence, as well as their impact on the project cost and time. The findings provide project managers with useful implications to identify non-conformance root cause in prefabrication, reduce the risk and impact of these issues, and improve the performance of future projects.

The remaining of this paper is structured as follows. Section 2 includes an overview of the relevant studies on reworking in construction in general and specific reworking challenges in prefabrication projects. Section 3 introduces the research methodology and background information of the nuclear project chosen for the empirical analysis. The subsequent analyses include defect root cause analysis in Section 4 and geometric defect impact analysis in Section 5. Lastly, Section 6 summarizes the conclusions and future work.

2 Literature Review

2.1 Reworking in Construction

Due to the nature of work in the industry, reworking is largely inevitable in traditional construction. Unlike manufacturing, where process automation could be achieved and optimized by machinery, the need for human involvement in standard construction projects introduce the risk of non-conformance errors associated with poor workmanship. There are several potential reworking root causes in addition to construction site human error, such as design change, defective materials, and lack of planning and coordination within the project team; nonetheless, their impact on the overall project performance is evident. In a survey of 161 Australian construction projects, it was observed that costs related to reworking contribute an average of 52% to a project's cost growth [5], which may include direct cost (labour and material to rework) and other intangibles such as schedule delays and litigation cost. From the same survey, the mean direct and indirect costs to rework were found to be 6.4% and 5.6% of the original contract value, respectively [5]. Other research studies reflect a similar impact in other types of construction projects, such that the cost to rework represents 4% of contract value in residential construction [6], adds 10% of contract value in civil infrastructure projects [7], and ranges from 3.1% to 6.0% of the project value in building projects [8].

Reworking root causes have been the subject of many subsequent research efforts to reduce its impact. In a study that analyzed 359 projects with varying project characteristics from the Construction Industry Institute (CII) database, it was found that heavy industrial projects for contractors were most affected by reworking, and the most important root causes are owner change and design error/omission for both owner and contractor reported projects [9]. These issues may result from inadequate planning and poor communication amongst owners, designers and constructors, thus they highlight the need for a comprehensive reworking management system that involves all the stakeholders and different organizational and technological measures at every stage of the project [10]. This recommendation echoed the findings from a survey of 115 civil infrastructure projects by Love et al. [7], where they identified the ineffective use of information technology to communicate as the primary factor contributing to reworking. Therefore, reworking reduction requires the need to better plan and manage the design and documentation process.

To minimize and rectify the impact of reworking, preventative methods must be applied in order to reduce the probability of errors occurring throughout a project lifecycle, and appraisal measures should be implemented to detect defects and assess conformance to the required tolerance level.

2.2 Reworking in Prefabrication

Prefabrication, preassembly, modularization, and off-site fabrication (PPMOF) research and practice have been reaping growing interest over the years. Its potential for increased project performance offers improvement in construction quality, productivity, safety, sustainability, cost, and schedule [11,12], thus becoming an appealing and effective alternative to traditional stick-built construction for owners and contractors alike. As a fundamentally distinct approach to construction, there are varying risks in PPMOF compared to traditional stick-built method, increasing demands and complexity to aspects of project organization, engineering, procurement, planning, monitoring, coordination, communication, and transportation [13]. Therefore reworking in prefabrication must be managed through understanding the risks at different stages of a PPMOF project, as well as recognizing the impact of these risks on project performance, such as cost and schedule.

A study identified and categorized risks into general risk factors, in-plant risk factors, and on-site risk factors, and subsequently quantified and assessed them to propose a risk management framework in modular construction, where the process was simulated to evaluate the exposure of cost and schedule to quantified risk factors [14]. This necessitates monitoring and controlling risks in PPMOF, from both the managerial and technical context. Specific to modular construction, dimensional and geometric compliance for strict tolerance requirements were examined, in which a structural analysis framework incorporates cost and risk to assess the optimal design solutions [15]. Another risk management framework also includes the evaluation of tolerance-related issues, where the compromise between off-site and on-site costs contribute to the identification of the optimum geometric variability, to improve modularization performance and maximize its benefits [16]. Owing to the advancements in technology research, additional tools can be used to help facilitate detection of non-conformance cases in design (component clashes) and construction (installation tolerance discrepancies), such as building information modelling (BIM) for project design and lifecycle control, robotics automation for fabrication control, and 3D sensing technology for quality control.

