Simulation Modelling and Analysis of Impact of 3D Feedback Workflow on Prefabrication of Industrial Construction

by

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

The construction industry has not been experiencing the same level of productivity increase as the manufacturing industry, due to their divergent production methods. While traditional construction projects are unique, craft-based, and typically done on-site, manufacturing is able to mass produce standardized products on assembly lines in a controlled environment. 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. Rework of items that failed quality checks leads to significant waste of resources, resulting in reduced overall productivity represented by additional time and manpower spent on correcting the errors. The solution set to this problem ultimately needs to address lost productivity due to rework, and generate value from its operation in the industrial fabrication workflow.

The use of 3D data acquisition and 3D feedback is proposed to be part of the quality control process of pipe spool fabrication, which takes place during fitting and before shipment to site. The existing prevailing workflow and the proposed workflow using the new technology are assessed using discrete-event simulation, and three implementation scenarios are investigated, which are: (1) nuclear projects, (2) small bore non-nuclear projects, and (3) large bore non-nuclear projects. They represent different quality control processes for their particular requirements, as well as their specific activity process times given the nature of their assemblies.

The analysis of the simulation results show that the revised workflow improved performance for all three project types, specifically in rework reduction and overall fabrication time reduction. Risk assessment was also carried out, in order to quantify the risk mitigation and accrued benefits by implementing the revised fabrication workflow for pipe spool assembly. The difference in risk was considered as a project benefit under economic analysis, and it was found that the relatively short payback period for the fabricator justifies the initial technology investment required to set up the platform for 3D feedback in the revised workflows.

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Chapter 1
Introduction

1.1 Background

Construction is an integral industry of the Canadian economy, such that its $140 billion market contributes to 7.3% of gross domestic product (GDP) (Statistics Canada 2019c). Likewise, more than 1.4 million Canadians are employed in construction and its related services, representing 7.7% of the national labour force (Statistics Canada 2019a). 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% at the same time (Statistics Canada 2019b). Though both industries produce goods, their production methods are divergent: traditional construction projects are unique, craft-based, and typically done on-site, while manufacturing is able to mass produce standardized products on assembly lines in a controlled environment. These fundamental differences and constraints preclude innovative technologies from being adopted at the same time and at the same rate between the two industries.

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 well as just-in-time (JIT) and lean production derived from the Toyota Production System (Winch 2003). Furthermore, recent rapid advancement and ubiquity of information and communications technology (ICT) allow the feedback loop of data sensors and computer analysis to continuously optimize work processes and deliver quality products. This new approach is a paradigm shift in production, in which work automation relies on the Internet of Things (IoT) to transfer information and data between different devices and systems. While examining the correlation between ICT investment and labour productivity, it was found that though ICT is still contributing positively to productivity growth, its declining contribution in Canada account for the productivity slowdown experienced since the early 2000s (Mollins and St-Amant 2019). Nonetheless, the implementation of any new technology is essential to the improvement of construction productivity; through analysis of variance and regression, it was determined that activities experiencing significant changes in equipment technology have witnessed substantially greater long-term improvements in labour productivity than those that have not experienced a change (Goodrum and Haas 2004).

Pertinent to the construction industry, steel is a critical source of material in every major construction project, used for reinforcing steel and structural framing in bridges and buildings, as well as pipe and tubing to transport fluids in industrial process facilities such as oil refineries and chemical plants. Steel product manufacturing from purchased steel in Canada is a $1.7 billion market in GDP (Statistics Canada 2019c), in which the production of steel pipe and tubing has an average annual volume of almost 2.5 million metric tonnes (Statistics Canada 2018). In steel construction, fabricators are at the centre of transition towards implementing manufacturing innovations, where industrialization of construction is driven in part by standardization and prefabrication, as well as the exploitation of advanced computer-based technology (Crowley 1998). With respect to pipe spools, they are now increasingly being prefabricated and preassembled before shipment to site (Song et al. 2005), due to the benefit of cost reduction, schedule acceleration, as well as quality improvement over on-site installation.

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. Rework of items that failed quality checks 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.

Innovative approaches to this complex challenge include: (1) three-dimensional (3D) imaging technology used for acquiring dimensional control data, (2) automated transfer of information between tools, platforms, and workflow steps, (3) features that would be conducive to conduct quality control, such as improved visualisation of design intent, and (4) strategies for deployment of these innovations in practice. The solution set to this problem ultimately needs to address lost productivity due to rework, and generate value from its operation in the industrial fabrication workflow.

In a report commissioned jointly by the Institute for Research in Construction of the National Research Council of Canada and by the Science, Innovation and Electronic Information Division of

Statistics Canada, it is argued that industries are able to increase their production capabilities and improve their productivity through the adoption of more advanced technologies and practices (Seaden et al. 2001). However, construction as a largely heterogeneous and fragmented industry lacks the horizontal and vertical integration necessary to effectively implement innovations and improve productivity substantially. For a given project, stakeholders involved throughout the entire process from start to finish may include clients who specify requirements, engineers who draft the designs, contractors who build the intended construction, sub-contractors who perform specialty craft work, and regulators who verify that final products are up to code. It is not surprising then that in a survey conducted on innovation, advanced technologies, and practices in the construction and related industries, ICT was identified as one of the most critical sources of competitive advantage for a business (Seaden et al. 2001). The ability to collect, disseminate, and receive information proved to be extremely valuable, such that the flow of updated data between relevant stakeholders allow decisions to be made effectively.

With rapid technological change as a clear impetus for engaging in innovative strategies, there is an increasing reliance on experienced personnel who are familiar with the new technology or method. The hiring of multi-skilled teams together with development of proprietary technologies are examples of firms promoting the culture for innovation, such that there is consideration for innovation from both the technology standpoint and the perspective of business strategy. Though innovation is generally considered an added risk rather than a competitive advantage (Seaden et al. 2001), it can still be viewed as an enabler or contributor to measures of success, whether it be reputation, profit, market share, or efficiency (Waugh et al. 2016). With that said, the evaluation and endorsement of any innovation must take these industry sentiments into account, in such a way that their operating value after workflow implementation is duly assessed. This includes quantification of current risk exposure with traditional and prevailing work processes, analysis of risk mitigation achieved through improved procedures, as well as proposition of a guideline for innovation deployment strategy in the construction industry. These means will be explored in this thesis to facilitate the drive towards rework reduction and productivity increase.

1.2 Scope and Objectives

The scope of this thesis is limited to assessing the impact of a custom augmented reality software application created for quality control of pipe spool fabrication. Work processes at the research industry partner's prefabrication facilities in Edmonton, AB and Cambridge, ON, were observed and examined to model the pipe spool fabrication workflow in nuclear and non-nuclear context. Three distinct quality control stages are derived based on the modelled workflow, these specific stages take place before or during: (1) material receipt, (2) spool assembly, and (3) final shipment. They represent major checkpoints of quality control being conducted along the existing fabrication workflow; quality control in this case entails the verification of geometric compliance, so features that require higher precision such as weld defects are not within the scope of this thesis.

Analysis is then carried out based on the use of 3D feedback within the custom software application, which acts as part of the modified fabrication workflow implemented during quality control. In this thesis, 3D feedback consists of two elements, namely: (1) 3D imaging and data acquisition, and (2) 3D visualization of design intent. Due to the characteristics of physical fabrication activities, discrete-event simulation (DES) is used to represent the sequence of events in the workflow. Impact assessment is restricted to tangible factors such as cost and time, therefore intangible effects like reputation are not researched.

The overall objective of this thesis is to assess the degree of risk mitigation that would be achieved by implementing revised fabrication workflows for pipe spool assembly. Though all the necessary technologies for 3D feedback are presently available on the commercial market, the value of their application in the construction prefabrication industry is not evident. Therefore it is imperative to quantify the costs and benefits accrued under different implementation scenarios, in order to determine the optimal deployment strategy. The following outcomes are anticipated:

- The use of 3D feedback within the custom software application in the pipe spool fabrication workflow will reduce risk by improving overall project productivity and diminishing required rework.
- The innovation effectiveness is contingent on spool complexity, such that the benefit will be higher in complicated assemblies (e.g. nuclear applications) than simple ones.
- The successful application of the innovation technology depends on strong partnership or clear contract stipulation between the fabricator and project stakeholders (e.g. designers).

1.3 Research Methodology

The proposed research in this thesis will be conducted in two major phases, which are summarized in Figure 1-1 as an overview of research methodology.

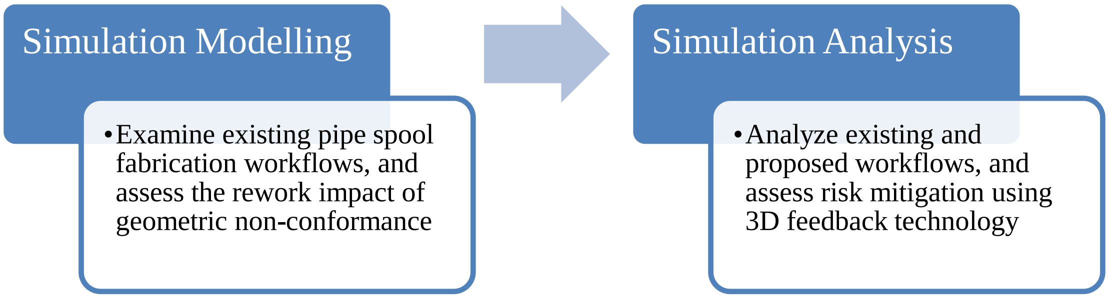


Figure 1-1. Major Research Phases

The first phase of the research investigates the risks associated with the current traditional and prevailing work processes. Fundamental tasks in this phase includes:

- Identify quality control processes along the fabrication workflow, more specifically, during the stages of: (1) material receipt, (2) spool assembly, and (3) final shipment.
- Conduct root cause analysis to determine proportion of geometric non-conformance, and evaluate the rework cost and schedule impact based on available project data.
- Propose revised workflows to implement augmented reality and 3D feedback during quality control of pipe spool fabrication in nuclear and non-nuclear context.
- Model the existing and proposed fabrication workflows using discrete-event simulation.

The second phase of the research evaluates the degree of risk mitigation achieved by implementing proposed innovation technology in industrial prefabrication. Major tasks in this phase includes:

- Evaluate and compare the impact difference between conventional and revised workflows on project performance, such as rework and overall fabrication time.
- Assess the impact of innovation deployment in proposed workflow:
    - Conduct sensitivity analysis to explore different workflow parameters.
    - Conduct risk assessment to quantify risk mitigation and accrued benefits.
    - Conduct economic analysis to validate technology implementation in practice.

A synopsis of research methodology is illustrated in Figure 1-2, outlining the progression of research activities including comprehensive literature review, work tasks associated with simulation modelling and analysis, as well as documentations in the form of this thesis and other publications.

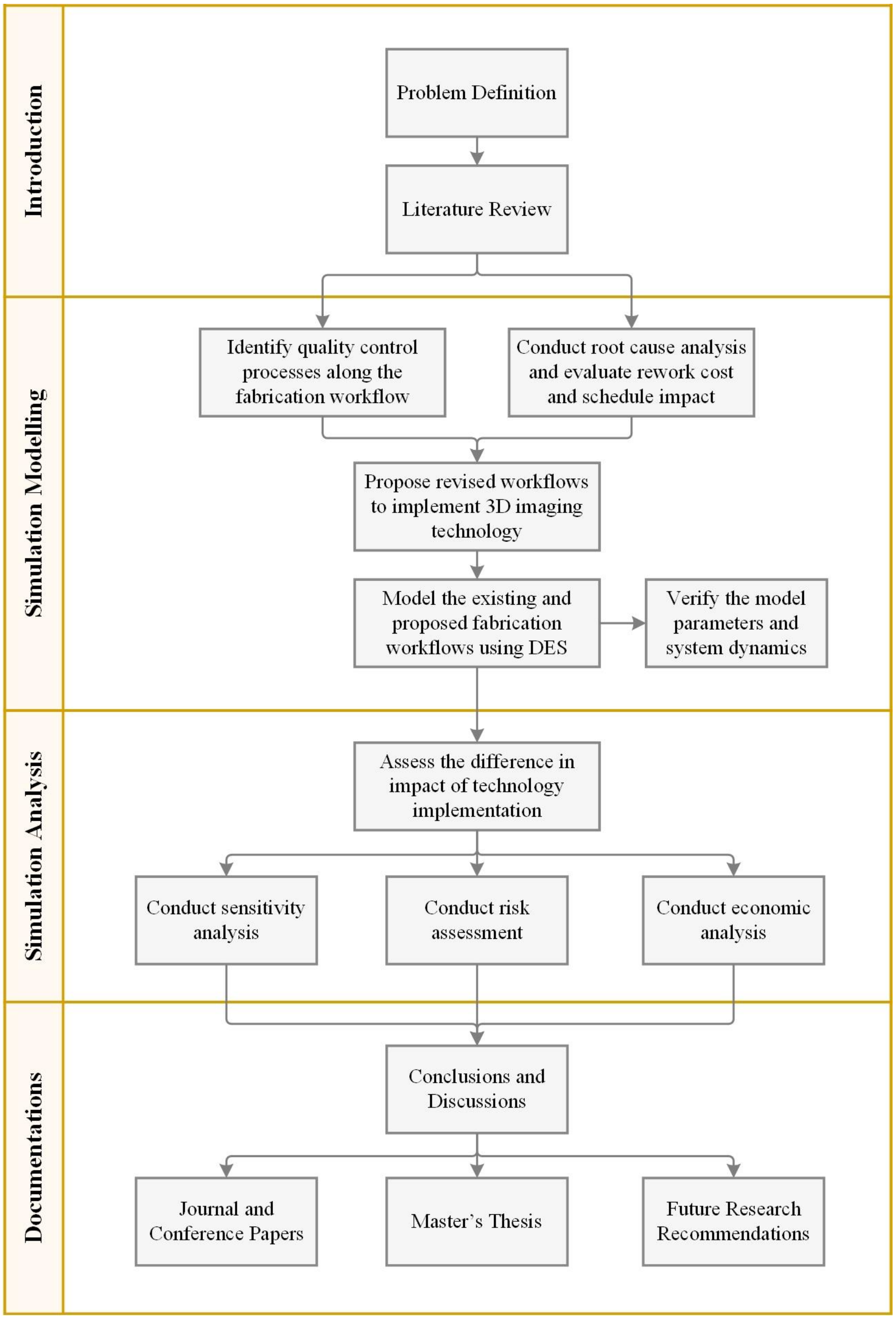


Figure 1-2. Research Methodology

1.4 Structure of Thesis

This thesis is divided into five chapters. A brief summary of each chapter is as follows:

Chapter 1, Introduction, provides general background and relevant information of the research to justify research motivations, outlines the thesis scope and research objectives, and summarizes the research methodology and the work that constitute each major research phase.

Chapter 2, Literature Review, discusses concepts and research published up to date that are pertinent to this thesis. This review includes the notions of rework, modular construction and prefabrication, building information modelling (BIM), 3D imaging technology, augmented reality application in construction, construction worker perception of technology adoption, as well as prevailing system simulation approaches and applications. This chapter concludes with a discussion of research gap and how this research contributes to existing body of knowledge.

Chapter 3, Simulation Modelling, introduces the traditional pipe spool fabrication workflow and common geometric quality control tools and procedures. Expanding on that, risk exposure with respect to cost and time impact are evaluated for the entire work process as well as at each quality control stage. Lastly, this chapter presents technologies and techniques relevant to the revised fabrication workflows, and proposes different application scenarios to be simulated.

Chapter 4, Simulation Analysis, applies the revised fabrication workflows and reports the results for each simulated model. The difference in impact of innovation implementation is assessed, in order to determine the optimal deployment strategy for pipe spool fabrication. Economic analysis is also carried out to determine the payback period of technology implementation in the fabrication work processes, in order to justify its investment from the fabricator's point of view.

Chapter 5, Conclusions and Discussions, summarizes the results drawn from the evaluation of simulation outcomes completed in Chapter 4. Based on the findings, a general guideline for risk mitigation of prefabrication in industrial construction is prescribed, specifying procedures based on production characteristics and tolerance requirements. Research limitations are discussed to define the circumstances particular to this thesis, and finally recommendations are proposed to further advance the research documented herein.

Chapter 2
Literature Review

2.1 Rework in Construction

Due to the nature of work in the industry, rework 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 many potential root cause of rework in addition to construction site human error, such as design change alteration, 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 rework contribute an average of 52% to a project's cost growth (Love 2002), which may include direct cost (labour and material to facilitate rework) and other intangibles such as schedule delays and litigation cost. From the same survey, the mean direct and indirect rework costs were found to be 6.4% and 5.6% of the original contract value, respectively (Love 2002). Other research studies reflect a similar cost impact in other types of construction projects, such that rework represent 4% of contract value in Australian residential construction (Mills et al. 2009), add 10% of contract value in Australian civil infrastructure projects (Love et al. 2010), and range from 3.1% to 6.0% of the project value in Malaysian building projects (Yap et al. 2017).

Rework root causes have been the subject of many subsequent research efforts for rework reduction. 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 rework, and the most important root causes of rework are owner change and design error/omission for both owner and contractor reported projects (Hwang et al. 2009). These issues may result from inadequate planning and poor communication among owners, designers and constructors, thus they highlight the need for a comprehensive rework management system that involves all the stakeholders and different organizational and technological measures at every stage of the project (Ye et al. 2015). This recommendation echoed the findings from a survey of 115 civil infrastructure projects by Love et al. (2010), where they identified the ineffective use of information technology to communicate as the primary factor contributing to rework. Therefore rework reduction requires the need to better plan and manage the design and documentation process.

To minimize and rectify the impact of rework, 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. This is part of a broader change to an organization's management practices and strategies to mitigate risk, which necessitates a continuous improvement loop, similar to a model of rework reduction program that support the Total Quality Management (TQM) framework (Zhang et al. 2012). The next sections introduce some of the approaches that could reduce rework in construction.

2.2 Modular Construction and 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, thus becoming an appealing and effective alternative to traditional stick-built construction for owners and contractors alike. The concepts of PPMOF have been applied to different types of construction projects, such as multi-storey residential buildings (Lawson et al. 2012), where precast technology (Jaillon and Poon 2009), building acoustic (Ljunggren and Ågren 2011), and joint connections (Sharafi et al. 2018) are some of the focus of technical challenge in practice.

2.2.1 Drivers

In industrial applications, research directed at decision frameworks help establish factors to consider for the feasibility of PPMOF approach. A computerized tool was developed to incorporate subjective judgment on the relative importance weights of each factor, culminating in a preliminary but straightforward framework of evaluating the applicability of prework in industrial projects (Song et al. 2005). In a study that highlighted the changes needed in the project delivery system to promote an environment of effective modularization, 21 critical success factors were identified and validated (O'Connor et al. 2014). Additional research examined PPMOF drivers and impediments in more detail, particularly of the difference between off-site and on-site performance, from the perspective of waste management (Tam et al. 2007; Quale et al. 2012), lifecycle and energy performance (Monahan and Powell 2011; Aye et al. 2012; Hong et al. 2016), lean principles (Nahmens and Ikuma 2012; Yu et al. 2013), design standardization (O'Connor et al. 2015; Banihashemi et al. 2018), planning and execution (O'Connor et al. 2016), as well as cost and schedule (Choi et al. 2016; Hong et al. 2018).

2.2.2 Risks and Barriers

As a fundamentally distinct approach to construction, there are varying risks in PPMOF techniques compared to traditional stick-built method, increasing demands and complexity to aspects of project organization, engineering, procurement, planning, monitoring, coordination, communication, and transportation (Song et al. 2005). 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 (Li et al. 2013). 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 (Shahtaheri et al. 2017). 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 (Enshassi et al. 2019). Owing to the advancements in technology research, additional tools can be used to help facilitate risk management, such as building information modelling (BIM) for project design and lifecycle control, robotics automation for fabrication control, and 3D sensing technology for quality control.

2.3 Building Information Modelling

BIM is an effective tool that offers capabilities beyond 3D visualization, including 3D modelling, generation of fabrication drawings, material quantification, cost estimation, construction scheduling, and detection of building system interference (Succar 2009; Gu and London 2010; Azhar 2011). In modular buildings construction, coordination for the mechanical, electrical, and plumbing (MEP) systems is especially crucial. While each system is typically designed by their respective specialty consultant, they all interact with architectural and structural elements, as well as with each other when fabricated into complete modules. The use of BIM allow multi-disciplinary collaboration within the project team, by aligning design objectives and defining constraint requirements, effectively taking into account modular constructability and element interdependency issues ahead of fabrication and on-site installation (Lu and Korman 2010). To this effect, BIM provides a platform and management of project information exchange within the team, operating as a process of collective decision-making between the stakeholders (Singh et al. 2011; Mostafa et al. 2018).

BIM can also be seen as a potential enabler of construction modularization. In a study that examined the use of BIM for PPMOF, it is argued that BIM can be used to enhance existing benefits and overcome existing challenges of off-site manufacturing, in which the qualitative and quantitative impact of BIM on the drivers and barriers to PPMOF were reviewed and assessed, including safety, rework, time, cost and labour saving. (Abanda et al. 2017). Another study investigated BIM-based 4D simulation frameworks to improve manufacturing productivity by managing the processing, quantity, and quality of module during fabrication, which aim to ultimately minimize rework and reduce construction delays, quality lapses, and cost overruns of the project (Lee and Kim 2017). BIM was also used as a link between an enterprise resource planning information system that supports manufacturing process and construction object related information, in order to integrate mass production prefabrication processes with construction site activities (Babič et al. 2010). In the context of quality control in construction, the potential of BIM implementation in quality management was proposed, by taking advantage of multi-dimensional data including: (1) design information for data consistency, (2) standardized and structured construction codes, and (3) 4D application for timely inspection and visualization of the whole process (Chen and Luo 2014).

Despite many reported project benefits of BIM, which include cost reduction and control through the project lifecycle (Barlish and Sullivan 2012), its full adoption and benefits realization in the construction industry relies on the agreement between stakeholders on BIM as a common IT platform, and no restriction to the flow of information to and from other parties by looking to protect ownership and intellectual property rights of BIM-generated output (Bryde et al. 2013).

2.4 3D Imaging Technology

As science and technology research continue to progress, tools developed for project surveying in the construction industry are becoming increasingly diverse and affordable. 3D surface imaging and photogrammetry techniques include RGB-D cameras, light detection and ranging (LiDAR), and structured light, where enhanced efficiency and reduced operational cost help improve fabrication, construction, and infrastructure management. Research in 3D imaging technology is executed from the perspectives of workflow and application; workflow entails the process of data acquisition, point cloud generation, and subsequent modelling, whereas the application stream targets the technology usage scenario (Wei et al. 2018). Some challenges in this research include the speed and accuracy of the workflow, as well as the interoperability and calibration between technology components across different platforms.

An example use case of 3D imaging technology in the civil engineering field is construction progress control, which is essential for the successful delivery of construction projects. 3D laser scanning was suggested as a potential tool to visualize the 3D status of a project and automate some tasks related to project control, including 3D progress tracking, productivity tracking, as well as construction dimensional quality assessment and quality control (Bosché et al. 2009). A system was proposed which incorporates schedule information with 3D object recognition, to automate the feedback flow of as-built information for construction project management as a 4D object oriented progress tacking system (Turkan et al. 2012). The system was further developed to transform objects to their earned values, in order to improve the accuracy of progress tracking (Turkan et al. 2013). As owners and contractors seek to improve aspects of project performance such as productivity, quality, safety, and cost savings, the integration of as-built information from sensor technologies and BIM data offers an opportunity for building construction automation, enhancing existing work processes that are prone to human error from manual work (Vähä et al. 2013).