These studies emphasized the importance of quick identification of risks and potential quality problems, but a comprehensive understanding of non-conformance issues resulting from those risks has been missing from the current body of knowledge. Therefore, an empirical analysis regarding the non-conformance root cause and their impact on project time and schedule performance is required to fill the gap.

3 Methodology and Project Background

To understand the types of non-conformances, their frequency of occurrence within a project, as well as their impact on the project cost and schedule, the research team collaborated with a major fabricator in the construction industry, and methodology as summarized in Figure 1 is followed throughout the research.

The research team chose one of the industry partner's completed nuclear projects, because of the systematic collection of data during quality control through all stages of fabrication, resulting in a comprehensive data log of non-conformance for this case study analysis. Due to the complex nature of this nuclear project, the information recorded were of higher granularity than other non-nuclear projects. A total of 1,179 non-conformance reports (NCRs) were raised during the three-year fabrication period for this project, which required the fabrication of six distinct modules and a ring girder for nuclear power plants (NPPs) in the United States. The research team obtained a copy of the entire NCR data log for the project, and it formed the basis of all subsequent analyses for this case study.

The nuclear modules range in size from 9,200 lbs (4,173 kg) to 102,000 lbs (46,266 kg). Figure 2 illustrates the 3D design of modules fabricated in the project case study. Each module contains vital components to mechanical systems within the NPPs, such as passive containment cooling, passive core cooling, liquid radioactive waste, demineralized water, fire protection, residual heat removal, as well as pressurizer safety and automatic depressurization. Given the design complexity of each module and the need to adhere to nuclear operational and safety requirements, they also have several challenges throughout the project, including:

- Management of the high number of system code changes, ensuring the quality requirements of each system are met.
- Module frame construction with "megabeam" and non-standard truss geometries.
- Assembly, welding and inspections of frame, spools and supports in a tight and complex geometry.
- Welding of high strength SA-517 steel requires specialized weld procedures and regimented pre-heat and post-weld heating cycles.

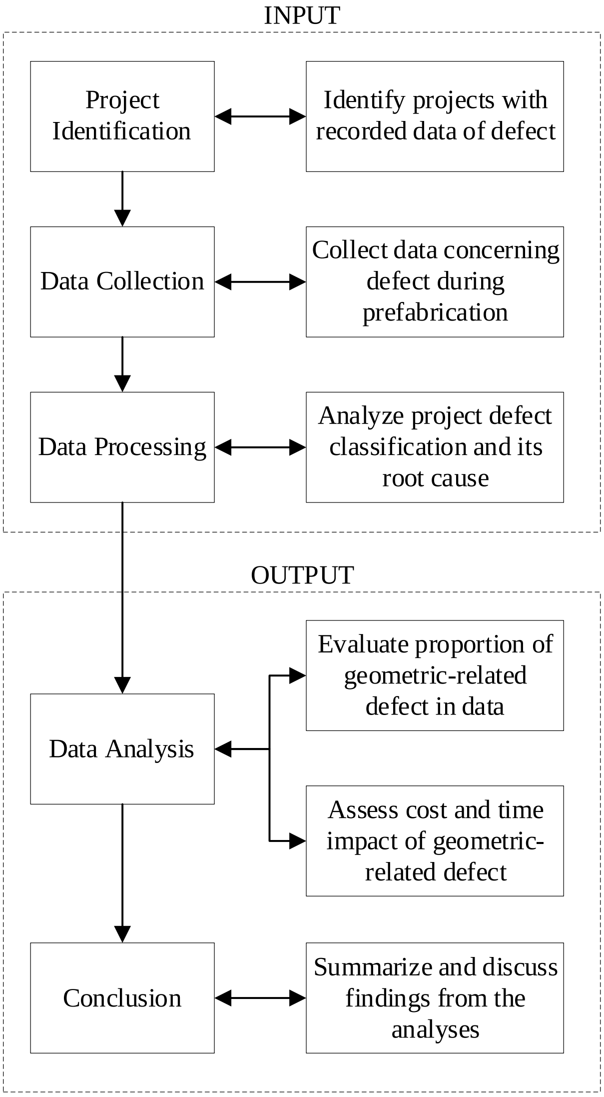

Figure 1. Research methodology

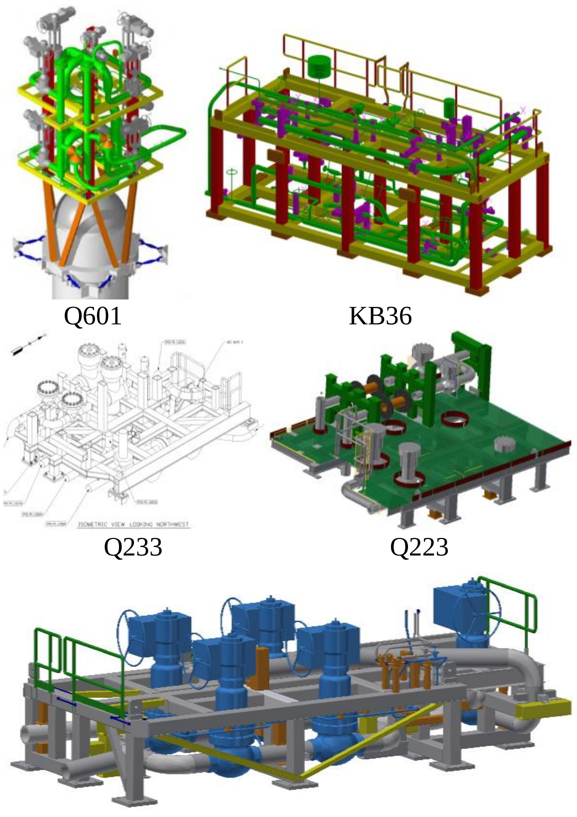

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Figure 2. Illustrations of some the prefabricated modules for NPPs in this project case study

Each module in the nuclear project is unique, and their fabrication required highly skilled craft workers to fit and weld all the pressure piping components and supporting structural assemblies. To meet project requirements and deadlines, the fabrication shop was at full capacity with 80 dedicated workers. The workforce included 20 quality control personnel, who are responsible for quality control throughout the project lifecycle, including all activities of material receipt, in-progress fabrication, and final release for shipment to site. The modules are also subjected to additional inspection by third-party Authorized Nuclear Inspectors, who ensure all fabricated components and systems are fit for use for nuclear applications according to design.

4 Defect Root Cause Analysis

In accordance with the industry partner’s internal Quality Control Procedure, each NCR is assigned a “defect code” to reflect the root cause of its non-conformance. These defect codes are categorized under five broad types, which are as follows:

1. Procurement Issue (Internal)
2. Material Issue from Vendor (External)
3. Fabrication / Construction Issue (Internal)
4. Engineering / Document Control Issue (Internal)
5. Free Issue Material from Customer (External)

These five categories encompass almost all possible non-conformances a fabrication shop would experience, during the two main phases of (1) material receipt and (2) fabrication. Material liabilities are further differentiated between materials procured through vendors and those supplied by the owner. They are considered as external responsibilities through no fault of the fabrication shop. On the other hand, drafting errors and omissions as well as fabrication miscues are viewed as internal accountabilities, where craft workers such as fitters and welders are responsible for rectifying their identified non-conformance.

A total of 33 defect codes as identified in the Quality Control Procedure reflect the specific root cause of each non-conformance. All 1,179 NCRs from the nuclear project were analyzed for their defect code as well as the specific nuclear module affected. Table 1 summarizes the frequency of each defect code as documented in the NCR data log. Furthermore, for clarity, defect codes related to geometric non-conformance are also highlighted grey.

Through qualitative assessment of all documented NCR, it was found that some of the defect codes were used interchangeably, such as codes 2.3, 2.4, and 2.9, which concerns “damaged material”, “material defect”, and “dimensional / out of tolerance” issues, respectively. Despite their difference in assigned code description, they are all related to specific tolerance measurements (i.e., dimensions) and relationships of angles and surfaces of the objects. Thus, based on the root cause analysis of non-conformance in this nuclear project, defect codes 2.3, 2.4, 2.9, 3.1, 3.3, 3.7, 5.1, and 5.2 are actually geometric in nature, and they represent the majority of reported issues, as summed at the end of Table 1. Figure 3 displays module difference in geometric defect code proportion, compared to the baseline average for the project.