Expanding on the technological tandem of 3D data acquisition instrument and BIM, new workflows incorporate the two tools for enhanced construction project control. For processing of as-built data, a framework that integrates Scan-to-BIM and Scan-vs-BIM approach was proposed to perform automatic detection, recognition, and identification of cylindrical MEP components in buildings construction, which helps facilitate the discrepancy assessment of percentage built as planned (Bosché et al. 2015). A continuously updated as-built model was achieved by using low-cost scanning devices attached to workers' helmets, where construction elements are captured in real time to identify deviation from as-designed model, such that construction schedule and project progress could be managed effectively (Pučko et al. 2018). However, the quality of the scan data is critical to the success of monitoring results. To address this gap, a metric for evaluation was proposed to define point cloud quality parameters based on building elements (Rebolj et al. 2017).

New techniques are also suggested to evaluate the quality of as-built components. A dimensional quality assurance technique was developed to automatically evaluate topical geometric compliance of precast concrete elements using scanned data, where subsequent BIM-assisted storage and delivery of information was proposed to allow stakeholders to share and update data throughout fabrication and construction assembly (Kim et al. 2016). In a similar light, data acquisition with a laser scanner was used to conduct on-site dimensional inspection of industrial piping systems, where as-built data and as-designed models were compared to verify geometric compliance (Nguyen and Choi 2018).

2.5 Augmented Reality

One of the more recent technological advancements is digital reality, which consists of two streams of development: virtual reality and augmented reality. While virtual reality is the creation of and interaction within a completely digital and simulated environment, augmented reality is the overlay of digital information onto the real environment in real time and in the correct spatial position. They are both perceived as an enabler of improvements in project delivery and possible provision of new and better services, however, their low level of adoption in the industry is limited by their impression as expensive and immature technologies that are not suitable for applications in engineering and construction (Davila Delgado et al. 2020).

Both visualization technologies have been reaping growing interest and implementation across different industries, such as gaming and entertainment for enhanced experience, as well as aerospace and healthcare for the purpose of education and training. Of greater consequence is the potential of augmented reality in manufacturing with its real-time and interactive solution, where there was a reported 90% improvement in first-time quality when compared to using 2D information, as well as 40% improvements in productivity when installing electrical wiring on an aircraft (Boeing 2018). In the context of piping assembly, augmented reality visualization compared with 2D isometric drawings yielded 55% reduction in original process time, 46% reduction in rework time, 50% reduction in assembly errors, and 66% reduction in cost of correcting erroneous assembly for 2D isometric drawings (Hou et al. 2015). The findings are echoed by Kwiatek et al. (2019) in their experiment of assembling a complex pipe spool, comparing the results through conventional means and augmented reality at different spatial cognitive abilities. Specific to professional pipe fitters, they found that augmented reality contributed to 83% reduction in overall time to complete the assembly, 53% reduction in time to absorb design information, 88% reduction in time to interpret rework information, and 57% reduction in time to complete rework. The results support the use of augmented reality application during fabrication for quality control, with marked improvement to worker productivity. For a comprehensive literature review of potential use cases and practical applications of virtual reality and augmented reality in the architecture, engineering and construction industry, the study presented by Davila Delgado et al. (2020) provide a state-of-the-art overview of the technology research, as well as drivers and limitations for their adoption in the industry. Trends in augmented reality applications, specifically the technologies of localization, natural user interface, cloud computing, and mobile devices, were also explored (Chi et al. 2013).

2.6 Perception of Technology Adoption in Construction

In order to (1) optimize the benefit of technology to enhance project performance, and (2) drive towards the automation of work processes in the construction industry, there is a need to incorporate information and communication technology (ICT) to facilitate collaboration among project stakeholders, transfer information between different technology platforms, and conduct real-time data analysis for continuous improvement loop. Though innovations in construction management and operation have been researched and developed regularly, their adoption in practice often does not occur immediately. The two main drivers to the stereotypical stagnant pace of technology enactment in construction are possibly stemmed from (1) lack of discourse between academics and industry, and (2) management complacency with existing work processes. Nonetheless, researchers continue to investigate the role of advanced technology in the construction industry, and examine the potential impact of their implementation.

From the technical perspective, perceived benefits of a given technology plays a central role in an organization's decision process, such that it not only performs its intended function well by replacing presumably manual and/or inefficient work activities, but also offers an opportunity for improvement in overall project performance. Investigating collaborative technologies in construction, it was found that pre-existing technological base and senior management support are some of the prerequisite resources that an organization should possess, while communication improvement and information system standardization are internal organizational drivers that have an effect on the intention to adopt a collaborative technology (Nikas et al. 2007). This is especially relevant in project management, where the practice of ICT in construction is proposed to be able to recognize interdependencies and enable management of increasingly complex and central information systems, thus improving the overall project performance with heightened level of integration (Froese 2010). A predictive model was developed to estimate the potential impact of an emerging technology on construction productivity, in which relative importance factor weight using analytic hierarchy process and historical analyses on costs, feasibility, usage history, and technical impact were aggregated to generate a performance score for the analyzed technology (Goodrum et al. 2011). However, it should be noted the authors recognize the basis of the model assumed that analysis on past experiences can reveal technology characteristics conducive to predict future success. Nonetheless, there is a need to understand the alignment between intended impacts of ICT and perceived benefits among users, as well as recognize discrepancies among end user's perception of ICT (Jacobsson and Linderoth 2012).

Due to the interaction between people and technology, their operation and structure can be viewed as a sociotechnical system, such that the impact of technology implementation considers social ramifications as well. The replacement and integration of any new elements into an existing system structure would inevitably induce change in organizational functions and operations (Ahmad et al. 1995), as people attempt to interpret and make sense of the unfamiliar artefacts, adjust behaviour based on their perception, and consequently transform the current dynamics into a new set of regulations. A study was conducted to investigate the relationship between ICT adoption and job satisfaction within the Jordanian construction industry, and it was found that there is a positive correlation between the two factors, suggesting an increase in employee job satisfaction with more investment in technology (Attar and Sweis 2009). Furthermore, examining the use of automated data collection technology for continuous management of construction activities, perceptions of the technology and barriers to its adoption were identified, where work process change acts as a critical roadblock towards the application of real-time data capture, analysis, and sharing across the construction industry (Majrouhi Sardroud 2015). As part of the experiment to assess the impact of spatial cognitive abilities on the effectiveness of augmented reality in construction and fabrication, a survey was conducted by Kwiatek (2018) to ask the craft workers about their opinions regarding technology. It was found that the majority of the participants were at best neutral to the idea of using technology in their lives, and the biggest apprehension was technology creating additional tasks to be done, as well as change to routine and less time for direct work, which echoes earlier findings by Majrouhi Sardroud. Therefore, if the technology adds value by making the work simpler and that the workers are able to receive adequate training prior to implementation, ultimately minimizing additional processes and replacing existing tasks with minimal impact to their routine, the craft workers would be more likely to be receptive of the new technology in practice (Kwiatek 2018).

2.7 Simulation

Simulation in general is composed of two key elements, which are simulation modelling and simulation analysis. Simulation modelling is a means to represent a system physical and logically in order to understand its behaviour over space and time and to assess possible consequences of actions; on the other hand, simulation analysis is a means, using a simulation model, to experiment with and test alternatives before deciding actions and committing resources (Greenwood 2018). Simulation is ultimately used to support decision-making, specifically to: (1) understand a system's dynamics, (2) analyze and predict a system's performance, and (3) compare alternatives for improvement.

In order to simulate operations systems, three key aspects must be addressed: interactions, variability, and dynamics (Greenwood 2018). A simulation must represent the basic actions that occur in an operations system, and the representation itself should also consider physical aspects such as size, distance, and speed, as well as logical aspects such as who, what, when, and where things are done, and for how much and how long. The variability of known parameters (e.g. work schedules and product mix) and unknown parameters (e.g. quality, process times, and breakdowns) causes system's resource interactions to change over time, thus resulting in the system's dynamics. There are four basic types of simulation that are used to model and analyze operations systems: (1) discrete-event simulation, (2) Monte Carlo simulation, (3) continuous simulation, and (4) agent-based simulation.

2.7.1 Discrete-Event Simulation in Construction Research

Due to the nature of construction activities, their sheer complexity and involvement of many stakeholders preclude construction research to be carried out easily in the field. Thus simulation offers a convenient solution to examine construction processes, and investigate their potential behaviour responding to changes introduced to the system.

Discrete-event simulation (DES) is one of the most popular tools in construction operations analysis. In DES, the states of a system change at discrete points in time as the result of specific events, which is very similar to how construction and fabrication processes operate in reality. For example, DES was developed to assess the impact of different variables on paving operations under lane closure conditions (Nassar et al. 2003). Over the years, DES has also been proposed to incorporate various optimization tools under constrained resources. DES was integrated with a heuristic algorithm to optimize dynamic resource allocation for construction scheduling, with the objective of minimizing project duration (Zhang and Li 2004). Similarly, DES was proposed to be used in conjunction with particle swarm optimization, in order to automate the formulation of a resource-constrained schedule with the shortest total project duration (Lu et al. 2008). A DES model also incorporated genetic algorithm to support hoist planners while preparing optimal plans with minimal time and effort for high-rise building construction (Shin et al. 2011). Furthermore, to account for sustainability during construction, a dynamic modelling framework based on DES includes environmental goals in the design of road construction operations, in terms of emissions generated by the production and traffic conditions (González and Echaveguren 2012). DES was also used to examine the relationship between various configuration factors and the performance of a sky lobby lifting system (Jung et al. 2017).

There are also applications to incorporate BIM and DES in construction research. A BIM-DES framework was proposed to enable the implementation and integration of DES in the planning and follow-up of construction activities; while BIM provides the process information to DES, facilitating the building and maintenance of the DES model, the DES model in turn evaluates the construction performances and provides feedback to the BIM process for decision support (Lu and Olofsson 2014). Another study developed a prototype information system based on BIM, and examined its effect when used by subjects working in a virtual construction site experimental setup using virtual reality and linked to a DES engine, to guide their performance of virtual work in a high-rise building construction (Gurevich and Sacks 2014).

In the context of PPMOF, a production planning and control system for a panelized home production facility was developed, where radio frequency identification data was used to build a DES model, which is then integrated with an optimization algorithm to generate the production schedule and for real-time performance monitoring (Altaf et al. 2018). Another study used DES to provide and evaluate recommendations to improve modular construction efficiency through the application of lean principles and concepts such as TQM and JIT, and assessed their impact on cycle time and process time, as well as process efficiency and labour productivity (Goh and Goh 2019).

2.7.2 Other Simulation in Construction Research

While DES methods are limited in their ability to model the behaviour of individuals who make decisions subject to their perceptions of uncertain conditions, agent-based simulation may offer a better solution since agents can be applied with behavioural models. A multi-agent-based simulation system was developed to evaluate the traffic flow of construction equipment in construction site, in order to account for their continuous dynamic behaviour (Kim and Kim 2010). Another study captured construction trade crew behaviours through interviews and encapsulated the behaviour in software agents, the system models each individual’s decision-making and situational awareness while using BIM to define the physical and the process environment for the simulation (Ben-Alon and Sacks 2017). In terms of safety, a study integrated BIM and agent-based model to evaluate different evacuation plans to improve evacuation performance for offshore oil and gas platforms based on time (Cheng et al. 2018). Similarly, a tool was developed by integrating fire dynamics simulation, agent-based crowd simulation and BIM using Industry Foundation Classes data structures, allowing it to be used by designers to analyze a building layout design under various fire scenarios, and for layout optimization based on multiple safety criteria (Mirahadi et al. 2019).

Monte Carlo simulation (MCS) relies on repeated random sampling to obtain numerical results, and is used extensively in problems with significant uncertainty in its input variables. In a study that introduced an analytical model to determine optimal lifecycle costs of fibre-reinforced polymer bridge deck panels, MCS was used to account for uncertainty in the model parameters (Hong et al. 2007). Another study developed a hybrid information fusion approach that integrates cloud model, Dempster-Shafer evidence theory, and MCS technique to perceive safety risk of tunnel-induced building damage under uncertainty; the Monte Carlo technique was used to simulate the input observation by using probability distribution in order to describe and reduce underlying uncertainty curing the characterization and measurement of input factors (Zhang et al. 2017). In the context of PPMOF, tolerance analysis through MCS was shown to be a proactive design tool with key advantages for prefabricated and offsite construction, where: (1) complex 3D geometric interactions can be readily modelled using basic tolerance configurations, (2) potential misalignments at key connection points can be identified and quantified in terms of a probability distribution of variation, and (3) design improvements can be achieved by comparing alternate construction processes to mitigate the risk of assembly rework (Rausch et al. 2019).

2.8 Research Gap

Literature review conducted heretofore examined: (1) causes of rework and its impact on project performance, as well as potential mitigation strategy, (2) PPMOF drivers, as well as risks and barriers in practice, (3) BIM benefits and integration with other technology platforms, (4) techniques and applications of 3D imaging technology, (5) augmented reality applications and impact on project performance, (6) perception of technology adoption in construction, and (7) simulation techniques and applications in construction research.

Kwiatek et al. (2019) examined the impact of augmented reality and 3D imaging technology on worker productivity, however, the potential of near real-time 3D feedback workflow on prefabrication of industrial construction has yet to be investigated. Furthermore, alignment of technology intended impact and its perceived benefits necessitates the quantification of risk mitigation. Therefore, this thesis fills the gap in state-of-the-art construction research with a case study on pipe spool fabrication, by examining quality control stages along the fabrication work processes in nuclear and non-nuclear context, proposing revised workflow using 3D feedback, modelling the existing and proposed workflows with discrete-event simulation, analyzing the simulation models' performance for rework and project time, as well as conducting risk assessment and economic justification on new workflow.

Chapter 3
Simulation Modelling

The purpose of this chapter is to provide background information on the research project that forms the backbone of this thesis, as well as to present simulation models for the prefabrication workflow of pipe spool assemblies in nuclear and non-nuclear contexts.

3.1 General

The project is a four-year collaborative research initiative between the University of Waterloo and the industry partner company ("the partner"), a major construction general contractor in Canada. The overarching goal of the project is to improve worker productivity and reduce rework through the development of a near real-time 3D feedback system, designed with the intention of providing a streamlined software service to the users. With this tool, quality control can be executed at an early stage of the assembly during construction prefabrication, consequently allowing workers to easily recognise discrepancies between the designed models and as-built information of fabricated spools. The use of augmented reality in this solution takes advantage of the increasingly affordable 3D data acquisition technology available on the commercial market, as well as the ubiquitous use of BIM in the industry, such that information can be conveyed by overlaying 3D as-built scans over 3D design model. The implementation of technology tools would fundamentally alter the current traditional work process, but offers a potential for increased productivity and a more efficient workflow (Henderson and Ruikar 2010).

The partner's operating structure is segmented into three core activities, namely infrastructure, industrial, and concessions, with a total of over 12,000 working employees. Within its industrial division, they own and operate four prefabrication facilities across Canada, each with varying capacity and typical work production. Table 3-1 summarizes the basic information of each facility.

Table 3-1. The Partner's Prefabrication Facility Summary (The Partner 2018a)

Facility	Facility Size (Square Feet)	Annual Spool Capacity (Number of Spools)	Annual Weld Capacity (Diameter Inches)	Yard Size (Acres)
Edmonton, AB	83,000	20,000	520,000	62
Pictou, NS	80,000	15,000	637,000	18
Cambridge, ON	120,000	40,000	1,000,000	N/A
Brantford, ON	50,000	4,200	338,000	5
Total	**333,000**	**79,200**	**2,495,000**	**85**

Most of the data in this research are gathered from site visits to the partner's prefabrication facilities in Edmonton, AB and Cambridge, ON, which represent over half of the partner's prefabrication capacity. During these site visits, interviews are usually held with the fabrication manager who oversees the entire plant operations, and if specific information are required, meetings would be arranged with the engineers who manage specific projects, shop superintendent who leads the fabrication shop, as well as fitters and welders who fabricate the components. Therefore there is an appropriate assortment of perspectives to include expertise from the management team, the core supervision personnel, and the craft workers themselves.

While the Edmonton plant primarily fabricates industrial components (e.g. utilities or oil and gas applications), the Cambridge plant has an additional capability of fabricating nuclear components. Consequently, though the workflow is generally the same between each prefabrication facility, the quality control procedure is different depending on the project type (i.e. nuclear vs. non-nuclear). This difference is discussed in detail later on in Section 3.3.2. Nevertheless, in either case, the developed technology must be fairly straightforward to operate with its streamlined user interface, be compatible with different 3D data acquisition hardware, and ultimately be able to be implemented under different fabrication workflows.

3.2 Technology Overview

An augmented reality software application was developed by the team of researchers at the University of Waterloo, focusing on improving visualization of design intent, offering robust analysis capabilities, and providing an intuitive display of the results. The current industry practice of presenting information to the workers is using isometric projections, which are not-to-scale symbolic line drawings representing 3D shape on a 2D drawing. This method of visualization is used for cutsheets, which are official paper documents sent to the fitters and welders during fabrication, detailing the cut lengths for individual pieces of elements indicated on the drawing, as well as labelling of the weld procedures required. An alternate visualization approach of design intent is proposed for the software, where a fully rotatable 3D model allows users to recognize the relationship between each component, and the interactive feature can "explode" the overall model into segments, providing a more detailed view of the elements of interest. Figure 3-1 on the next page shows a side-by-side comparison of the two visualization methods in the current software solution, in which the user has the option to click on either of them for an enlarged view.

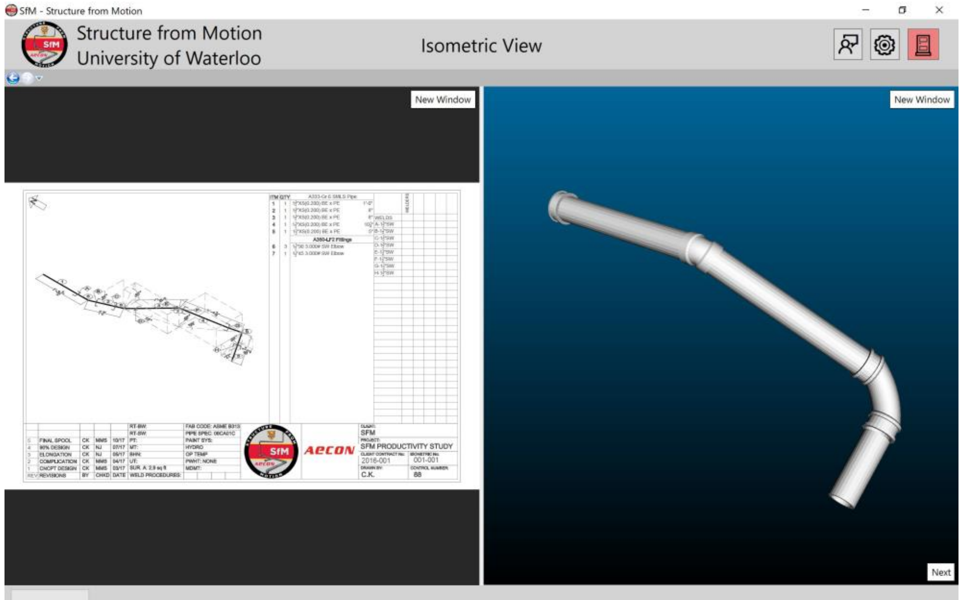


Figure 3-1. Isometric and 3D Visualization

Quality control analysis of the software requires two sets of point clouds: (1) point cloud from the 3D design model, and (2) point cloud from the as-built spool. Point clouds are essentially a set of spatial data points, where each point contains associated Cartesian coordinates in the x, y, and z axis. 3D imaging technology needs to be used in order to obtain a surface point cloud of as-built components. The two point clouds are then superimposed over each other using the Iterative Closest Point algorithm, and a heat map is generated to visualize discrepancy, which is essentially a large distance between two supposedly corresponding points that exceeds specified threshold. Figure 3-2 demonstrates the difference between a pipe spool that exceeds tolerance and one that is conformant.

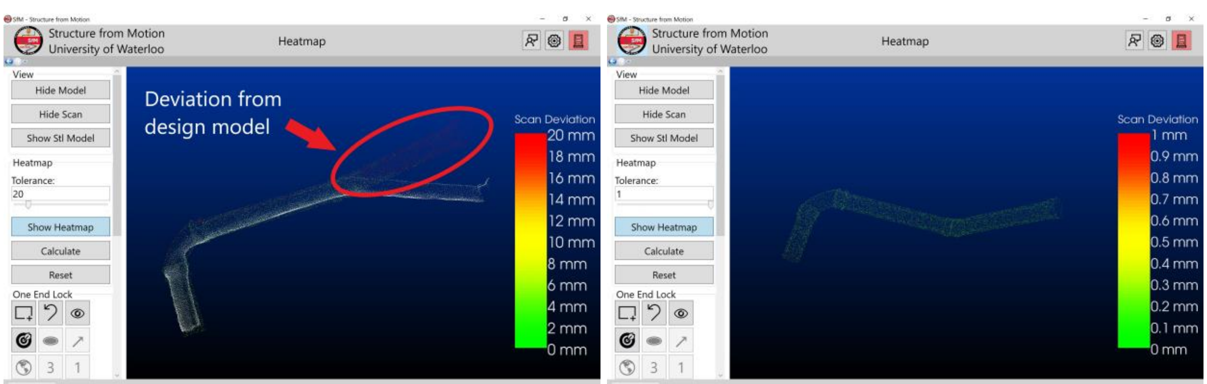


Figure 3-2. Discrepancy Analysis: Unacceptable vs. Acceptable

The software application developed by the research project team was used previously to examine the impact of augmented reality and its relation to human spatial cognitive abilities. Kwiatek et al. (2019) summarized the application workflow in detail, as shown in Figure 3-3.

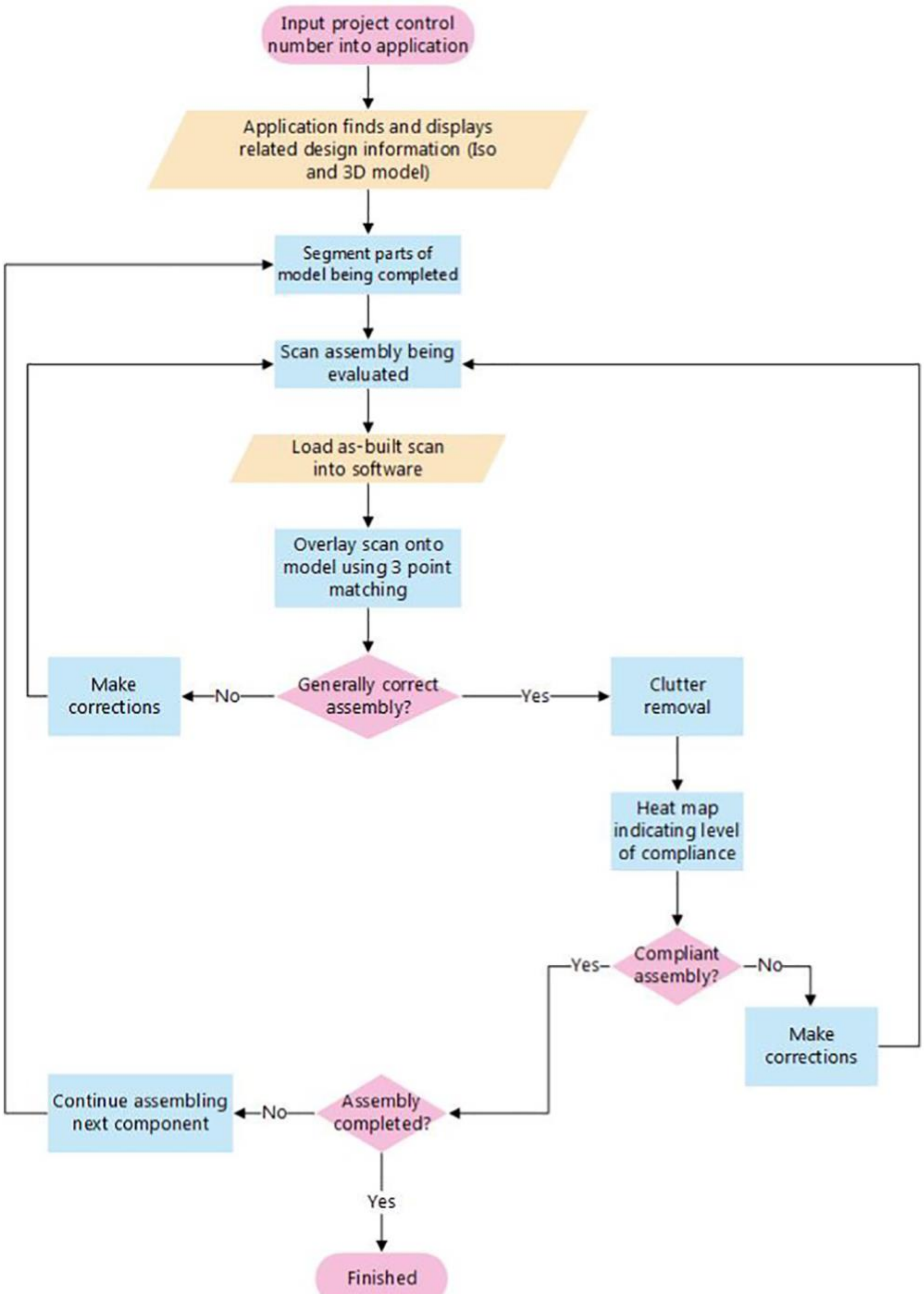


Figure 3-3. Software Application Workflow (Kwiatek et al. 2019)

3.3 Technology Implementation

In pipe spool fabrication, much like any other industrial prefabrication process, there is a number of key stakeholders along the workflow who ensure everything from project start to final product delivery is carried out smoothly and up to standards. Thus quality control procedures are an integral part of the production system, such that through iterative review and inspection, non-conformance of assembly can be detected and corrected. Material receivers, fitters, welders, as well as QC personnel all follow the same protocol, and are aligned with their responsibilities. The complete material receipt and fabrication flow for non-nuclear projects are detailed next page in Figure 3-4, and it sheds light on specific quality control steps in current prevailing pipe spool fabrication process.