While it is unclear how module complexity affects geometric non-conformance, it is evident from Figure 3 that defect codes 2.9 (material “dimensional / out of tolerance” issues) and 3.3 (fabrication “dimensional / out of tolerance” issues) are the two most frequently cited non-conformance. The two defect codes together represent over half of the geometric-related issues for each module, except for Q305, which had a higher proportion of non-conformance concerning “material defect”. This further demonstrates the strict design and tolerance requirements for nuclear projects, therefore, any tools used for quality control must be able to meet the specific accuracy and precision demand for effective inspection.

Table 1. Non-conformance root cause and their frequency

Defect Codes		Frequency	Percentage
1.	Procurement Issue		
1.1	Purchase Order Error	2	0.17%
2.	Material Issue (Vendor)		
2.1	Missing MTR / Documentation	8	0.68%
2.2	Incorrect MTR (Material Test Report)	4	0.34%
2.3	Damaged Material / Item - Incoming	23	1.95%
2.4	Material Defect	100	8.48%
2.5	Wrong Material / Improper Specification	16	1.36%
2.6	Contamination	11	0.93%
2.7	Identification / Traceability	30	2.54%
2.8	Counterfeit Material / Item	0	0.00%
2.9	Dimensional / Out of Tolerance	191	16.20%
2.10	Improper Material Substitution	3	0.25%
3.	Fabrication / Construction Issue		
3.1	Damaged Material / Item - Production	69	5.85%
3.2	Improper Material Substitution	1	0.08%
3.3	Dimensional / Out of Tolerance	212	17.98%
3.4	Use of Detrimental / Unapproved Product	9	0.76%
3.5	Unqualified Welder / Welding Operator	4	0.34%
3.6	Wrong WPS Used	6	0.51%
3.7	Fitting Error	20	1.70%
3.8	Weld Defect	71	6.02%
3.9	Wrong Material / Consumable Used	10	0.85%
3.10	Lack of Process / Procedural	168	14.25%
3.11	Drawing Error	17	1.44%
3.12	Machining Error	12	1.02%
3.13	Loss of FME (Foreign Material Exclusion)	2	0.17%
3.14	PWHT (Post Weld Heat Treatment) Error	2	0.17%
3.15	Pressure Test Failure	6	0.51%
3.16	Paint Defect	22	1.87%
4.	Engineering / Document Control Issue		
4.1	Drawing or Drafting Error	17	1.44%
4.2	Non-current Revision	1	0.08%
4.3	Process Compliance	26	2.21%
5.	Free Issue Material (Customer)		
5.1	Damaged Material / Item	12	1.02%
5.2	Does Not Meet Code / Specification / Standard / Contract	66	5.60%
5.3	Insufficient / Incomplete Documentation	38	3.22%
Total		1,179	100.00%
Geometric		693	58.78%

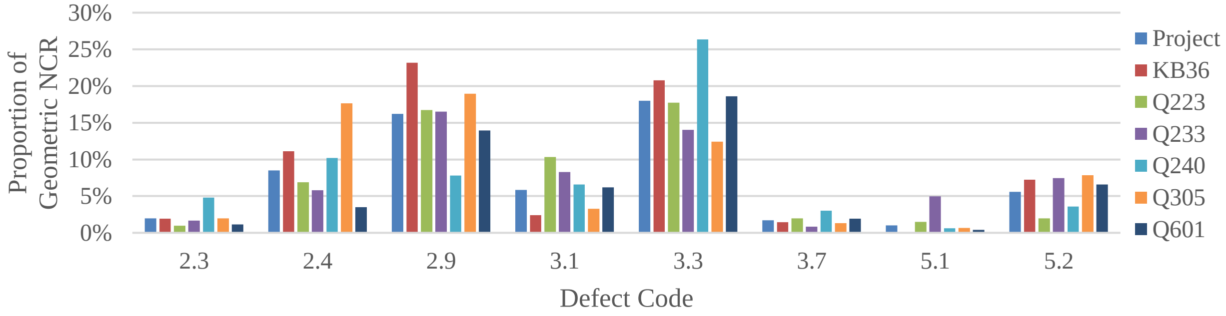

Figure 3. Module difference in geometric defects

5 Geometric Defect Impact Analysis

Although each NCR in the data log summarized information such as the module affected, description of non-conformance, remedy proposal, as well as explicit instructions on how to rectify the errors, it is almost impossible to cross-reference a project change order to a specific non-conformance root cause. Consequently, a preliminary estimate was carried out to assess the cost and time impact of correcting geometric-related issues. An interview was conducted with the fabrication manager who oversaw the entire nuclear project, having experience handling almost all the issues reported in the data log, including proposing defect remedies and overseeing their execution.

Out of the 693 geometric-related non-conformances, 84 NCRs were sampled, and this is based on having a confidence level of 95% that the real value is within ±10%. While it would be better to have more random samples for a higher confidence level and lower margin of error, the estimate is also constrained by time availability of the project team that has direct knowledge of these NCRs. Nonetheless, the proportion of each defect code within the population of geometric-related NCR is preserved.

During the interview with the fabrication manager, these sampled NCR were reviewed individually for their non-conformance root cause, and further assessed for their impact on the nuclear project. Table 2 summarizes the number of samples from each defect code that constitute the estimate, as well as the statistics of estimated cost and time impact of the 84 sampled geometric non-conformances.

In general, a baseline man-hour of six hours is applied to each NCR, to account for the time it takes to review the non-conformance, file the report, formulate a solution, and release the assembly after adjustments are executed if required. Furthermore, a base hourly rate of $65 is assumed for both the quality control personnel and craft workers (i.e., fitters and welders). For each NCR, any additional time is based on labour required to rework, and any additional cost is based on new materials and extra man-hour. As shown in Table 2, the average cost impact of sampled geometric non-conformance is almost $1,000, and the time impact is approximately 14.5 man-hours. The results of the estimate are further evaluated to characterize the sampled data, which would allow curve fitting of probability distributions. Figure 4 presents the cost and time impact histograms.

Probability paper plotting is used to verify assumed probability distribution. Three common distributions are assessed, including normal, lognormal, and Weibull distribution. Due to the linear relationship of the plot, coefficient of determination (R^2) can be used to measure how well a linear regression model fits the dataset. Comparing the three distributions, it was found that lognormal distribution had the strongest linear association, as it had the highest R^2 value for both time and cost impact metrics. Figure 5 shows lognormal probability paper plots for the impact of sampled NCRs.

Table 2. Estimate cost and time impact of geometric non-conformance

Defect Code		Number of		Cost ($)			Time (Man-Hour)		
		Population	Sample	Min	Max	Mean	Min	Max	Mean
Material Receipt	2.3	23	3	390	1,040	607	6	16	9.3
	2.4	100	12	390	910	531	6	14	8.2
	2.9	191	24	650	3,250	1,354	10	50	19.3
	5.1	12	1	390	390	390	6	6	6.0
	5.2	66	8	390	3,250	934	6	50	14.4
Fabrication	3.1	69	8	390	1,730	712	6	22	10.4
	3.3	212	26	390	1,770	1,065	6	25	15.7
	3.7	20	2	455	590	523	6	7	6.5
Total		693	84	390	3,250	988	6	50	14.5

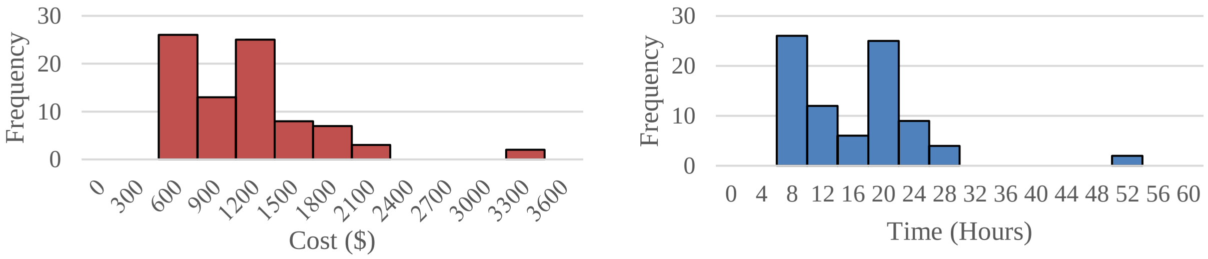

Figure 4. Sampled geometric non-conformance impact histogram: cost (left) and time (right)