In general, despite project types, there are three major potential steps along the fabrication process to implement 3D scanning and the software solution as described previously in Section 3.2. These steps are identified as follows:

1. Material receipt when components arrive to the shop and are to be stored into warehouse,
2. Spool assembly in-process check during fitting and welding, and
3. Quality check after completion of spools (before final shipment to site).

While flawed incoming materials may contribute to potential errors during fabrication, they make up a smaller percentage of geometric non-conformance since most items are standard sizing. The only risk during material receipt would be custom materials received from suppliers, where geometric non-conformance may be present from errors during supplier's fabrication process. On the other hand, due to the manual nature of pipe spool fabrication, fittings during layout of components pose a significantly higher risk of producing erroneous assemblies that to not meet design requirements. This is especially true for highly complex projects such as pipes for nuclear power plant refurbishment, where the geometry is often very intricate in order to match site conditions. For large bore projects, it is also challenging for the fitters to maneuver components to the correct positions. In both cases, quality control becomes a challenging task since the tools available may not be sufficient for the precision required. As such, the software technology developed by the research team at the University of Waterloo offers an additional flexibility for the workers to check for geometric errors.

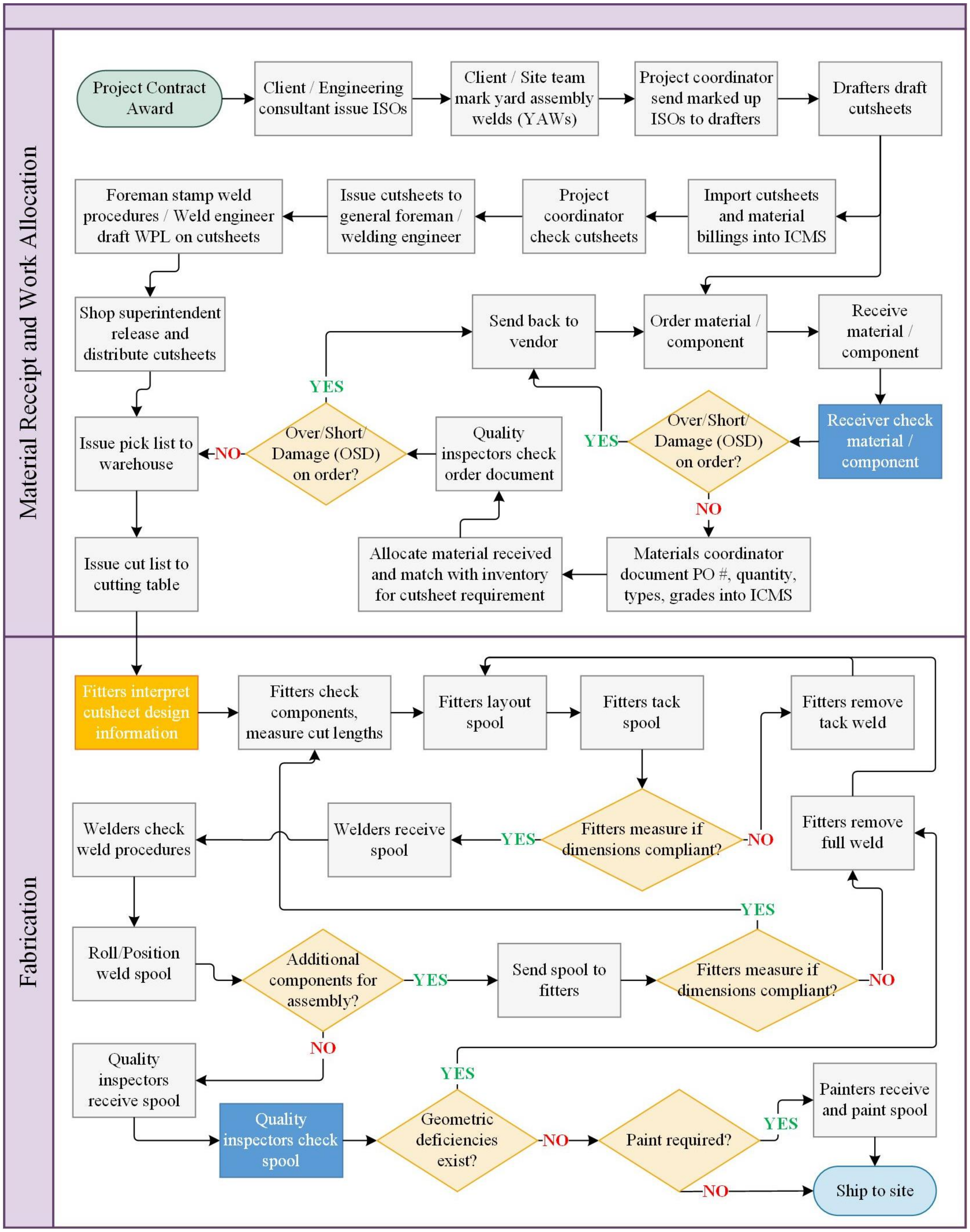


Figure 3-4. Material Receipt and Fabrication Flow of Non-Nuclear Pipe Spool Assembly

3.3.1 Material Receipt

When materials arrive in the fabrication shop, they are offloaded onto the receiving bay. Receivers would then confirm the materials match the order; this entails documenting the purchase order number, quantity of order, as well as types and grades of materials. This step of quality control is commonly referred to as "OSD" (over/short/damage) in the industry, and it is intended to make sure there is sufficient materials (the over or short part of OSD) for the project, and that the materials are up to standards (the damage part of OSD). If there is not enough materials, or if certain materials are flawed and not fit for use, then they will be sent back to the vendor, and the new batch of materials will go through the same process of quality control when they arrive.

Once materials are received, they are then stored in the warehouse for future project use. A barcode tag may be attached to each material, and information such as project number, heat number (source of batch material) and material description (type, grade, and nominal dimensions) are then uploaded onto the partner's internal information system, the Integrated Construction Management System. Figure 3-5 shows examples of the barcode tags applied to materials stored into the warehouse.

Figure 3-5. Material Barcode Information

When materials are needed for fittings, the warehouse receives a pick list, and the cutting table receives a cut list. After fitters pick up the materials, they measure their length and diameter, and record the heat number to keep track of the components that make up an assembly. As such, there is a duplicated effort where the receiver conducts a visual inspection of the materials, and the fitters perform another quality control step before fittings. There is a potential for the warehouse to 3D scan incoming materials when they are being stored, so their associated dimensions can be confirmed and uploaded onto the information system. In this workflow, the fitters would simply pick up the materials, and they would not have to spend time checking their geometry. This level of modification would require the upload, transfer, and distribution of said information between warehouse and fitters; however, this is out of scope for this thesis since it concerns in-house IT capability and the level of software integration into existing workflows.

3.3.2 Fabrication In-Process Check

During fabrication, fitters and welders are responsible for the fittings of pipe spool assembly. After the fitters pick up the materials, and their dimensions have been confirmed to be accurate, they would attempt to layout the components in the correct orientation according to design information. Fitters would then tack the connection so the spool would stay in place. At this point, the spool may not be within tolerance, as the overall steel assembly will contract and distort after full penetration weld. Currently there is no consistent metrics to determine how out of line the spool would be after tack, as it depends on the fitters' understanding of what the welders like and don't like. Therefore, without standard procedure for geometric compliance after tack weld, it depends on fitters' experience to suit the preference of the welders.

As mentioned briefly before, the quality control procedure is distinct based on the project type. Their difference is outlined in Table 3-2.

Table 3-2. Quality Control Requirements Based on Project Type

Quality Control	Nuclear Project	Non-Nuclear Project
Before Tack	✓	✗
After Tack	✓	✓
After Weld	✓	✓
QC Performed by	QC Personnel	Fitters

Fabrication in-process check would typically see a strict quality assurance program in nuclear projects, as the partner adheres to code requirements set forth by the Canadian Standards Association (CSA). Specific to the Canada Deuterium Uranium (CANDU) reactor, as a fabricator of components for the nuclear power plant, the partner must comply with CSA N285 (Systems and Components) and CSA N286 (Quality Assurance). The inspection of any pressure-retaining systems and components would therefore require qualified personnel who are certified and authorized to perform quality control. On the other hand, for non-nuclear projects, the level of formal quality control involvement depends on the pipe bore size; however, most of the time the craft workers would conduct undocumented self-checks on the work they have done. This hidden time is hard to track, and as a result may reflect poorly on the overall productivity of the project. It is worth mentioning that fitters are the only ones performing checks, since welders are focused on maximizing weld time.

After tack, the pipe spool is ready for full penetration weld. Due to the circular cross section of these assemblies, roll weld provides the easiest access for welders to weld the components together. One end of the spool would be attached to a pipe rotator, and as the entire spool spins about the principle axis, the welder is able to stay in position and weld accordingly. Figure 3-6 demonstrates what these rotators look like, and a close-up view reveals the mechanisms that secure the pipe spools.

Figure 3-6. Pipe Rotators

When welding is complete, the finished spool would be transported to a laydown area for final inspection; this step is described next in Section 3.3.3. However, if additional components are still needed, it would be sent back to the fitters for layout again. At this stage, the workers would check for weld quality and overall spool geometric compliance. If rework needs to be done, depending on spool complexity, it may take up an incredible amount of time to remove the full weld. This process involves documenting the non-compliance, developing a rework strategy, cutting through the joints, grinding and preparing the edges, and going through the entire fitting and welding workflow again. Consequently, craft workers rely on a variety of tools in order to perform all the tasks during fabrication and rework. Figure 3-7 depicts typical work stations, where workers' tools are organized.

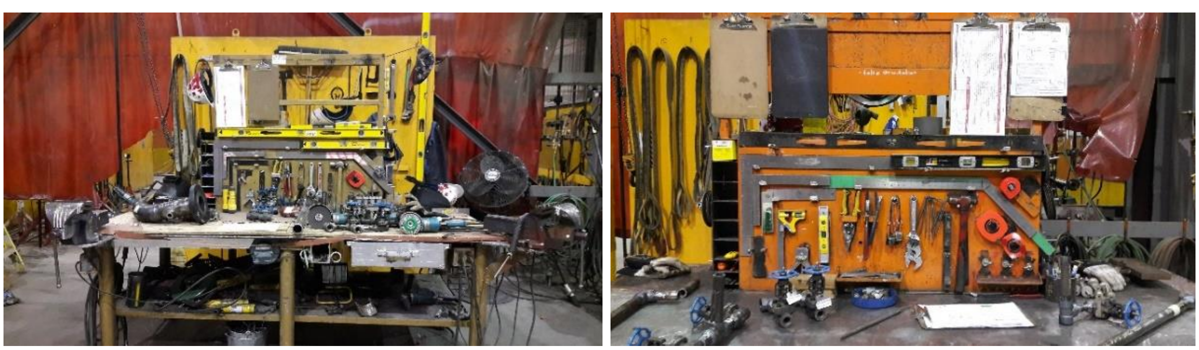


Figure 3-7. Typical Fabrication Work Station

Traditional tools to check for geometric compliance include steel tape measure, steel right-angle measure, spirit level, and caliper. While they are and have been sufficient for the majority of pipe spools with straightforward design, these tools may not be precise enough for more complex geometry. This challenge is evident regardless of project type. For example, when there is an extremely long pipe segment, sag would invariably occur if the fitters use a tape measure to confirm its length. Figure 3-8 shows some of the tools as described earlier being used by fitters during active fabrication, and Figure 3-9 provides a sense of understanding for how long some pipe spools can be.

Figure 3-8. Traditional Tools for Geometric Verification

Figure 3-9. Sample Long Pipe

The challenge to verify geometric compliance is further exacerbated by strict tolerance requirements in nuclear applications. Some components have a specified tolerance of one-sixteenth of an inch, which is approximately 1.5mm of margins for an entire pipe spool. For pipe spools with complicated length and angle of elbow end, coupled with their unconventional orientation, it is very difficult to verify those dimensional parameters. In some instances, in order to validate the spool was fabricated according to design, custom jigs would have to be developed and constructed so the quality control personnel can confirm and approve these spools for final shipment to site. Figure 3-10 on the next page demonstrates one of such jigs being used during quality control.

Figure 3-10. Custom Jig for Geometric Verification (Photo by Mohammad Mahdi Sharif 2019)

Similar to the inadequacy of using a steel tape measure to measure a long pipe, custom jigs are also prone to inaccuracy due to its material (wood shrinkage and expansion) and the manual nature of the process in which they were created. While total station may be used, its operation requires someone very knowledgeable about the hardware system and measurement process, and the entire operation may take a while to complete. During site visits by the research team, although a total station was located within the prefabrication facility, the team learned that the equipment has not been used in a long time, and no one in the current staff knows how to properly operate it.

This presents an excellent opportunity for 3D scanning to replace or complement the existing arsenal of tools for geometric verification during quality control. The developed software technology has an intuitive user interface, so the learning curve for new users would be quite shallow; this enables rapid deployment and integration into existing fabrication workflows. Furthermore, the streamlined services including data acquisition, data processing, and final results presentation offer a rewarding user experience, such that the workers would be able to quickly and accurately assess geometric compliance of the pipe spools. The ability to accommodate different 3D scanning hardware also means the flexibility to use a different system under different scenarios. For example, with the DotProduct DPI-8S, a hand-held 3D scanner, the worker can walk around awkward position of the entire assembly and maneuver around the environment in order to capture as much information as possible. On the other hand, the FARO Focus Laser Scanner, though stationary, is a reliable system that offers accurate measurements of up to ±1mm. Readers may refer to Appendix A for detailed technical specifications of the 3D data acquisition hardware used in this research.

3.3.3 Final Quality Control

In the last stage of pipe spool fabrication, a final quality control is administered by dedicated QC personnel before spools are transported to site for installation, or if paint is required, transported to the paint shop. The tools and procedure remain the same as described earlier in Section 3.3.2, with inspection conducted primarily on the overall spool geometry; however, if contract requires, additional quality control may be performed, including but not limited to hydrostatic testing, ultrasonic testing, penetrant testing, and magnetic particle testing. Figure 3-11 exhibits spools undergoing hydrostatic test to check for pressure loss and leaks.

Figure 3-11. Hydrostatic Test

When no deficiency is found, and the pipe spool successfully meets all requirements concerning its overall geometry, strength, and weld quality, the QC personnel would finally approve and release it. At this point, the completed spool would typically be moved to a temporary laydown area within the prefabrication facility, until enough spools have been fabricated for shipment to site. Figure 3-12 shows spools in laydown area after fabrication and passing quality control, and Figure 3-13 on the next page shows trucks in the loading bay before shipment to project site for installation.

Figure 3-12. Spools in Laydown Area after Fabrication

Figure 3-13. Trucks for Spool Shipment to Site

For spools that did not pass quality control and are deemed non-conformant to design requirements, they are attached with a red “non-conformance tag”, which summarizes the specific job/project number the spool belongs to, the associated drawing and spool/item number, description of the non-conformance and where the defects exist, as well as the Non-Conformance Report (NCR) number where all the specific details are documented. Figure 3-14 shows examples of non-conformance tags applied to spools that failed quality control after their fabrication.

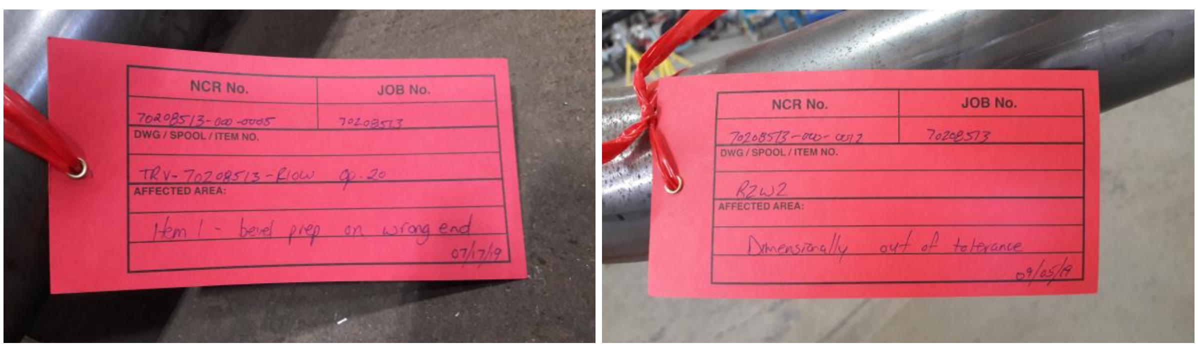


Figure 3-14. Non-Conformance Tags

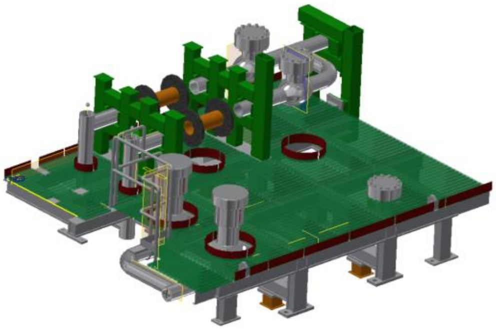
Under the partner’s Quality Control Procedure, a non-conformance is defined as “a deficiency in characteristic, documentation or procedure that renders the quality of material, component or activity unacceptable or indeterminate.” Therefore the tags may also be declared on incoming materials from their suppliers, as well as spools under active fabrication during fitting and welding. When non-conformances are identified, six decisions are available, which are: (1) use-as-is, (2) repair, (3) rework, (4) scrap, (5) return & replace, and (6) other. No work may proceed on the affected area of the non-conforming item until the NCR is issued with an approved “disposition”, which is based on one of the six choices. Only QC personnel may remove a non-conformance hold tag. Readers may refer to Appendix B for the partner’s Quality Control Procedure observed by prefabrication facilities.

3.3.4 Non-Conformance Root Causes

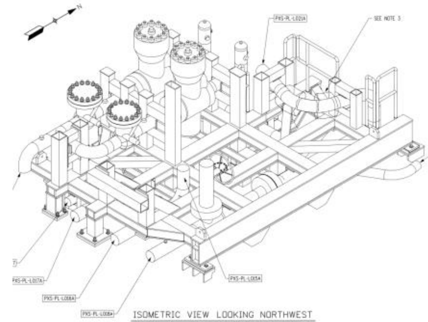
To further understand the types of non-conformance, their frequency of occurrence within a project, as well as their impact on the project cost and schedule, the research team obtained a copy of the entire NCR data on one of the partner's completed nuclear projects. The project required the partner to fabricate six distinct modules and a ring girder for nuclear power plants in the United States. A total of 1,179 NCRs were raised during the three-year fabrication period for this project. Table 3-3 summarizes the total weight, operating purpose, and fabrication challenge of these nuclear modules, and Figure 3-15 on the next page illustrates the 3D design of each module.

Table 3-3. Summary of Nuclear Modules (The Partner 2018b)

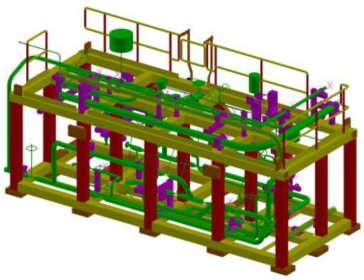
Module	Weight	Operating Purpose	Primary Challenge
KB36	37,200 lbs (16,873 kg)	Module contains vital components to the following systems: Passive Containment Cooling, Liquid Radioactive Waste, Demineralized Water, Fire Protection	Management of the high number of system code changes, ensuring the quality requirements of each system are met
Q223	59,000 lbs (26,762 kg)	Module contains Passive Core Cooling system components which activate in case of emergencies	Preparation of frame and supports to house two redundant Pyrotechnic Valves which operate in case of an emergency condition
Q233	65,150 lbs (29,552 kg)	Module contains Passive Core Cooling system components which activate in case of emergencies	Frame construction with "megabeam" and non-standard truss geometries
Q240	57,150 lbs (25,923 kg)	Contains components of the Normal Residual Heat Removal system to cool the reactor during standard operation	All pipe welds are specified as Leak Before Break (LBB) to mitigate catastrophic failures (100% GTAW)
Q305	9,200 lbs (4,173 kg)	Module houses components of the Containment Isolation system and associated piping and valves for multiple components	Assembly, welding and inspections of frame, spools and supports in a tight and complex geometry
Q601	102,000 lbs (46,266 kg)	Contains components of the Pressurizer Safety and Automatic Depressurization system	Frame is constructed of a unique SA-517 high strength steel which requires a large amount of tooling and heating apparatuses throughout fabrication
Q601 Box Beams	2,300 lbs (1,043 kg)	The Box Beams are custom fabricated components of the Q601 frame	Welding of high strength SA-517 steel requires specialized weld procedures and regimented pre-heat and post-welding heating cycles
Ring Girder	14,000 lbs (6,350 kg)	The Ring Girder is a structural support for the Pressurizer Vessel and is the base to the Q601 module	Large amounts of welding while maintaining very tight tolerances



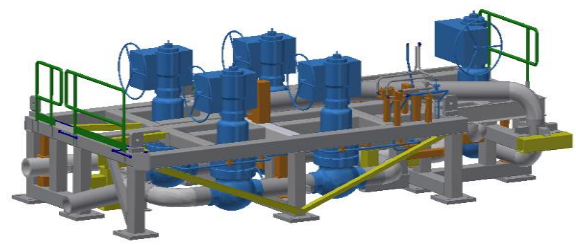
Module Q223



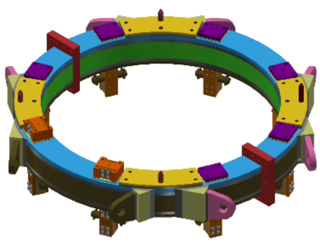
Module Q233



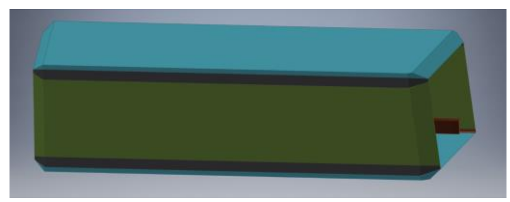
Module KB36



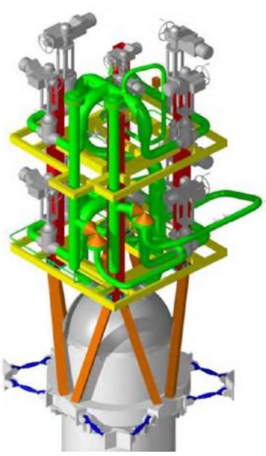
Module Q240



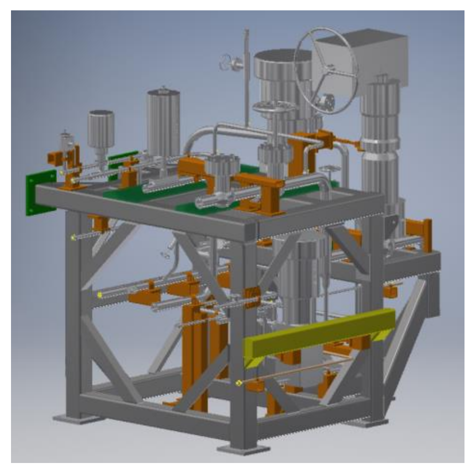
Ring Girder



Module Q601: Box Beams



Module Q601



Module Q305

Figure 3-15. Illustrations of Prefabricated Modules for Nuclear Power Plant (The Partner 2018b)

All modules were fabricated at the partner's Cambridge shop, which has nuclear capabilities beyond its traditional pipe spool and module portfolio. Each nuclear module in the project is unique, and their fabrication required highly skilled craft workers to fit and weld all the pressured piping components and supporting structural assemblies. To meet project requirements and deadlines, the shop was at full capacity with 80 dedicated workers. The workforce included 20 QC personnel, who are responsible for quality control throughout the project lifecycle, including all activities from material receipt to in-process fabrication to final shipment release. The modules are also subject to scrutiny by third-party Authorized Nuclear Inspectors, who ensure all fabricated components and systems are fit for use for nuclear applications as designed.

In accordance with the partner's 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 seven broad types, which are as follows:

1. Procurement Issue
2. Material Issue (Vendor)
3. Fabrication/Construction Issue
4. Engineering/Document Control Issue (the Partner)
5. Free Issue Material (Customer)
6. Regulatory
7. Miscellaneous

These seven categories encompass almost all possible non-conformances a prefabrication facility would experience, ranging from materials supplier liabilities (whether procured through vendor or supplied by owner) to internal accountabilities concerning fabrication errors and drafting errors. A total of 35 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 3-4 on the next page summarizes the frequency of each defect code as documented in the NCR, throughout the three-year fabrication period of the project. Furthermore, for clarity, defect codes related to geometric non-conformance are also highlighted in yellow in Table 3-4, and their summation is reported at the end of the table.

Table 3-4. Non-Conformance Root Causes and Their Frequency

DEFECT CODES	FREQUENCY	PERCENTAGE
1. PROCUREMENT ISSUE (THE PARTNER)		
A. PURCHASE ORDER ERROR	2	0.17%
2. MATERIAL ISSUE (VENDOR)		
A. MISSING MTR/DOCUMENTATION	8	0.68%
B. INCORRECT MTR (MATERIAL TEST REPORT)	4	0.34%
C. DAMAGED MATERIAL/ITEM - INCOMING	23	1.95%
D. MATERIAL DEFECT	100	8.48%
E. WRONG MATERIAL/IMPROPER SPECIFICATION	16	1.36%
F. CONTAMINATION	11	0.93%
G. IDENTIFICATION/TRACEABILITY	30	2.54%
H. COUNTERFEIT MATERIAL/ITEM	0	0.00%
I. DIMENSIONAL/OUT OF TOLERANCE	191	16.20%
J. IMPROPER MATERIAL SUBSTITUTION	3	0.25%
3. FABRICATION/CONSTRUCTION ISSUE (THE PARTNER)		
A. DAMAGED MATERIAL/ITEM - PRODUCTION	69	5.85%
B. IMPROPER MATERIAL SUBSTITUTION	1	0.08%
C. DIMENSIONAL/OUT OF TOLERANCE	212	17.98%
D. USE OF DETRIMENTAL/UNAPPROVED PRODUCT	9	0.76%
E. UNQUALIFIED WELDER/WELDING OPERATOR	4	0.34%
F. WRONG WPS USED	6	0.51%
G. FITTING ERROR	20	1.70%
H. WELD DEFECT	71	6.02%
I. WRONG MATERIAL/CONSUMABLE USED	10	0.85%
J. LACK OF PROCESS/PROCEDURAL	168	14.25%
K. DRAWING ERROR	17	1.44%
L. MACHINING ERROR	12	1.02%
M. LOSS OF FME (FOREIGN MATERIAL EXCLUSION)	2	0.17%
N. PWHT (POST WELD HEAT TREATMENT) ERROR	2	0.17%
O. PRESSURE TEST FAILURE	6	0.51%
P. PAINT DEFECT	22	1.87%
4. ENGINEERING/DOCUMENT CONTROL ISSUE (THE PARTNER)		
A. DRAWING OR DRAFTING ERROR	17	1.44%
B. NON-CURRENT REVISION	1	0.08%
C. PROCESS COMPLIANCE	26	2.21%
5. FREE ISSUE MATERIAL (CUSTOMER)		
A. DAMAGED MATERIAL/ITEM	12	1.02%
B. DOES NOT MEET CODE/SPECIFICATION/STANDARD/CONTRACT	66	5.60%
C. INSUFFICIENT/INCOMPLETE DOCUMENTATION	38	3.22%
6. REGULATORY		
A. REGULATORY NON CONFORMANCE	0	0.00%
7. MISCELLANEOUS		
A. DEFECTS NOT COVERED BY THOSE ABOVE	0	0.00%
TOTAL	**1,179**	**100.00%**
GEOMETRIC NON-CONFORMANCE	**693**	**58.78%**

Through qualitative assessment of all documented NCR, it was found that some of the defect codes were used interchangeably, such as codes 2C, 2D, and 2I, 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 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 2C, 2D, 2I, 3A, 3C, 3G, 5A, and 5B were actually geometric in nature, and they represent the majority of reported issues, as shown previously at the end of Table 3-4. All of the NCR with one of these geometric defect codes are further examined to assess the relationship between module complexity and how it affects non-conformance. Table 3-5 below summarizes the percentage of each geometric defect code for all modules, their total number of geometric-related NCR, as well as their total number of NCR. Note that the summation of total NCR for all modules does not equal to the project total NCR, since some non-conformance were process-related and did not affect any specific nuclear modules.

Table 3-5. Module Difference in Geometric Defects

Defect Code		Project	KB36	Q223	Q233	Q240	Q305	Q601
2C		2.0%	1.9%	1.0%	1.7%	4.8%	2.0%	1.2%
2D		8.5%	11.1%	6.9%	5.8%	10.2%	17.6%	3.5%
2I		16.2%	23.2%	16.7%	16.5%	7.8%	19.0%	14.0%
3A		5.9%	2.4%	10.3%	8.3%	6.6%	3.3%	6.2%
3C		18.0%	20.8%	17.7%	14.0%	26.3%	12.4%	18.6%
3G		1.7%	1.4%	2.0%	0.8%	3.0%	1.3%	1.9%
5A		1.0%	0.0%	1.5%	5.0%	0.6%	0.7%	0.4%
5B		5.6%	7.2%	2.0%	7.4%	3.6%	7.8%	6.6%
Sum		**58.8%**	**68.1%**	**58.1%**	**59.5%**	**62.9%**	**64.1%**	**52.3%**
NCR	Geometric	693	141	118	72	105	98	135
	Total	1179	207	203	121	167	153	258

While modules with a more complex fabrication challenge, such as KB36 and Q601, have a higher number of NCR (207 and 258, respectively), they correspondingly have a higher number of geometric issues as well (141 and 135, respectively). Though the proportion of geometric-related NCR differs between modules (52% to 68%), they still represent over half of the documented non-conformance. Based on the results from Table 3-5, Figure 3-16 on the next page displays module difference in geometric defect code proportion in graphical form, compared to the baseline average for the project.

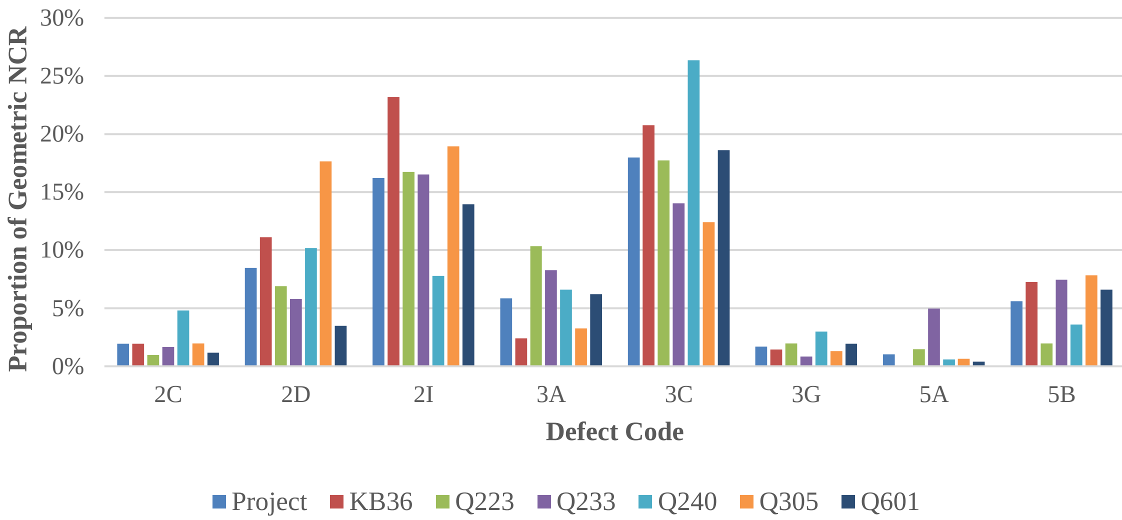


Figure 3-16. Module Difference in Geometric Defects

It is evident from Table 3-5 and Figure 3-16 that defect codes 2I (material "dimensional/out of tolerance" issues) and 3C (fabrication "dimensional/out of tolerance" issues) are the two most frequently cited non-conformance, and they 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". Nonetheless, 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.

Although each NCR 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, and 84 NCRs were sampled out of the 693 geometric-related non-conformance. This is based on having a confidence level of 95% that the real value is within ±10%. While it is obvious that 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 NCR. Nonetheless, the proportion of each defect code within the population of geometric-related NCR is preserved, and Table 3-6 on the next page summarizes the number of samples from each defect code that constitute the estimate.

Table 3-6. Sampling Geometric NCR

		Population	Percentage	Sample
Material Receipt				
2C	Vendor: Damaged Material/Item – Incoming	23	3.3%	3
2D	Vendor: Material Defect	100	14.4%	12
2I	Vendor: Dimensional/Out of Tolerance	191	27.6%	23
5A	Customer: Damaged Material/Item	12	1.7%	1
5B	Customer: Does Not Meet Code/Specification/Standard/Contract	66	9.5%	8
Fabrication				
3A	Partner: Damaged Material/Item – Production	69	10.0%	8
3C	Partner: Dimensional/Out of Tolerance	212	30.6%	26
3G	Partner: Fitting Error	20	2.9%	2
	Sum	**693**	**100%**	**84**

Based on the calculated results, 84 NCRs were sampled randomly from the project database, while also maintaining the proportion of geometric defect codes. Readers may refer to Appendix C for the complete description of each sampled NCR, as well as their proposed remedy. 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 3-7 summarizes the estimate cost and time impact of the 84 sampled geometric non-conformance. Readers may refer to Appendix D for the total breakdown of estimate for each sample.

Table 3-7. Estimate Cost and Time Impact of Geometric Non-Conformance

Defect Code	Sample	Cost ($)			Time (Hours)		
		Min	Max	Mean	Min	Max	Mean
Material Receipt							
2C	3	390	1,040	607	6	16	9.3
2D	12	390	910	531	6	14	8.2
2I	24	650	3,250	1,354	10	50	19.3
5A	1	390	390	390	6	6	6.0
5B	8	390	3,250	934	6	50	14.4
Fabrication							
3A	8	390	1,730	712	6	22	10.4
3C	26	390	1,770	1,065	6	25	15.7
3G	2	455	590	523	6	7	6.5
Total	**84**	**390**	**3,250**	**988**	**6**	**50**	**14.5**

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 QC personnel and craft workers (i.e. fitters and welders). Any additional time is based on labour required to perform rework, and any additional cost is based on new materials and extra man-hour. As shown previously in Table 3-7, 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 sample data, which would allow curve-fitting of probability distributions. Figure 3-17 and Figure 3-18 presents the cost and time impact histogram, respectively.

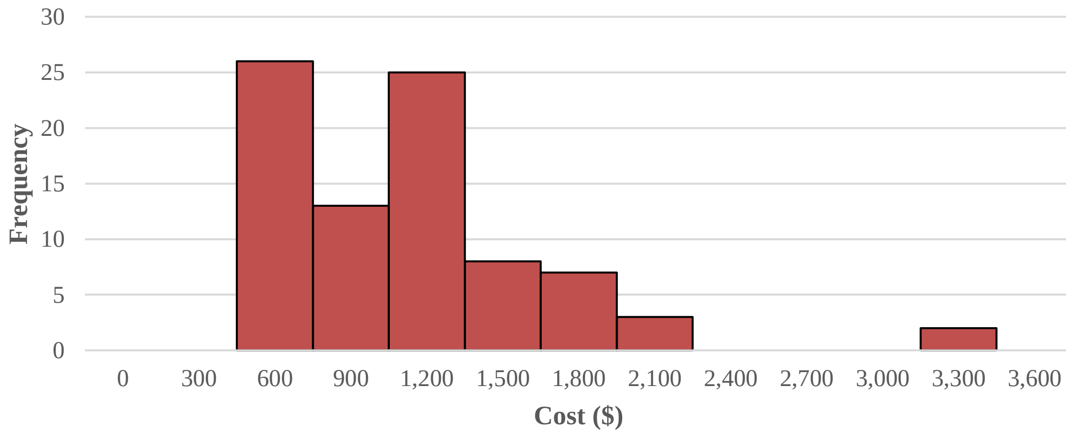


Figure 3-17. Sampled Geometric Non-Conformance Cost Impact Histogram

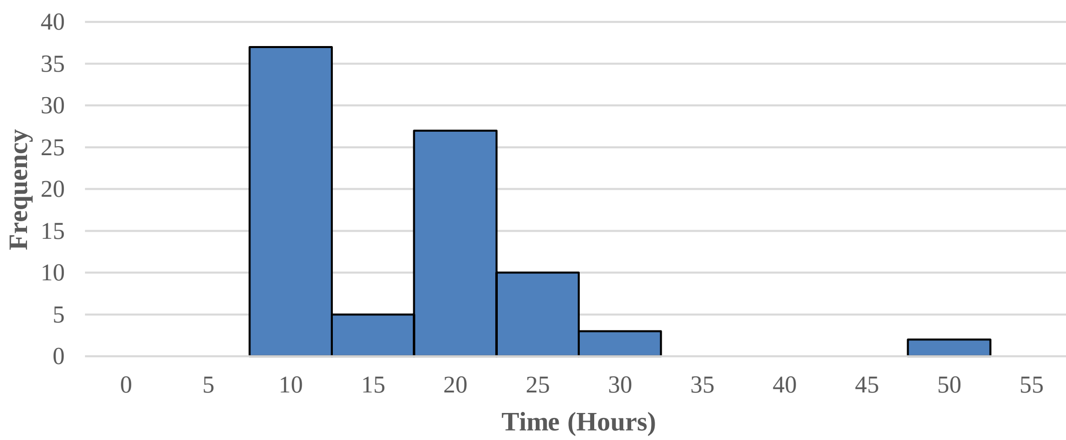


Figure 3-18. Sampled Geometric Non-Conformance Time Impact Histogram

Based on visual inspection, both histograms concerning cost and time impact resemble closely to lognormal distribution. To confirm this assumption, 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 impact metrics. Figure 3-19 and Figure 3-20 plots lognormal probability paper plot for cost and time impact, respectively. Readers may refer to Appendix E for complete probability paper plots of cost and time impact for all three distributions.

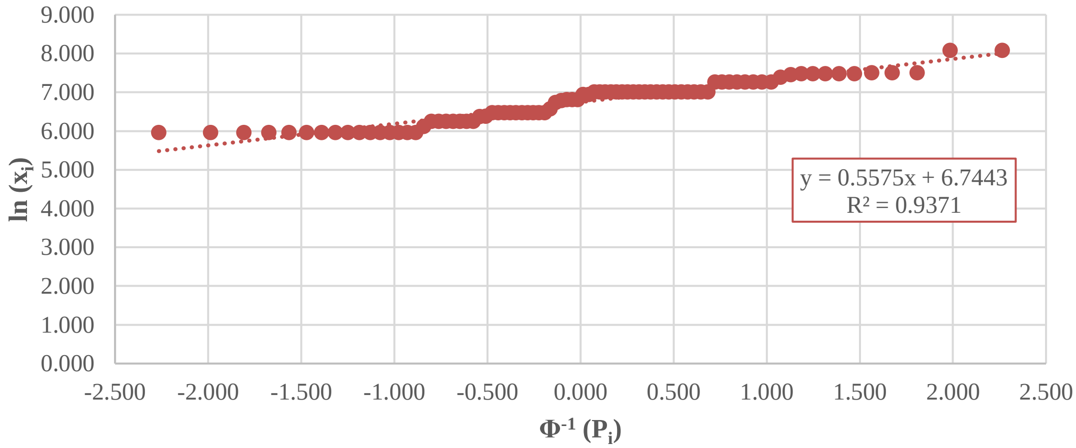


Figure 3-19. Cost Impact: Lognormal Probability Paper Plot

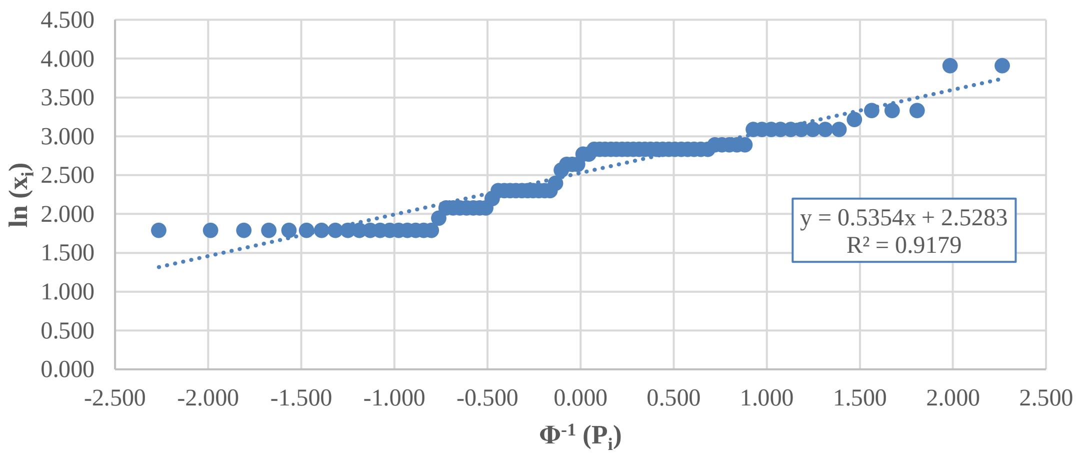


Figure 3-20. Time Impact: Lognormal Probability Paper Plot

In summary, there are some key findings from the non-conformance root cause analysis of the nuclear project. According to the partner's Quality Control Procedure, seven 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 35 "defect codes" are classified under these seven 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 2C, 2D, 2I, 3A, 3C, 3G, 5A, and 5B are actually geometric in nature, and they represent almost 60% of reported issues. Within these geometric-related NCR, over half of them are issues concerning dimension and tolerance for incoming materials and assembly fabrication.

In the interest of understanding the impact of 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 do rework and to release the assembly. Subsequent analysis confirm that the two impact metrics conform very closely to lognormal distribution.

It should be noted that this is the only dataset available where all non-conformances are tracked and documented throughout the project lifecycle within the prefabrication facility, therefore the findings from this analysis may not be representative of all pipe spool fabrication projects. Moreover, the dataset does not include non-conformance reported at project site, meaning the impact does not account for fabrication errors that are overlooked, or any liability dispute between the fabricator and site installation team. For example, in another one of partner's high volume and relatively complex projects, it required 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 remedy any errors, which include but are not limited to crew travel, lodging, schedule change, spool and/or module transport, rework at site and/or back in the facility, as well as performing required non-destructive testing again. These expenses can amount to hundreds of thousands of dollars, or even millions of dollars depending on the project. Consequently, this necessitates accurate and precise documentation of the final assembly, before it leaves the prefabrication facility to project site. With 3D scanning for quality control, the developed software technology by the research team could also function as an approved internal record to mitigate the risk of legal disputes of assigning rework responsibility.

3.4 FlexSim: 3D Simulation Modelling

To model and analyze the pipe spool fabrication workflow, there are several all-purpose discrete-event simulation tools currently being offered on the commercial market. Some of the more robust and established software include AnyLogic, Arena, FlexSim, ProModel, SIMUL8, and WITNESS. Trials were conducted to investigate the functions of these software in their free version as well as the capabilities of their analysis. FlexSim was ultimately chosen for several reasons:

1. FlexSim allows 3D simulation to model the physical system for realistic visualization.
2. FlexSim includes robust standard objects with pre-built logic and task execution.
3. FlexSim supports custom 3D objects to be imported into the software.
4. FlexSim integrates with third-party plug-in tools OptQuest (multi-objective optimization) and ExpertFit (data distribution-fitting)
5. FlexSim provides an intuitive user interface and engaging user experience with its drag-and-drop controls to layout the model and link its elements.
6. FlexSim permits coding with its FlexScript language (subset of C++) to specify object parameters and modify their behaviours for custom logic.
7. FlexSim maintains an online platform for users to post software and simulation questions, actively answered by the community and software developers.
8. FlexSim offers free educational licenses for academic research.

FlexSim Software Products first released FlexSim 1.0 in 2003, offering a 3D object-oriented simulation environment and seamless integration with C++. The software has been in constant development since then, with tools meeting simulation modelling demands of manufacturing, warehousing, material handling, healthcare processes, airport systems, and mining operations, as well as applications for digital twin, programmable logic controller (PLC) emulation, and value stream mapping (FlexSim Software Products, Inc. 2020).

At the time of conducting research for this thesis, FlexSim version 19.2.2 is used for all simulation modelling and analysis. This version represents FlexSim released in 2019, after the second major update to the software. The computer used to run the software is a Microsoft Surface Pro 4 Tablet, and its specifications are outlined in Table 3-8 on the next page. All components meet the minimum system requirements specified by FlexSim.

Table 3-8. Research Computer Specifications

Component	Specification
CPU	x64 Intel Core i5-6300U @ 2.40 GHz
Integrated Graphics	Intel HD Graphics 520
RAM	8 GB
Memory	128 GB Solid State Drive
Operating System	64-bit Windows 10 Professional

3.4.1 FlexSim in Academia

A review was conducted to identify published journal articles that featured FlexSim, and to assess its use as a discrete-event simulation tool in various research areas concerning process evaluation and process optimization.

Three academic databases, namely Science Direct, Scopus, and Web of Science, were searched to identify the journal with the largest number of related papers published. Keywords such as 'FlexSim', 'discrete-event simulation', and 'manufacturing' were used in the 'title/abstract/keyword' fields. Only peer-reviewed academic journals were selected for review. Book reviews, editorials, and papers for conference proceedings were excluded from this survey. A total of 45 journal articles were identified as of November 27, 2019 as relevant for subsequent analysis.