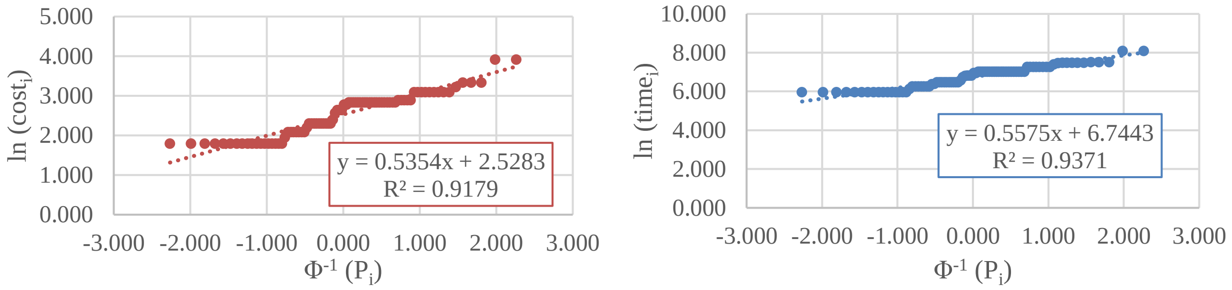

Figure 5. Lognormal probability paper plot of impact: cost (left) and time (right)

6 Conclusions and future work

In summary, there are some key findings from the non-conformance root cause analysis of the nuclear project case study. According to the industry partner's internal Quality Control Procedure, five categories are used to distinguish general liabilities (internal vs. external) of non-conformance, as well as at which stage along the project the non-conformance occurred (material receipt vs. fabrication). A total of 33 "defect codes" are classified under these five broad categories, specific to the type of non-conformance observed. Upon qualitative analysis of all 1,179 documented NCRs, it was found that defect codes 2.3, 2.4, 2.9, 3.1, 3.3, 3.7, 5.1, and 5.2 per Table 1 are actually geometric in nature, and they represent nearly 60% of all reported issues during the three-year fabrication period. Within these geometric-related NCRs, over half of them are issues concerning dimension and tolerance for incoming materials and fabrication.

In the interest of understanding the impact of these geometric-related issues on the project, 84 NCRs were sampled for evaluation; they were reviewed and assessed individually by an industry expert who is familiar with the nuclear project in question, to estimate the cost and time impact of these sampled non-conformance. Based on the estimate, the average cost impact is almost $1,000 and the average time impact is 14.5 man-hours; they account for additional resources required to rework and to release the assembly. Subsequent analysis confirms that both of the impact metrics conform very closely to lognormal distribution.

It should be noted that this is the only data log available where all non-conformances are tracked and documented throughout the project lifecycle within the fabrication shop; however, the methodology and findings may be applied to other prefabrication projects in the industry, specifically the classification of defect codes as well as the need to address geometric-related non-conformances during fabrication.

Moreover, the data log does not include non-conformance reported at project site, meaning the impact does not account for fabrication errors that are overlooked before shipment, or any liability dispute between the fabricator and site installation team. For example, in a high volume and relatively complex project, it may require a crew of four for three months to inspect, count, and bill all materials of the prefabricated spools at the project site. Additional costs may also be considered to rework any errors, which include but are not limited to crew travel, lodging, schedule change, spool and/or module transport, reworking at site and/or back in the shop, as well as performing required non-destructive testing again. These expenses can amount to hundreds of thousands to millions of dollars depending on the project. Consequently, this necessitates accurate and precise documentation of the final assembly, before it leaves the fabrication shop to project site. With 3D scanning becoming increasingly affordable and accurate for industrial use, it could function as a tool for geometric quality control during material receipt and fabrication in-process check, as well as act as an approved internal record to mitigate the risk of legal disputes of assigning responsibility to rework after shipment to site.

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References

[1] Statistics Canada, Table 36-10-0434-03: Gross domestic product (GDP) at basic prices, by industry, annual average, (2019). https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3610043403 (accessed September 20, 2019).