These 45 articles were quantitatively analyzed in terms of years and citations. The number of citations of a journal article was used as a key index to assess its research quality and determine its contribution. Keywords and abstract were assessed to identify broad research interests associated with each article; nine topics were identified, which are: (1) production planning, (2) warehouse logistics, (3) supply chain, (4) simulation technique, (5) scheduling, (6) material handling, (7) transportation, (8) healthcare, and (9) construction. All selected articles were classified into the most suitable topic.

The first journal article that featured the use of FlexSim in its research was published in 2008, concerning warehouse logistics. The software was used as a simulation experiment to validate a proposed model. Since then, there is a general increase in articles that use FlexSim for model evaluation as well as process optimization. The trend is illustrated in Figure 3-21 on the next page. The 45 articles under review were published in 22 peer-reviewed journals by researchers from Austria, Belgium, Brazil, China, France, Germany, Hong Kong, Italy, Malaysia, the Netherlands, New Zealand, Norway, Poland, Singapore, Taiwan, the UK, and the USA.

Figure 3-21. The Number of Articles Published in Peer-Reviewed Journals featuring FlexSim

As a discrete-event simulation tool, its application in academia research ranges from production planning and warehouse logistics in industrial and manufacturing engineering, to management science and operations research within the field of transportation (aviation) as well as healthcare. Figure 3-22 shows the number of articles associated with each broad research topic, where colour gradient indicates the total number of citations for each research category.

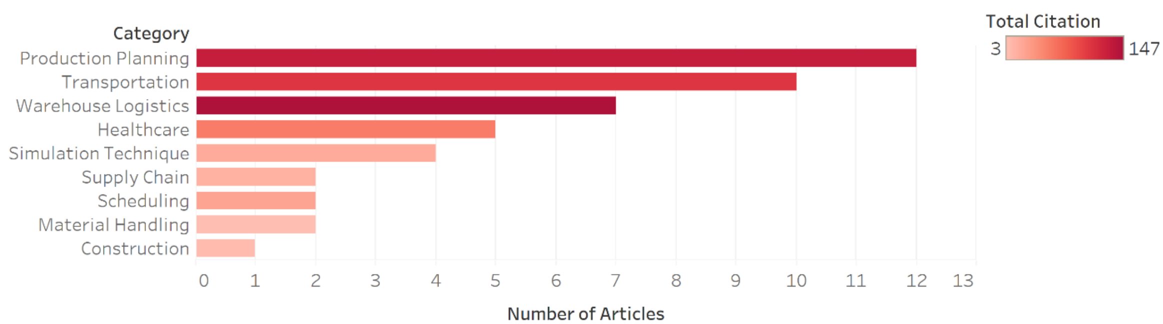


Figure 3-22. The Number of Articles for Each Research Category featuring FlexSim

Production planning, transportation, and warehouse logistics are the three research topics that most frequently used FlexSim, constituting almost 65% of the total number of selected articles, and over 75% of the total citations that referenced these papers. Some common keywords featured in the articles include ‘discrete-event simulation’, ‘simulation model’, ‘multi-objective optimization’, ‘warehouse management’, ‘order picking’, and ‘storage assignment’. Figure 3-23 on the next page illustrates a word cloud of keywords suggested by authors of the selected articles, where word size in the figure is dependent on their frequency.

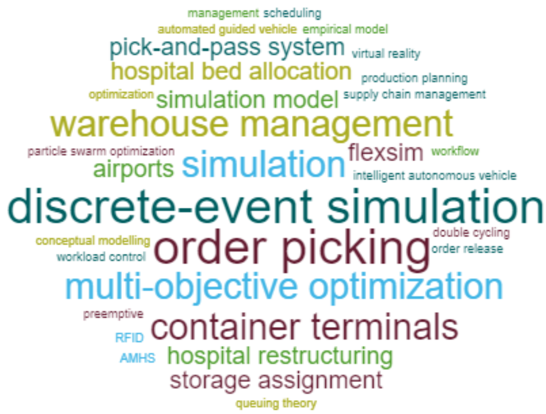


Figure 3-23. Word Cloud of Frequently Used Keywords in Reviewed Articles featuring FlexSim

The majority of the 45 journals under this review are influential and they place in the top quartile within their respective field. Table 3-9 organizes the journals in descending total citations, and summarizes the academic reputation of these journals by outlining their associated *h* index and impact factor in 2018. Lastly, as shown in Figure 3-24, the top three journals with the most publications featuring FlexSim are Computers and Industrial Engineering, Simulation Modelling Practice and Theory, and International Journal of Simulation Modelling; these journals represent over a third of the total number of selected articles as well as total number of citations.

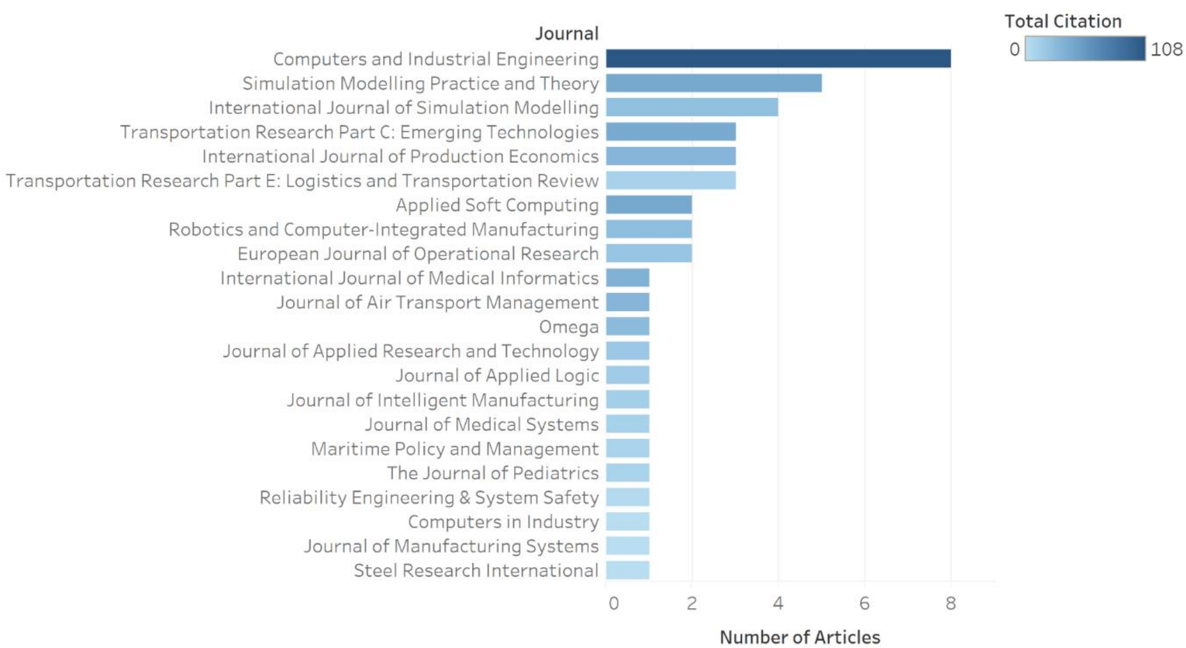


Figure 3-24. The Number of Articles Published by Each Journal featuring FlexSim

Table 3-9. Quantitative Review of Journals that Published Selected Articles featuring FlexSim

Journal	Journal *h* Index	Journal Impact Factor (2018)	Number of Articles	Number of Citations	Citations per Article
Computers and Industrial Engineering	111	3.518	8	108	13.5
Simulation Modelling Practice and Theory	58	2.426	5	42	8.4
Applied Soft Computing	110	4.873	2	42	21.0
Transportation Research Part C: Emerging Technologies	100	5.775	3	40	13.3
International Journal of Medical Informatics	93	2.731	1	34	34.0
International Journal of Production Economics	155	4.998	3	31	10.3
Journal of Air Transport Management	60	2.412	1	31	31.0
Omega	120	5.341	1	27	27.0
Robotics and Computer-Integrated Manufacturing	78	4.392	2	25	12.5
International Journal of Simulation Modelling	20	1.825	4	23	5.8
European Journal of Operational Research	226	3.806	2	20	10.0
Journal of Applied Research and Technology	18	1.960	1	17	17.0
Journal of Applied Logic	29	1.230	1	14	14.0
Journal of Intelligent Manufacturing	67	3.535	1	12	12.0
Transportation Research Part E: Logistics and Transportation Review	93	4.253	3	10	3.3
Journal of Medical Systems	63	2.415	1	10	10.0
Maritime Policy and Management	48	3.410	1	9	9.0
The Journal of Pediatrics	188	3.739	1	9	9.0
Reliability Engineering & System Safety	119	4.039	1	3	3.0
Computers in Industry	87	4.769	1	0	0.0
Journal of Manufacturing Systems	54	3.642	1	0	0.0
Steel Research International	42	1.522	1	0	0.0
		Total	**45**	**507**	**11.3**

3.5 FlexSim Modelling Elements

The basic operations of FlexSim involve the creation and execution of events that are based on the logic specified in the model. The events generate actions and activities that occur over time. As a result of the events and/or the current state of one or more objects, items move or flow from object to object. In FlexSim, the items that flow through a model are called flow items. FlexSim objects are defined and programmed in four classes: (1) fixed resource class, (2) task executer class, (3) node class, and (4) visual object class. The items typically move between resources, which are either fixed resources (e.g. machines, conveyors, and storage areas) or mobile resources (e.g. operators, trucks, and AGVs). Mobile resources in FlexSim are called task executers since they execute a sequence of tasks such as travel, load, unload, etc. Items move into and out of objects via ports, i.e. input ports for receiving and output ports for releasing. Over the duration of a simulation, information on the conditions (or states) of a system are gathered, summarized, and used for analysis (Greenwood 2018).

3.5.1 Fixed Resources

While different types of fixed resources receive and release flow items at different times, the logic for receiving and releasing a flow item are generally the same for all fixed resources. Each fixed resource goes through a certain set of steps for each flow item that it receives and releases. Some of these steps are automatically handled by the fixed resource, and some allow the modeler to define the way flow items are received and released. All of these modeler-defined inputs can be edited. Figure 3-25 illustrates the steps that a fixed resource object goes through for each flow item that it receives and subsequently releases. The flowchart can be broken down into four major steps: (1) open input ports and find a flow item to receive, (2) process the flow item, (3) release the flow item and determine which output ports to open, and (4) transfer the flow item to the next station.

The flow of items between fixed resources can be controlled using standard port connection mechanism. Ports specify the objects a fixed resource can send to and pull from, defining the search patterns by which upstream fixed resources can find downstream fixed resources to send their items to, and/or the search patterns by which downstream fixed resources can find items to pull from upstream fixed resources. Ports also contain open/closed state to determine availability, to decide where items can go. Furthermore, port rankings enable routing rules based on defined values, such as the type or label of an item; therefore the order of port rankings is important.

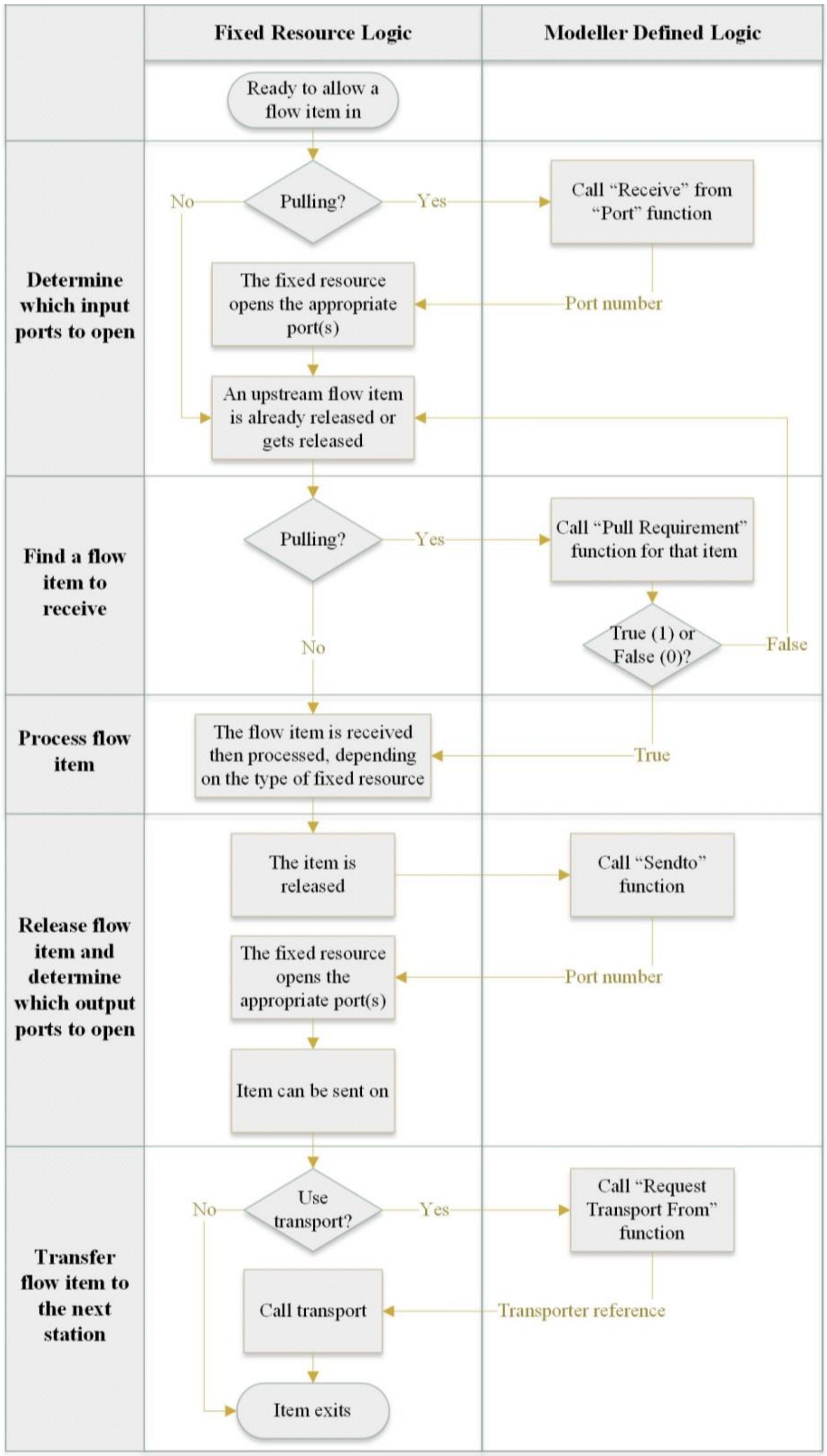
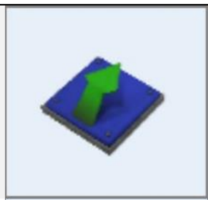
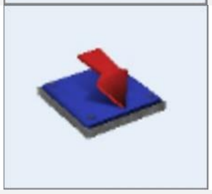
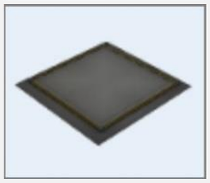
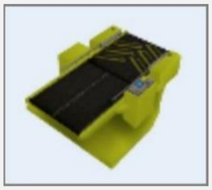
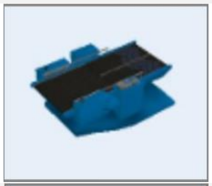


Figure 3-25. FlexSim Execution Logic (adapted from FlexSim Software Products, Inc. 2019)

There are seven standard fixed resources in FlexSim, which are: (1) Source, (2) Sink, (3) Queue, (4) Processor, (5) Combiner, (6) Separator, and (7) MultiProcessor. Table 3-10 summarizes the description for each fixed resource.

Furthermore, there are several standard statistics tracked by each fixed resource, such as "state", "throughput", "content", and "staytime". The state reveals its condition, such as being idle, processing flow items, being blocked by other fixed resource, waiting for operator, or undergoing scheduled breakdown. Throughput is made up of the input statistic and the output statistic, representing the rate of processing. Content records how many flow items are inside of the fixed resource, and can include the minimum, maximum, and average value from the entire model run. Lastly, the staytime statistic is recorded for each flow item that exits the fixed resource, and is calculated as the difference between the exit time and the entry time of the flow item.

Table 3-10. FlexSim Fixed Resources (adapted from FlexSim Software Products, Inc. 2019)

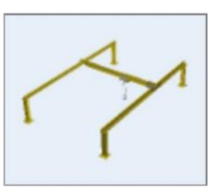
Fixed Resource Name	FlexSim Standard Object	Description
Source		The source is used to create the flow items that travel through a model. Each source creates one class of flow item and can then assign properties such as labels or colour to the flow item it creates. Sources can create flow item per inter-arrival rate, per a scheduled arrival list, or simply from a defined arrival sequence.
Sink		The sink is used to destroy flow items that are finished in the model. Once a flow item has travelled into a sink, it cannot be recovered. Any data collection involving flow items that are about to leave the model should be done either before the flow item enters the sink or in the sink's "On Entry" trigger.
Queue		The queue is used to store flow items when a downstream object cannot accept them yet. By default, the queue works in a first-in-first-out manner, meaning that when the downstream object becomes available, the flow item that has been waiting for that object the longest will leave the queue first. The queue has options for accumulating flow items into a batch before releasing them.
Processor		The processor is used to simulate the processing of flow items in a model. The process is simply modelled as a forced time delay. The total time is split between a setup time and a process time. The processor can process more than one flow item at a time. Processor may call for operators during their setup and/or processing times. When a processor breaks down, all of the flow items that it is processing will be delayed.
Combiner		The combiner is used to group multiple flow items together as they travel through the model. It can either join the flow items together permanently, or it can pack them so that they can be separated at a later point in time. The combiner will first accept a single flow item through input port number 1 before it will accept the subsequent flow items through the remaining input ports. The user specifies the quantity of subsequent flow items to accept through input ports 2 and higher. Only after all subsequent flow items required by the user have arrived will the setup/process time begin.
Separator		The separator is used to separate a flow item into multiple parts. This can either be done by unpacking a flow item that has been packed by a combiner or by making multiple copies of the original flow item. The splitting/unpacking is done after the process time has completed.
MultiProcessor		The multiprocessor is used to simulate the processing of flow items in sequentially ordered operations. The user defines a set of processes for each multiprocessor object. Each flow item that enters will go through each process in sequence.

3.5.2 Task Executers

All objects classified as task executers can travel, load flow items, unload flow items, act as shared resources for processing stations, and perform many other simulation tasks. When the task executer receives a task sequence, it first checks to see if it already has an active task sequence. If there is no active task sequence, or if the newly received task sequence is pre-empting and has a priority greater than the currently active task sequence, then it will start executing the new task sequence, pre-empting the active one if needed. If the task sequence is not passed on immediately, then it will queue up in the task executer's task sequence queue, and if the task sequence is still in the queue when the task executer finishes its active task sequence, the task executer will then execute the task sequence.

There are several standard task executers in FlexSim, the ones used in this research are: (1) Dispatcher, (2) Operator, (3) Transporter, and (4) Crane. Table 3-11 summarizes the description for each task executer.

Table 3-11. FlexSim Task Executers (adapted from FlexSim Software Products, Inc. 2019)

Task Executer Name	FlexSim Standard Object	Description
Dispatcher		The dispatcher is used to control a group of transporters or operators. Task sequences are sent to the dispatcher from an object and the dispatcher delegates them to the transporters or operators that are connected to its output ports. The task sequence will be performed by the mobile resource that finally receives the request. Depending on the modeler's logic, task sequences can be queued up or dispatched immediately once they are given to a dispatcher.
Operator		Operators can be called by objects to be utilized during setup, processing, or repair time. They will stay with the object that called them until they are released. Once released, they can go work with a different object if they are called. They can also be used to carry flow items between objects. Operators can be placed on a network if they need to follow certain paths as they travel.
Transporter		The transporter is used mainly to carry flow items from one object to another. It has a fork lift that will raise to the position of a flow item if it is picking up or dropping off to a rack. It can also carry several flow items at a time if needed.
Crane		The crane has similar functionality to the transporter but with a modified graphic. It is designed to simulate rail-guided cranes such as gantry, overhead, or jib cranes. By default, the crane picker rises to the height of the crane object after picking up or dropping off a flow item before it will travel to the next location. The default crane travel sequence is: (1) lift the hoist, (2) move the gantry and trolley simultaneously, and (3) drop the hoist to the offset position.

Other standard task executers available in the software include Elevator, Robot, and ASRS (Automated Storage and Retrieval System) for environments specific to the model (e.g. hospital and warehouse). All task executers have modeler-defined properties, such as capacity, speed, acceleration, travel offsets, and load time. They also have the capability of detecting collisions with other objects, performed by adding collision spheres to a task executer and its collision members.

Similar to the fixed resources, all task executers also track several standard statistics, such as “state”, “throughput”, “content”, and “staytime”. An additional tracked statistic is “travel distance”, which is the total travel distance as travel tasks are performed. The travel distance of a particular task is added to the total travel distance when the task is begun, not once the task is complete.

3.5.3 Travel Systems

By default, when a task executer travels between two objects, FlexSim will simply choose the shortest distance between two points: a straight line. If task executers use the default travel system, they might end up travelling through other objects or through barriers such as walls. To have a better visualization of movements in the model, and to track better statistics of the resources, accurate travel paths are essential in modelling a rigorous simulation. To this effect, FlexSim offers two different tools to create travel systems for task executers: (1) travel networks and (2) A* navigation.

Travel networks define the specific paths that task executers can use to get from one location to another using network nodes. The paths can be modified using spline points to add curvature to the path. By default, objects travelling on a network will follow the shortest path between their origin and destination; however, unlike fixed resources and task executers, network nodes do not implement any states or track any statistics. Traffic controllers can also be used in the model to help prevent collisions on certain paths, by defining a restricted area that will only let a specific number of task executers in the area at a time. If a task executer tries to enter a restricted area while another traveller is occupying that area, the task executer will wait.

On the other hand, A* navigation requires the modeler to create travel barriers for task executers. Any fixed resources or 3D objects connected to the A* system will also be treated as a barrier that cannot be passed through directly. The A* search algorithm will then use these barriers and the travel threshold around fixed resources to calculate the shortest distance between two locations. A* is an open-source graph traversal and informed path search algorithm, which determines the minimum cost path based on the evaluation function presented on the next page:

$$f(n) = g(n) + h(n) \quad (1)$$

where *n* is the next node on the path, *g(n)* is the actual cost of an optimal path from the start node to node *n*, and *h(n)* is a heuristic function that estimates the cost of an optimal path from *n* to a preferred goal node; therefore *f(n)* is the cost of an optimal path constrained to go through *n* to the goal node, and the algorithm expands into the next available node having the minimum value (Hart et al. 1968). A* algorithm is essentially an improved extension of Dijkstra's Shortest Path First algorithm, which only evaluates *g(n)* in Equation 1, the real cost to reach the next node *n*, without heuristics to guide its search (Dijkstra 1959).

In FlexSim, both travel systems work with most simulation models, but each tool has their ideal use case scenarios. Table 3-12 summarizes their advantages and disadvantages.

Table 3-12. FlexSim Travel Systems (FlexSim Software Products, Inc. 2019)

	Travel Networks	A* Navigation
Advantages	• Gives the modeler more control over task executer travel paths • Models might run faster because travel networks don't need to perform as many calculations • Can be used to restrict the direction that travellers can travel on a path • Can set speed limits on certain travel paths	• Fairly easy to set up and handles most of the logic on modeler's behalf • Easier to set up a model with a high number of possible destinations and many possible paths between those destinations
Disadvantages	• Takes a slightly longer time to set up • Creating paths between every possible destination can be cumbersome	• If the model is large and complex, the algorithm could slow down the model while it computes the ideal travel path • When the calculations take too much time to process, it can sometimes create strange visuals

Due to the intrinsic simplicity to apply A* navigation, and the robustness of A* algorithm to guarantee an optimal path for the task executers to travel between locations, it will be used in the simulation modelling of this research. Although the workers in the prefabrication facility may not necessarily always follow the theoretical optimal path, and while the physical environment with which the model is based on is fundamentally dynamic, the planning of routes for the workers is not within the scope of this thesis. It is assumed that the result of the algorithm is reasonably acceptable, therefore A* navigation is sufficient to represent transport systems in this research.

3.6 Modelling Pipe Spool Fabrication

As mentioned briefly earlier, there is a wide variety of projects in pipe spool fabrication, ranging from typical oil and gas processing facilities to nuclear power plant refurbishment. In general, all projects can be categorized as nuclear or non-nuclear. Figure 3-26 delineates the types of projects related to pipe spool fabrication.

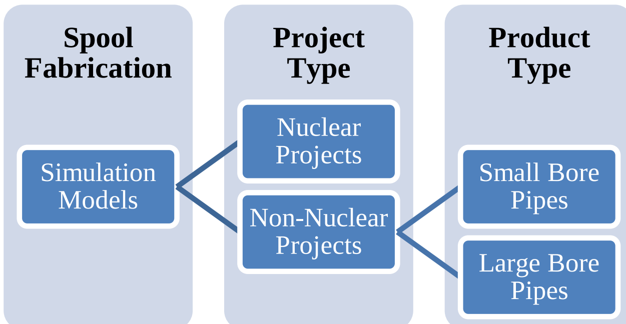


Figure 3-26. Simulation Models

The differences in quality control procedure between nuclear and non-nuclear projects were already discussed in detail in Section 3.3.2. In nuclear projects, quality control is performed by dedicated QC personnel, who would have to sign off on the components and spools before any work can continue. Nuclear work are generally very complex in geometry, and have strict tolerance requirements in order to comply with safety design prerequisites and adhere to narrow site conditions. Figure 3-27 depicts typical feeder tube assembly on a CANDU reactor, and Figure 3-28 on the next page illustrates the complexity of piping network that support various systems at the Bruce A Nuclear Generating Station in Ontario, Canada, which was commissioned in 1977.

Figure 3-27. Feeder Tube Assembly on Reactor Face (Chaplin 2014)

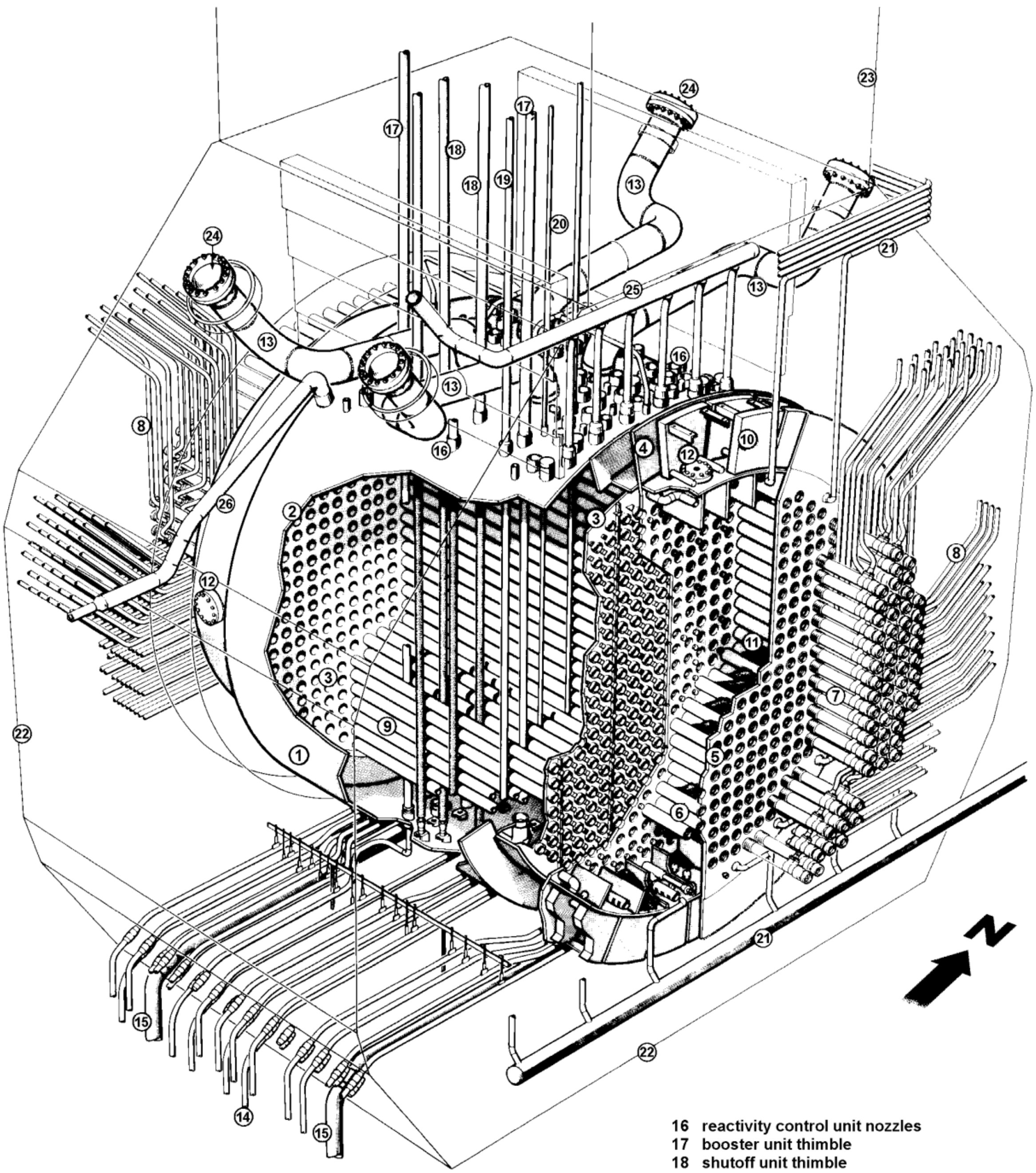


Figure 3-28. Bruce A Reactor Cutaway Illustration (Brown 2016)

On the other hand, typical non-nuclear projects would see undocumented self-checks by the craft workers after tack and weld, followed by a formal quality control protocol before shipment to site. These projects can be broadly divided into small bore and large bore pipes, where activity process times would differ given the ease of component maneuverability. Small bore pipes are usually much easier to fit, whereas some large bore pipes may require additional geometric quality control at the receiving stage as well. In either case, there are opportunities to streamline certain activities during quality control, and improve the overall workflow of pipe spool fabrication.

With the benefits of 3D scanning and near real-time 3D feedback system, their implementation before, during, and after fitting have the potential to increase productivity by distributing tasks between different stakeholders within the project, and to reduce rework by detecting errors early on before the ramification is aggravated when new components are attached to the assembly. This necessitates modification to the existing prevailing pipe spool fabrication work processes, and more specifically to the quality control procedure for both nuclear and non-nuclear projects. Deployment of innovation technology would not only offer additional arsenal of tools available for the workers to use for geometric inspection, but their ease of use as well as objective precision and accuracy would also enable anyone in the fabrication shop to effectively operate and control the technology, regardless of their spatial cognitive skills.

In order to reflect the two distinct quality control procedures between nuclear and non-nuclear projects, corresponding simulation models are created according to their specific fabrication workflow. Therefore two models will be presented hereafter, where nuclear and non-nuclear pipe spool fabrication workflow are discussed in Subsection 3.6.1 and Subsection 3.6.2, respectively. Under the non-nuclear model, the difference between small bore and large bore projects will also be explored; thus a total of three technology deployment scenarios are investigated in this thesis, which are: (1) nuclear projects, (2) small bore non-nuclear projects, and (3) large bore non-nuclear projects. Assessing the impact of implementing near real-time 3D feedback system during quality control, adjustments to the existing workflow will also be clarified, describing how the technology would fit within the current workflow, as well as how it would maintain or improve quality control capability throughout the fabrication of pipe spool assemblies. A single simulation model would be used to represent both the existing and proposed fabrication workflows, by changing certain key variables. This allows for comparison and evaluation of their difference in tracked performance metrics, such as total simulated project fabrication time, as well as total number of rework for each simulation run.

3.6.1 Modelling Nuclear Projects

Nuclear pipe spool fabrication has several stakeholders involved throughout the entire project lifecycle, however, of particular interest are the craft workers who fit and weld the assemblies, as well as quality control personnel who make sure fabricated components are up to codes and standards. Figure 3-29 on the next page outlines specific tasks and responsibilities for each relevant stakeholder during fabrication, and highlights the three quality control steps during fabrication, which takes place before tack, after tack, and after weld. The usual labour composition for the project workforce would be in the ratio of 15 fitters to 10 welders to 1 QC; however, number of workers assigned to a project depends entirely on deliverable deadline. Nonetheless, site observations by the research team revealed that quality control is often the bottleneck during fabrication, since the QC would be responsible for multiple projects, and the time it takes to conduct geometric inspection is actually quite significant.

The proposed fabrication workflow takes advantage of simple operation of 3D data acquisition hardware, as well as streamlined software service to detect discrepancy between as-built components and their intended design. The task of conducting geometric inspection using the developed innovation technology can be distributed among the fitters, before acquiring final approval and release from the QC personnel. This involves operating the 3D scanner to capture surface information of the assembly, registering the scan data into useable point clouds, and uploading as-built data to the software for overlay and comparison with design. The precision and accuracy offered by the hardware enables objective analysis and reduces human-induced errors during quality control; this means that regardless who is performing the task, using the same 3D scan data would produce identical end results every time. Figure 3-30 outlines stakeholder tasks and responsibilities for proposed nuclear pipe spool fabrication, and highlights modifications to quality control procedure involving the use of 3D scanning to aid geometric inspection and decision-making for QC personnel.

To represent both of the existing and proposed nuclear fabrication workflows, a simulation model is created that includes process activities for self-check by the workers themselves as well as inspection by the QC personnel. The parameters of the model would change according to which workflow it follows, that is, for example, existing workflow would see 0 minutes of self-check and 30 minutes of QC check after full penetration weld, while proposed workflow would see 30 minutes of self-check (3D scanning) and 5 minutes of QC check (for review and final approval). Since it is difficult to interpret the 3D simulation model itself, Figure 3-31 illustrates the logic that guides every element of the model, and reflects the existing and proposed nuclear pipe spool fabrication workflow.

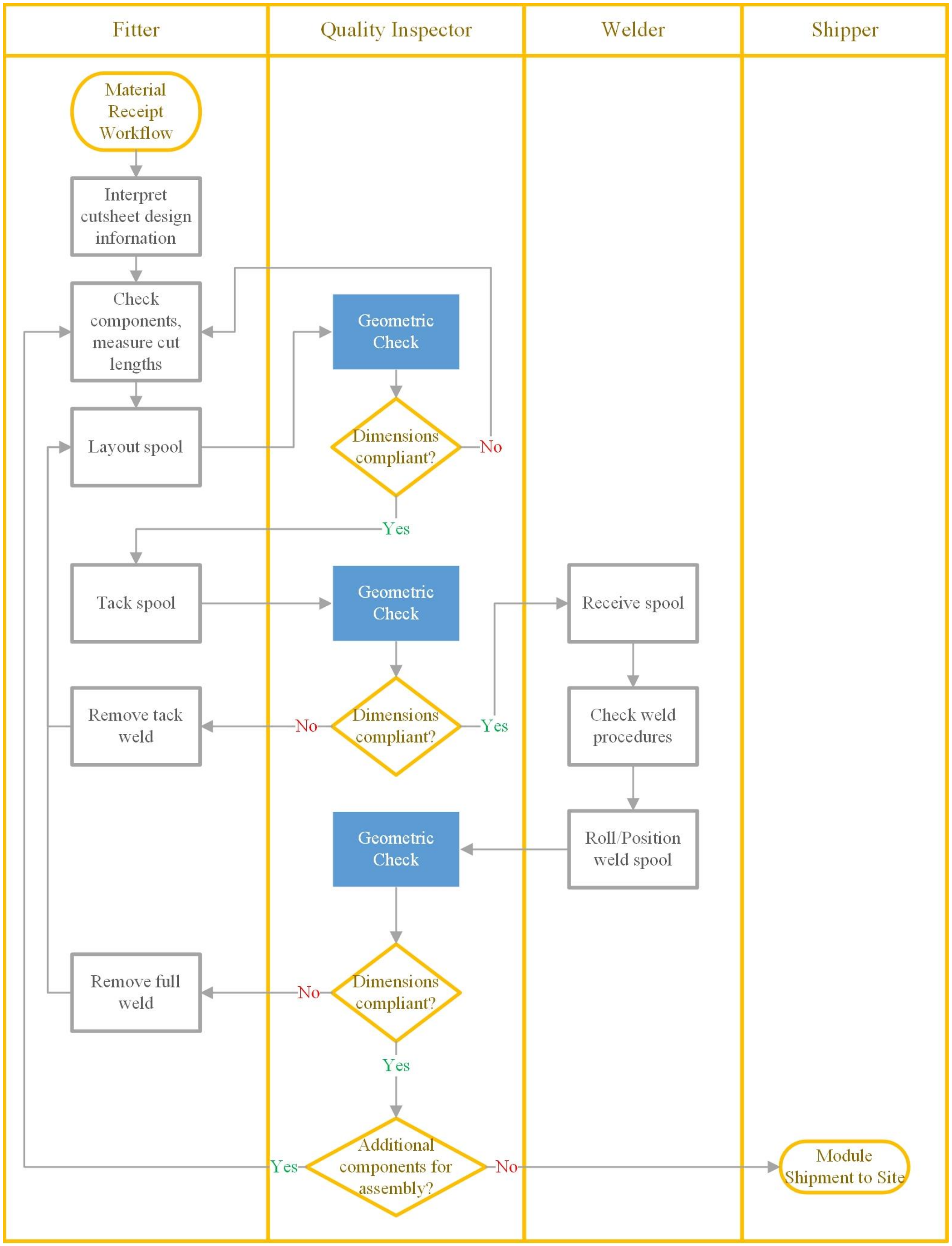


Figure 3-29. Swimlane Diagram of Existing Nuclear Pipe Spool Fabrication

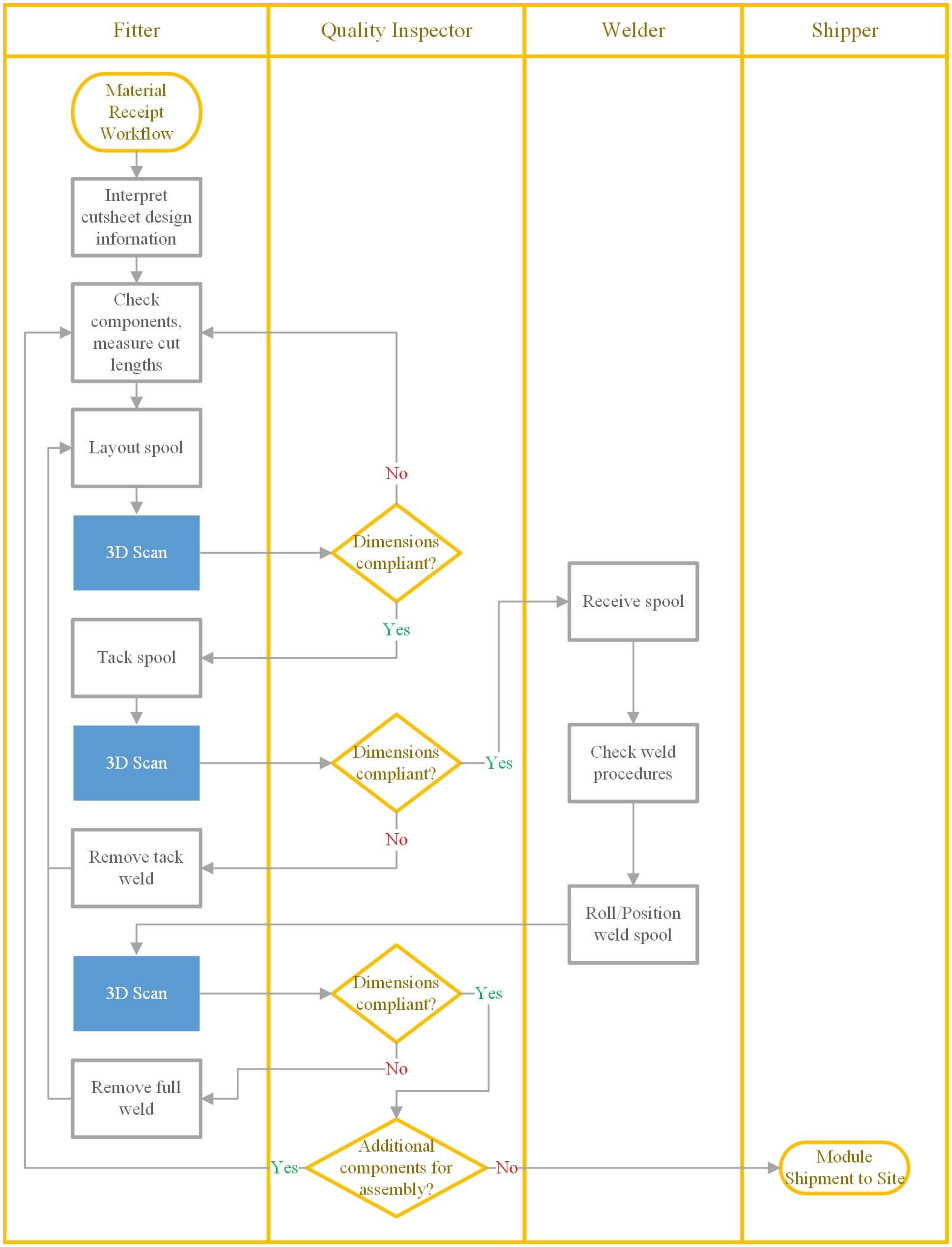


Figure 3-30. Swimlane Diagram of Proposed Nuclear Pipe Spool Fabrication

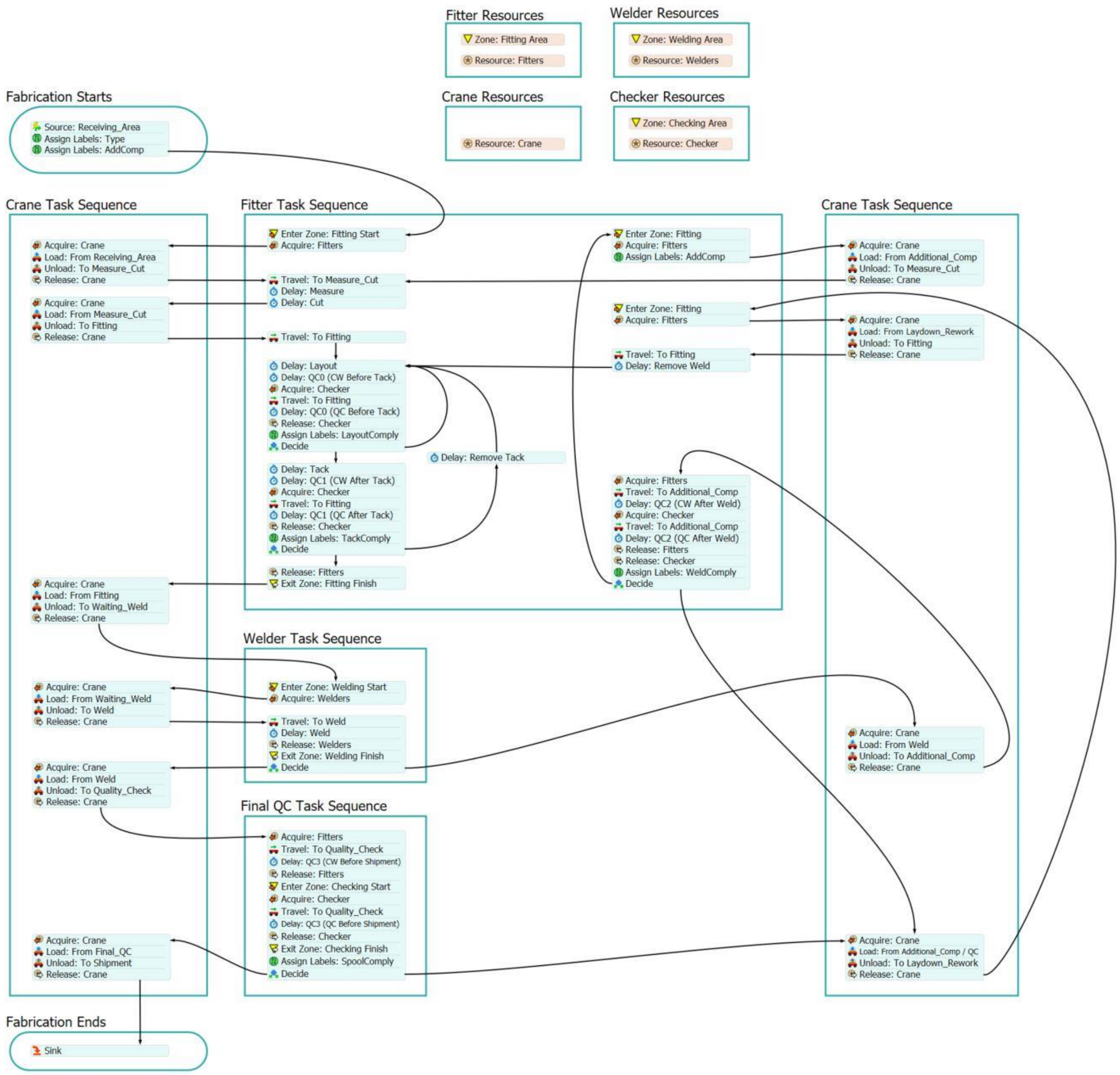


Figure 3-31. FlexSim Nuclear Pipe Spool Fabrication Simulation Model

In this simulation model for nuclear projects, tasks and responsibilities are grouped by specific roles assigned to execute them, which are also limited by the number of resources (people) available for each role. All of the variables in the model, including processing times for each activity as well as probability of non-conformance after quality control, are linked to a global table, which are specified according to the particular parameters associated with the existing or proposed workflow. Readers may refer to Appendix F for a more thorough explanation on how the model was developed using FlexSim, as well as the specific mechanisms used to indicate decision-making during quality control.

3.6.2 Modelling Non-Nuclear Projects

Non-nuclear pipe spool fabrication also rely on craft workers for fitting and welding, as well as quality control personnel who ensure the final products are within tolerance requirements so they can be released for shipment to site for installation. Figure 3-32 on the next page outlines specific tasks and responsibilities for each relevant stakeholder during fabrication, and highlights the two quality control steps during fabrication, which takes place after tack and after weld. It is important to note that QC only check the final assembly when it is complete, therefore if additional components are still needed, the task of geometric inspection would be performed by the fitters as they continue the fabrication process. Similar to nuclear projects, the usual labour composition for the project workforce would be in the ratio of 15 fitters to 10 welders to 1 QC; however, again, number of workers assigned to a project depends entirely on deliverable deadline. The issue of quality control as a bottleneck is not as apparent for non-nuclear projects, since formal documented quality control is conducted at the end of the workflow. In spite of that, the time it takes to conduct geometric inspection is still significant.

The proposed fabrication workflow takes advantage of the developed software ability to integrate with different 3D data acquisition hardware, thus enabling deployment scenarios specific to the need of the non-nuclear projects. While the stationary FARO Focus Laser Scanner is a reliable system that offers a wide field of view, therefore it can scan multiple assemblies at the same time, the hand-held DotProduct DPI-8S allows the users to maneuver around awkward position that might otherwise be obstructed from the scanner, and thus it may capture as much surface information as possible. To support consistent worker responsibilities across different projects, the tasks of conducting geometric inspection is similarly distributed among the fitters, before acquiring final approval from the QC personnel as required. Figure 3-33 outlines stakeholder tasks and responsibilities for proposed non-nuclear pipe spool fabrication, and highlights modifications to quality control procedure involving the use of 3D scanning to aid geometric inspection and decision-making for QC personnel.