[2] Statistics Canada, Table 36-10-0480-01: Labour productivity and related measures by business sector industry and by non-commercial activity consistent with the industry accounts, (2019).

https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3610048001 (accessed September 20, 2019).

[3] M.S.A. Enshassi, S. Walbridge, J.S. West, C.T. Haas, Probabilistic Risk Management Framework for Tolerance-Related Issues in Modularized Projects: Local and Global Perspectives, ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering. 6 (2020) 04019022. https://doi.org/10.1061/AJRUA6.0001036.

[4] C. Rausch, C. Haas, Automated shape and pose updating of building information model elements from 3D point clouds, Automation in Construction. 124 (2021) 103561. https://doi.org/10.1016/j.autcon.2021.103561.

[5] P.E.D. Love, Influence of Project Type and Procurement Method on Rework Costs in Building Construction Projects, Journal of Construction Engineering and Management. 128 (2002) 18–29. https://doi.org/10.1061/(ASCE)0733-9364(2002)128:1(18).

[6] A. Mills, P.E. Love, P. Williams, Defect Costs in Residential Construction, Journal of Construction Engineering and Management. 135 (2009) 12–16. https://doi.org/10.1061/(ASCE)0733-9364(2009)135:1(12).

[7] P.E.D. Love, D.J. Edwards, H. Watson, P. Davis, Rework in Civil Infrastructure Projects: Determination of Cost Predictors, Journal of Construction Engineering and Management. 136 (2010) 275–282. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000136.

[8] J.B.H. Yap, P.L. Low, C. Wang, Rework in Malaysian building construction: impacts, causes and potential solutions, Journal of Engineering, Design and Technology; Bingley. 15 (2017) 591–618. http://dx.doi.org.proxy.lib.uwaterloo.ca/10.1108/JEDT-01-2017-0002.

[9] B.-G. Hwang, S.R. Thomas, C.T. Haas, C.H. Caldas, Measuring the Impact of Rework on Construction Cost Performance, Journal of Construction Engineering and Management. 135 (2009) 187–198. https://doi.org/10.1061/(ASCE)0733-9364(2009)135:3(187).

[10] G. Ye, J. Jin, B. Xia, M. Skitmore, Analyzing Causes for Reworks in Construction Projects in China, Journal of Management in Engineering. 31 (2015) 04014097. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000347.

[11] L. Aye, T. Ngo, R.H. Crawford, R. Gammampila, P. Mendis, Life cycle greenhouse gas emissions and energy analysis of prefabricated reusable building modules, Energy and Buildings. 47 (2012) 159–168. https://doi.org/10.1016/j.enbuild.2011.11.049.

[12] J. Hong, G.Q. Shen, C. Mao, Z. Li, K. Li, Life-cycle energy analysis of prefabricated building components: an input–output-based hybrid model, Journal of Cleaner Production. 112 (2016) 2198–2207. https://doi.org/10.1016/j.jclepro.2015.10.030.

[13] J. Song, W.R. Fagerlund, C.T. Haas, C.B. Tatum, J.A. Vanegas, Considering Prework on Industrial Projects, Journal of Construction Engineering and Management. 131 (2005) 723–733. https://doi.org/10.1061/(ASCE)0733-9364(2005)131:6(723).

[14] H.X. Li, M. Al-Hussein, Z. Lei, Z. Ajweh, Risk identification and assessment of modular construction utilizing fuzzy analytic hierarchy process (AHP) and simulation, Can. J. Civ. Eng. 40 (2013) 1184–1195. https://doi.org/10.1139/cjce-2013-0013.

[15] Y. Shahtaheri, C. Rausch, J. West, C. Haas, M. Nahangi, Managing risk in modular construction using dimensional and geometric tolerance strategies, Automation in Construction. 83 (2017) 303–315. https://doi.org/10.1016/j.autcon.2017.03.011.

[16] M.S.A. Enshassi, S. Walbridge, J.S. West, C.T. Haas, Integrated Risk Management Framework for Tolerance-Based Mitigation Strategy Decision Support in Modular Construction Projects, Journal of Management in Engineering. 35 (2019) 05019004. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000698.