Similar to the nuclear model, to represent both of the existing and proposed non-nuclear fabrication workflows, a simulation model is created that includes process activities for self-check by the workers themselves as well as inspection by the QC personnel. The parameters of the model would change according to which workflow it follows. Figure 3-34 illustrates the logic that guides every element of the simulation model, and reflects the existing and proposed non-nuclear pipe spool fabrication workflow.

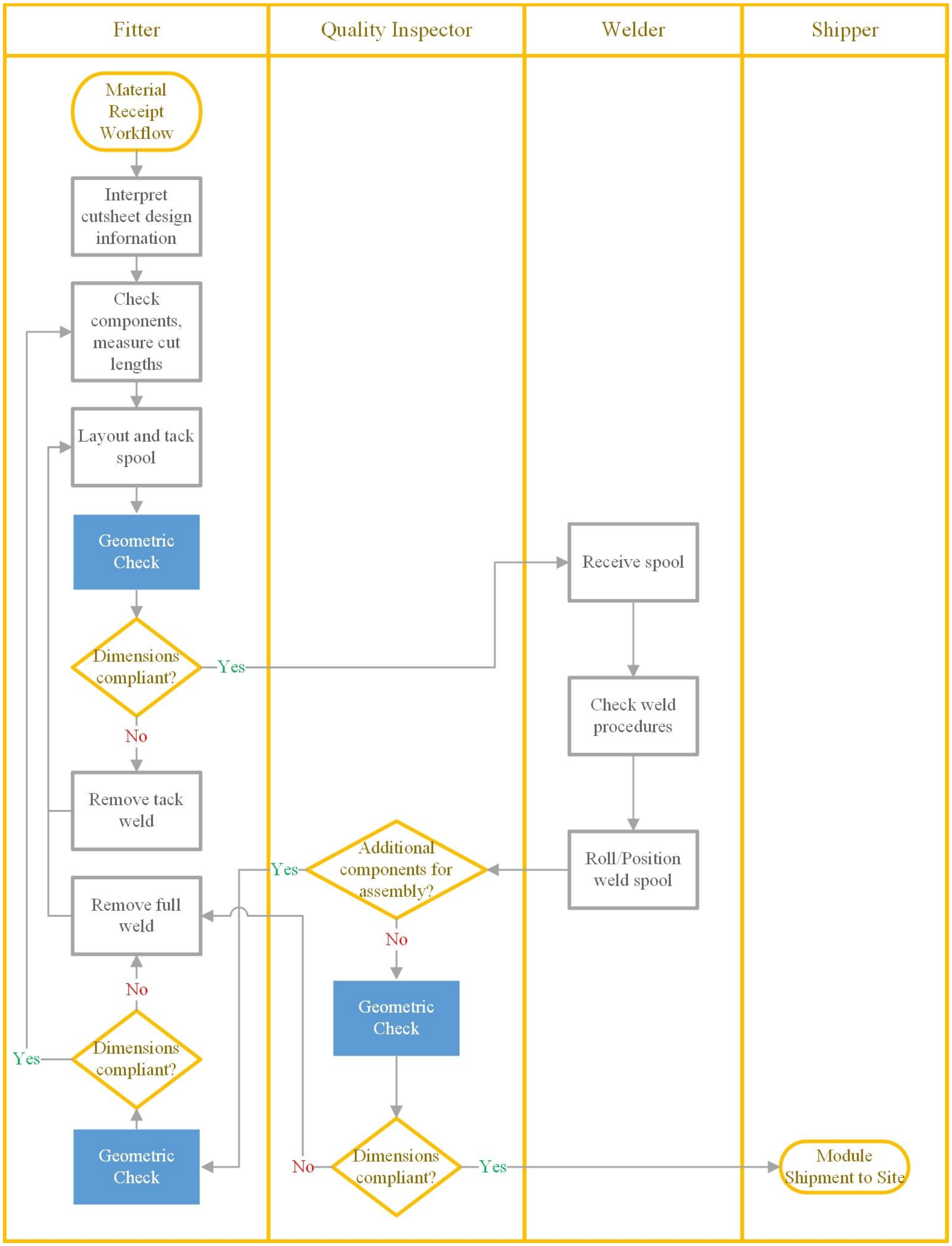


Figure 3-32. Swimlane Diagram of Existing Non-Nuclear Pipe Spool Fabrication

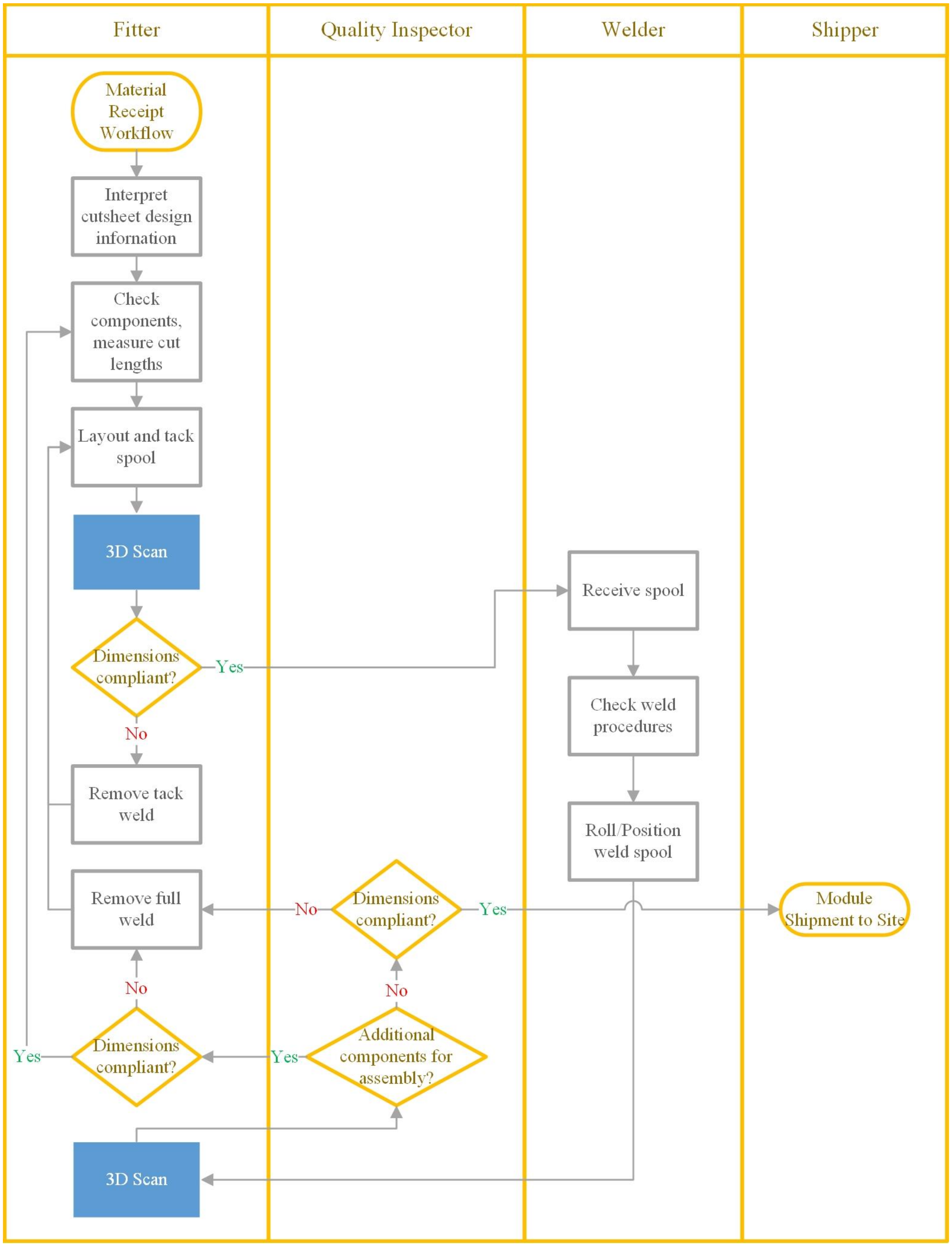


Figure 3-33. Swimlane Diagram of Proposed Non-Nuclear Pipe Spool Fabrication

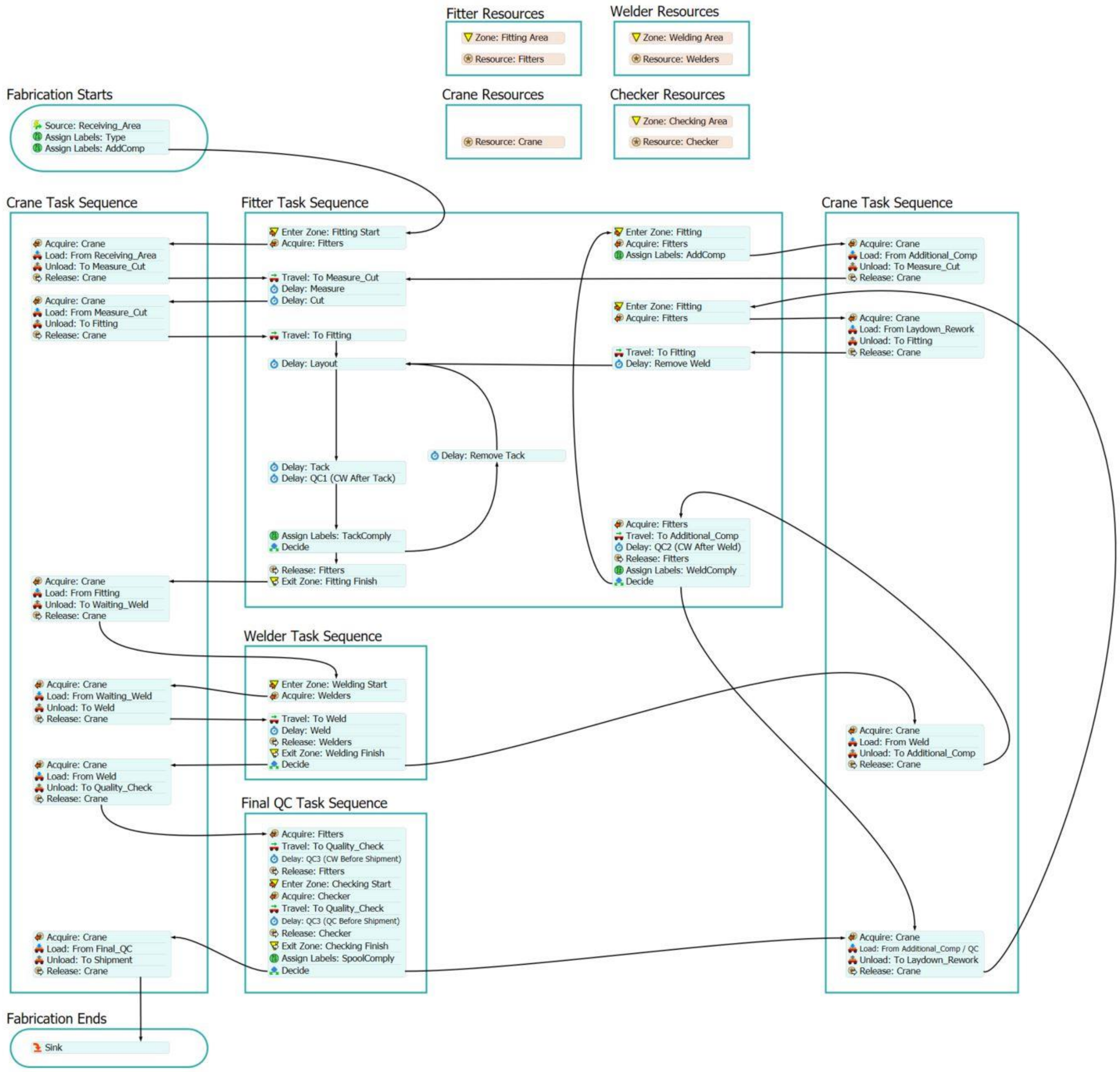


Figure 3-34. FlexSim Non-Nuclear Pipe Spool Fabrication Simulation Model

In this simulation model for non-nuclear projects, tasks and responsibilities are also grouped by specific roles, and are limited by the number of resources available. All of the variables in the model, including processing times as well as probability of non-conformance, are linked to a global table. Since the fabrication workflow is the exact same between small bore and large bore projects, their difference is reflected by the specific activity process times, where large bore projects may require a longer time to conduct quality control under both existing and proposed workflow. The development of this model is almost identical to the nuclear model, which is explained in detail in Appendix F.

3.6.3 Visualization of 3D Simulation Models

As presented earlier in Section 3.5, FlexSim includes a robust library of standard objects with pre-built logic and task execution. Its ability to support custom 3D objects to be imported into the software allows 3D simulation to model the physical system for realistic visualization. For the modelling of both nuclear and non-nuclear projects, the physical space is modelled based on the shop layout of the partner's prefabrication facility in Cambridge, ON. Readers may refer to Section F.3 of Appendix F for steps taken to model the spatial environment, and how custom objects are created to replicate physical equipment and system.

While Figure 3-31 and Figure 3-34 illustrate the nuclear and non-nuclear workflow logic, respectively, it is difficult to visualize the interaction between each stakeholder (i.e. fitters, welders, and QC personnel), as well as the flow of activities along the fabrication cycle. Thus 3D simulation models offer an intuitive snapshot of the system itself, and throughout a simulation run, the modeler may observe the work process as if it is a real system. At simulation system reset, Figure 3-35 shows the overhead view of the 3D simulation model, and Figure 3-36 on the next page presents the same model from different perspectives.

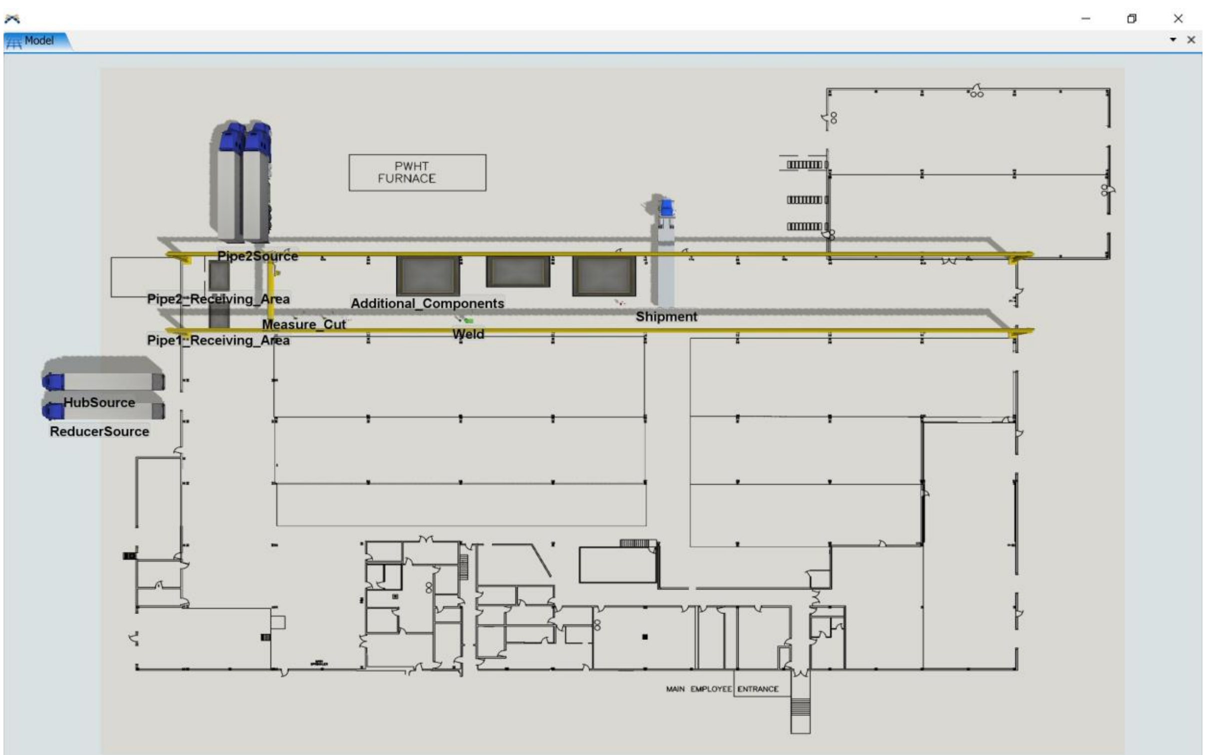


Figure 3-35. Overhead View of the 3D Simulation Model

Figure 3-36. Different Perspectives of the 3D Simulation Model

All objects in the model have been scaled appropriately according to the actual shop layout, as shown in the background. The trucks to the left of the model represent the receiving bay, where incoming materials are offloaded. There are several laydown areas, each one specific to the stage of the components along their fabrication workflow. In reality, most components and assemblies may be mixed together in one general area, however, to illustrate and visualize the fabrication process, they have been separated. Specifically, there is a laydown area for individual components that make up an assembly, a laydown area for rework of assemblies that failed geometric inspection, a laydown area for assemblies that require more components to be attached, and a laydown area for final quality check before shipment to site.

Specific equipment that have been included in the 3D simulation model include a rail-guided crane that runs along the entire bay of the fabrication shop. The crane is responsible for transporting heavy materials to different areas within its reach. The stands are where the fitting process takes place, which may include cutting, measuring, and tack welding. Also, a pipe rotator represents where the welders would weld an assembly while the pipe rotates about its principal axis. Lastly, different workers represent specific roles during fabrication, including fitters, welders, and QC personnel. They move about in the 3D environment of the simulation model, carrying out tasks according to their assigned logic.

3.7 Model Verification

There are two performance metrics tracked in both nuclear and non-nuclear models, which are the total simulated project fabrication time and the total number of rework tasks for each simulation run. While there are many variables that can affect either of these two metrics, assuming the worker composition stays the same and the number of spools to be fabricated is consistent across different simulations, variables concerning activity process time and probability of non-conformance would have the biggest impact on both of the tracked performance metrics. The process of verification during model development is an iterative process, where the output is constantly being evaluated to ensure the simulation model reflects changes to each input variable, as well as to specific workflows and mechanisms that represent pipe spool fabrication. Figure 3-37 below illustrates the exact inputs and outputs of interest for model verification, and the feedback nature of adjusting model parameters to correctly implement the specifications and assumptions of the fabrication simulation models.

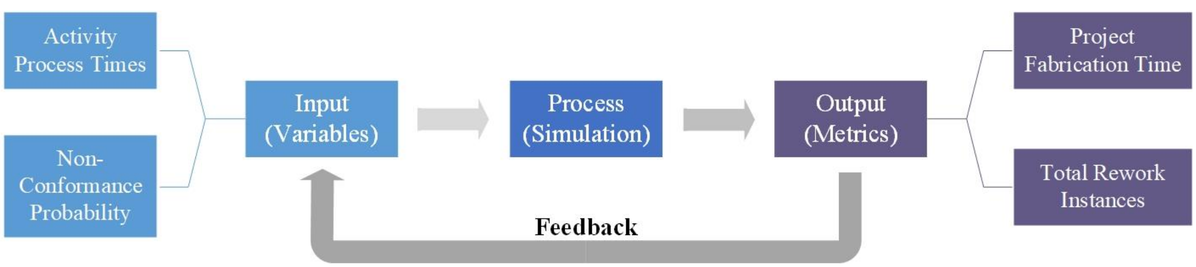


Figure 3-37. Iterative Model Verification

In FlexSim, there is a tool available called the Experimenter, which enables the modeler to run the same simulation model multiple times, changing one or more variables each time to see if the results would change. This involves setting up various variables for different scenarios of interest, as well as specifying what information is gathered to represent performance measures. The modeler also has the option to define the number of replications that will run for each scenario.

For all statistical distributions in the simulation software, the code returns a unique random stream associated with the current object. If the object does not yet own a stream attribute, or if its stream attribute is 0, FlexSim will assert the attribute and assign it a unique stream number. The algorithm uses a prime modulus multiplicative linear congruential generator (PMMLCG) (Johnson 2009) as a "random number generator" to create a stream, which is actually a list of pseudo-random numbers. The algorithm is based on the formula as presented in Equation (2):

$$Z_i = (aZ_{i-1}) \bmod m^* \tag{2}$$

where a is assigned the value of 630,360,016 and m^* is assigned the value of $2^{31} - 1$ (Marse and Roberts 1983). Each stream will generate a uniquely different set of numbers because each stream is initiated with a unique seed value.

During an experiment, each stream is initiated with a predefined seed value that is unique to both the stream and the replication being run. By using predefined seed values for each of the streams based on the replication number, the modeler is able to: (1) better compare results for a specific replication number across various scenarios defined in an experiment, and (2) manually rerun a specific replication of a specific scenario to further investigate something of interest discovered for a particular run of the experiment (King 2016).

Six scenarios are created to assess and verify the robustness of the nuclear and non-nuclear pipe spool fabrication models. These simulation scenarios are as follows:

1. Existing workflow
2. Same Inspection Time and Reduced Error Probability
3. Reduced Inspection Time and Same Error Probability
4. Reduced Inspection Time and Reduced Error Probability
5. Increased Inspection Time and Same Error Probability
6. Increased Inspection Time and Reduced Error Probability

The first scenario represents the current prevailing fabrication workflow, and it acts as a reference to be compared against the other five scenarios. Table 3-13 outlines the expected outputs for each scenario, and how they compare with the baseline scenario.

Table 3-13. Model Verification Scenarios

Scenario	**Input (Variables)**		**Expected Output (Performance Metrics)**	
	Inspection Time	Error Probability	Project Fab Time	Rework Instance
1	Baseline	Baseline	Baseline	Baseline
2	Same as Baseline	Reduced	Same as Baseline	Reduced
3	Reduced	Same as Baseline	Reduced	Same as Baseline
4	Reduced	Reduced	Reduced	Reduced
5	Increased	Same as Baseline	Increased	Same as Baseline
6	Increased	Reduced	Increased	Reduced

For nuclear pipe spool fabrication, there are four quality control steps in the workflow, which are: (1) before tack, (2) after tack, (3) after weld, and (4) before shipment. Therefore, there are eight variables that need to be adjusted for each scenario, in order to reflect the varying inspection time and non-conformance failure probability. On the other hand, for non-nuclear pipe spool fabrication, there is no inspection before tack, therefore there are six variables that would need to be changed for each scenario. For the purpose of model verification, Table 3-14 and Table 3-15 outlines the value for each variable across all scenarios for the nuclear and non-nuclear simulation model, respectively.

Table 3-14. Nuclear Model Verification Variables

Variables		Scenario					
		1	2	3	4	5	6
Inspection Time (Minutes)	Before Tack	10	10	5	5	20	20
	After Tack	10	10	5	5	20	20
	After Weld	30	30	15	15	60	60
	Before Shipment	30	30	15	15	60	60
Failure Probability (%)	Before Tack	5	2.5	5	2.5	5	2.5
	After Tack	5	2.5	5	2.5	5	2.5
	After Weld	10	5	10	5	10	5
	Before Shipment	11	5.5	11	5.5	11	5.5

Table 3-15. Non-Nuclear Model Verification Variables

Variables		Scenario					
		1	2	3	4	5	6
Inspection Time (Minutes)	After Tack	5	5	2.5	2.5	10	10
	After Weld	15	15	7.5	7.5	30	30
	Before Shipment	30	30	15	15	60	60
Failure Probability (%)	After Tack	5	2.5	5	2.5	5	2.5
	After Weld	10	5	10	5	10	5
	Before Shipment	11	5.5	11	5.5	11	5.5

The model references a global table that contains all the variables, in order to create the six scenarios for model verification. Each scenario is simulated 1,000 times, and both nuclear and non-nuclear models assume 100 spools to be fabricated. Figure 3-38 and Figure 3-39 on the next page show the results for nuclear model verification of rework instances and simulated project fabrication time, respectively. Similarly, Figure 3-40 and Figure 3-41 show the results for non-nuclear model verification of rework instances and simulated project fabrication time, respectively. The goal is to confirm the results from both models correspond to the expected outputs as outlined in Table 3-13.

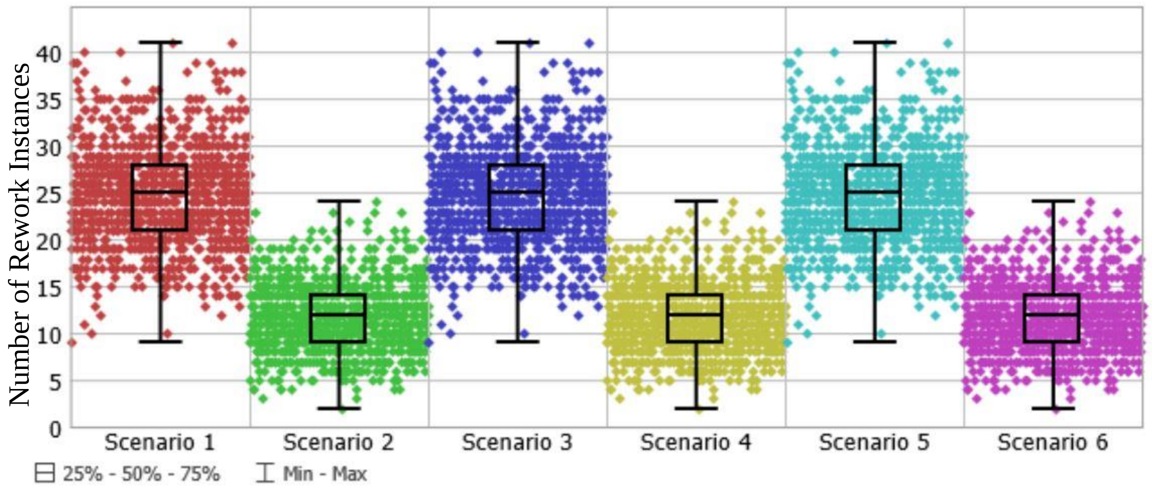


Figure 3-38. Nuclear Model Verification: Number of Rework Instances

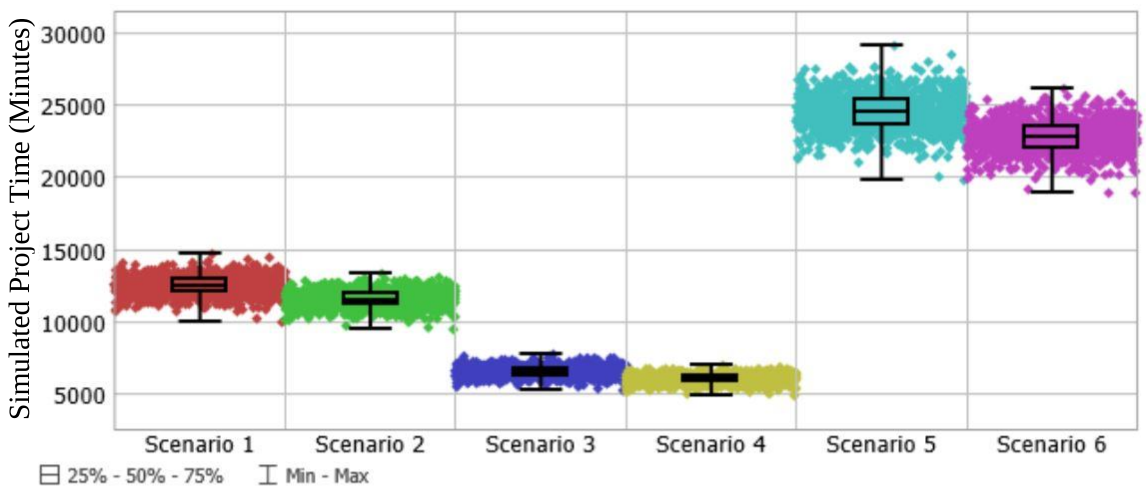


Figure 3-39. Nuclear Model Verification: Simulated Project Fabrication Time

As shown in Figure 3-38, it is fairly obvious to see the identical rework results between Scenario 1, 3, and 5, as well as between Scenario 2, 4, and 6. This is consistent with the defined input variables where Scenario 1, 3, and 5 shared the same non-conformance failure probability, as well as between Scenario 2, 4, and 6. The rework results confirm the same predefined seed values for each stream are used for the same replication number across all scenarios. This function is especially useful for troubleshooting unexpected output during model verification, so any discrepancy can be identified easily, thus allowing the model to be corrected accordingly.

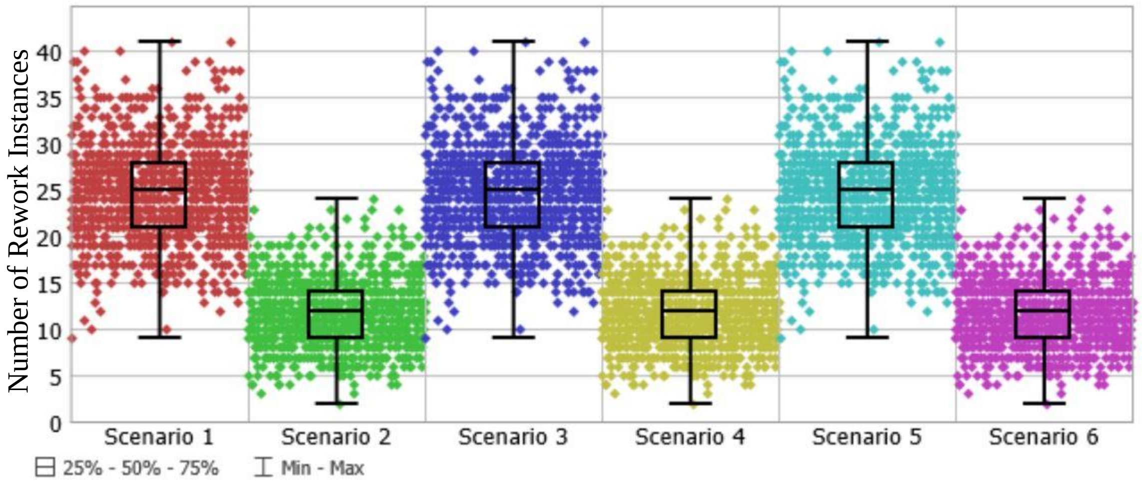


Figure 3-40. Non-Nuclear Model Verification: Number of Rework Instances

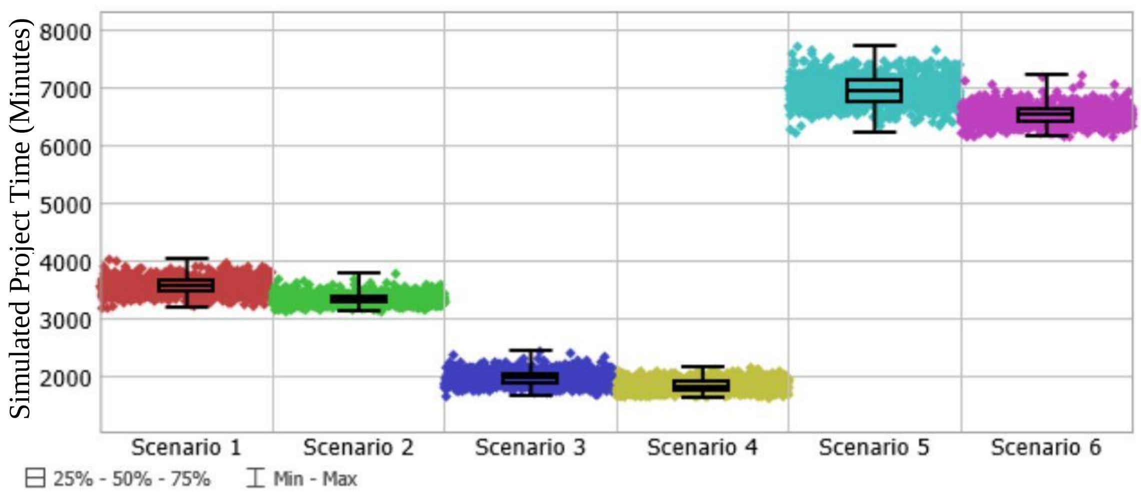


Figure 3-41. Non-Nuclear Model Verification: Simulated Projected Fabrication Time

The simulation results confirm that both nuclear and non-nuclear models perform as intended; when the inspection time remains the same between each set of scenarios while the non-conformance failure probability decreases, the associated number of rework in the model also decreases. When the inspection time is decreased, the overall simulated projected fabrication time decreases as well, and the same correlation is observed when the inspection time is increased. Therefore it could be concluded that these model verification results validate the nuclear and non-nuclear models are implemented accurately according to the conceptual workflow models.

3.8 Modelling Assumptions

There are several simplifying assumptions for the models in this research; while they would not pose an adverse impact on the simulation, changing the parameters could potentially alter the results of the coming analysis. Some of the modelling assumptions include:

1. Retrieval of flow item with the longest queuing time.
2. Linear progression of spool fabrication

By default, task executers in the model retrieve flow items in the queue that have the longest wait time. This may not necessarily represent fact since different products within the project might have competing priorities. It would be difficult to specify and randomize priorities in the model since priority would be constantly changing to fit project requirements, such as meeting a deadline for certain batches of products, or delay in the supply chain to deliver materials. Nonetheless, changing the order of flow item retrieval would have little impact on the overall simulated fabrication time, since the processing times for the fixed resources themselves are already defined.

Three types of spools are created in the models, where Type 1 spool contains four components, Type 2 spool contains three components, and Type 3 spool contains two components. For simplicity sake, all three spools use interchangeable components, meaning Type 2 spool is an extension of Type 3 spool with an additional component, and Type 1 spool is likewise an extension of Type 2 spool with an additional component. The model combines the first two components for all the spools first. As Type 3 spools exit the model, Type 2 spools are processed next by joining the next component, and the simulation continues until Type 1 spools are processed as well and exit the model. However, in reality, spools may be fabricated in the same cycle until it is complete; in other words, a Type 1 spool may continue through the feedback loop of fabrication until all four components have been combined, as opposed to wait in queue along with other Type 1 spools after only two or three components have been combined. This is similar to changing the order of flow item retrieval, in that defined processing times for the fixed resources would have little impact on the overall simulation runtime. Figure 3-42 on the next page illustrates the logic of how different types of spools are created in the models. Readers may refer to Appendix F for more detail on the model mechanisms that guide the creation of all three types of spools.

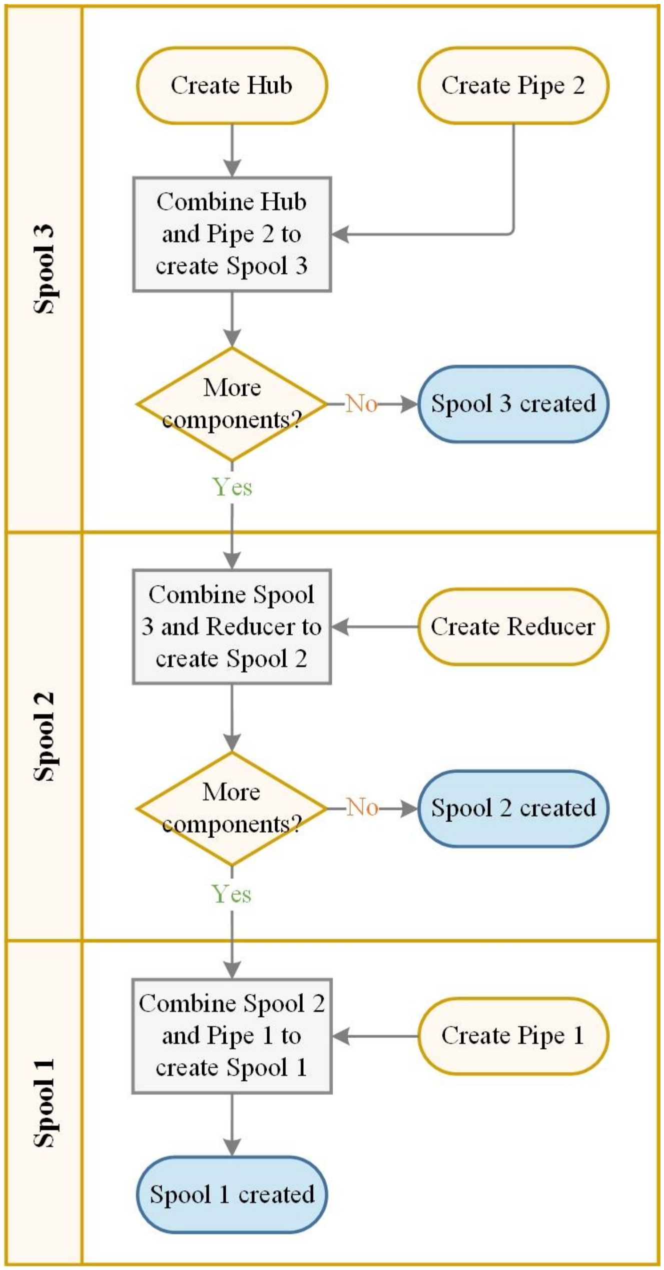


Figure 3-42. Model Spool Creation Flow

Lastly, literature lacks any information regarding the specific activity process times of pipe spool fabrication, whether it is for nuclear or non-nuclear applications. Therefore craft workers at the partner's prefabrication facility in Cambridge were consulted for the usual fabrication time for each activity. Table 3-16 summarizes the process time assumptions used in this thesis, based on the information provided by experienced fitters and welders.

Table 3-16. Fabrication Activity Process Time Assumptions

Activity	Activity Process Time (Minutes)		
	Nuclear	Small Bore Non-Nuclear	Large Bore Non-Nuclear
Measure	30	15	20
Cut	20	10	15
Layout	60	30	45
Tack	Triangular (15, 30, 22.5)	Triangular (5, 15, 10)	Triangular (10, 30, 20)
Remove Tack	20	15	20
Weld	Triangular (60, 120, 90)	Triangular (20, 40, 30)	Triangular (30, 60, 45)
Remove Weld	60	30	45
QC Before Tack	10	N/A	N/A
QC After Tack	10	5	5
QC After Weld	30	15	20
QC Before Shipment	30	30	30

Chapter 4
Simulation Analysis

The purpose of this chapter is to present and discuss the simulation results for the three innovation technology implementation scenarios, which are: (1) nuclear projects, (2) small bore non-nuclear projects, and (3) large bore non-nuclear projects. In the interest of understanding the impact of 3D scanning and 3D feedback on improving worker productivity, the two primary performance metrics to be tracked in the simulation models are the total simulated project fabrication time and the total number of rework instances for each simulation run.

An important change to the model setting is instead of using the same predefined seed values for each stream, the models would initialize random streams based on system time. While this essentially dismisses the ability to troubleshoot and repeat the simulations, it would ensure the results are truly randomized for analysis based on specified model parameters. Moreover, the measures presented in Section 3.7 concerning model verification already validated that both nuclear and non-nuclear models reflect their specific workflows and mechanisms which represent pipe spool fabrication.

Kwiatek et al. (2019) have previously studied the impact of augmented reality and spatial cognition on assembly in construction, and an earlier version of the 3D feedback augmented reality software application was used during their experiment. Although they also used a different 3D data acquisition hardware, the technology workflow remains the same, therefore their findings that augmented reality can help save substantial time in pipe spool assembly over conventional methods would be applicable to this thesis. Their experimental results on trained professional pipe fitters will be used as a basis of productivity improvement and rework reduction. Table 4-1 summarizes the difference in mean activity time regardless of cognitive ability from Kwiatek's thesis (2018), and improvement multiplier is calculated to show the difference between using isometric drawings and the technology.

Table 4-1. Productivity Improvement with 3D Scanning (adapted from Kwiatek 2018)

	Mean Activity Time			**Number of Errors**
	Absorb Design Information	Interpret Rework Information	Complete Rework	
Fitters with Technology	0:05:36	0:01:06	0:01:12	2.5
Fitters with Isometric	0:11:49	0:08:56	0:02:46	3.5
Mean Difference	0:06:12	0:07:49	0:01:33	1
Improvement Multiplier	0.47	0.12	0.43	0.71

To simplify Kwiatek's results on rework, the two activities concerning interpreting rework information and completing rework are combined into one single rework activity, and its average improvement multiplier would be applied to the baseline rework process time. While their studies examined specific activities in detail, this thesis focuses on the overall impact on the entire fabrication cycle, therefore rework is taken as the fitters' responsibilities of receiving the pipe spool for rework, absorbing and interpreting rework information, and laying out the components correctly for subsequent fabrication tasks. Table 4-2 outlines the two improvement multipliers that will be used as a basis of technology benefit over conventional workflows.

Table 4-2. Rework Activity Time and Failure Probability Improvement Multiplier

	Rework Activity Process Time		**Non-Conformance Failure Probability**
	Interpret Rework Information	Complete Rework	
Improvement Multiplier	0.12	0.43	0.71
	0.28		

Simulation analysis will subject both nuclear and non-nuclear models to the same parameters, except for fabrication activity process times. Both models will assume 100 spools are to be fabricated for the project, and each scenario will run 1,000 times to ensure sufficient data are gathered to conduct any meaningful analysis. Three input variables will be adjusted to observe their impact on the fabrication workflow; these variables are: (1) rework time, (2) failure probability, and (3) quality control time. Figure 4-1 outlines the sensitivity analysis on how the three variables would affect performance metrics related to productivity improvement and rework reduction.

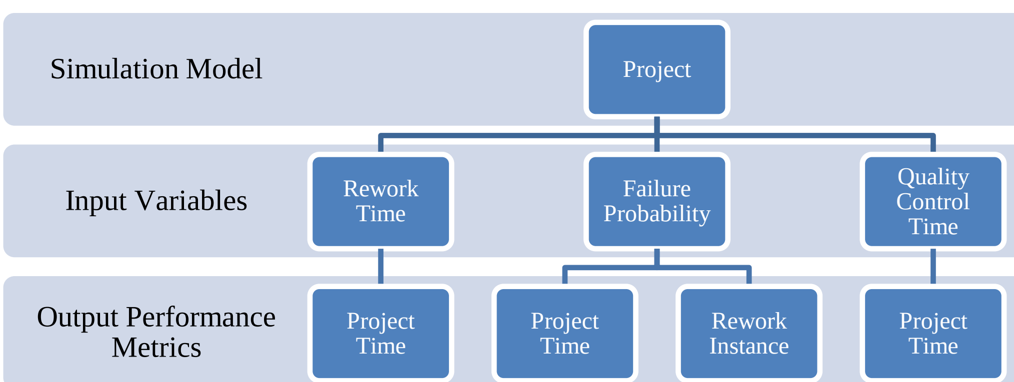


Figure 4-1. Simulation Sensitivity Analysis

4.1 Analysis on Nuclear Projects

The difference between existing and proposed workflow for nuclear projects is the distribution of geometric inspection responsibility from the QC personnel to fitters, taking advantage of the relative ease of technology operation and the worker composition ratio of 15 fitters to 1 QC. The task of data collection, which takes roughly 30 minutes, involves operating the 3D data acquisition hardware, uploading scanned data to developed software application, and overlaying the scanned point cloud over the point cloud from the design model to visually identify discrepancy. It is assumed it would take 5 minutes for the QC personnel to review the final results and release the spool for its next stage along the fabrication workflow. Improvement multipliers of 0.28 and 0.71 from Kwiatek's results are applied to rework time and non-conformance failure probability, respectively. Table 4-3 outlines the changing variables between existing and proposed nuclear pipe spool fabrication workflow.

Table 4-3. Nuclear Simulation Analysis: Existing vs. Proposed Workflow

Variables		**Scenario**	
		Existing	Proposed
Inspection Time by Fitters (Minutes)	Before Tack	0	30
	After Tack	0	30
	After Weld	0	30
	Before Shipment	0	30
Inspection Time by QC (Minutes)	Before Tack	10	5
	After Tack	10	5
	After Weld	30	5
	Before Shipment	30	5
Failure Probability (%)	Before Tack	5	3.6
	After Tack	5	3.6
	After Weld	10	7.1
	Before Shipment	11	7.9
Rework Time (Minutes)		60	17

The variables are implemented into the nuclear simulation model, and their impact is tracked on three performance metrics, which are: (1) number of rework instances, (2) total simulated project fabrication time, and (3) queue time for final geometric inspection before shipment to site; the results on these metrics are summarized in Table 4-4, Table 4-5, and Table 4-6, respectively, as well as presented in Figure 4-2, Figure 4-3, and Figure 4-4, respectively. The tables are statistics based on the 1,000 samples collected for each scenario, and the figures are taken from the FlexSim Experimenter results output, where Scenario 1 denotes existing workflow, and Scenario 2 denotes proposed workflow.

Table 4-4. Nuclear Simulation Analysis Results: Impact on Rework Instances

Scenario	Mean (99% Confidence) Number of Rework	Sample Std Dev	Min	Max
Existing	23.74 < 24.17 < 24.61	5.25	11	39
Proposed	16.53 < 16.90 < 17.27	4.47	5	33

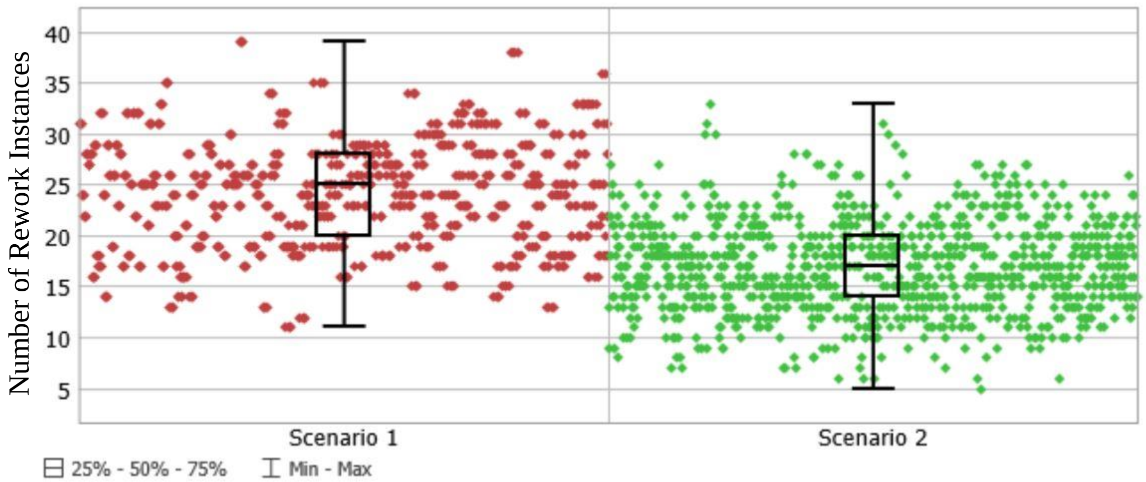


Figure 4-2. Nuclear Simulation Analysis Results: Impact on Rework Instances

The average number of rework instances decreased from 24.17 in the existing nuclear workflow (Scenario 1), to 16.90 in the proposed workflow (Scenario 2). This 30% reduction in rework corresponds to the non-conformance failure probability improvement multiplier of 0.71 (29% reduction) taken from Kwiatek's experiment results.

Table 4-5. Nuclear Simulation Analysis Results: Impact on Project Fabrication Time

Scenario	Mean (99% Confidence) Project Time (Minutes)	Sample Std Dev	Min	Max
Existing	12,422 < 12,471 < 12,521	593	10,475	14,478
Proposed	4,717 < 4,740 < 4,763	274	4,116	5,809

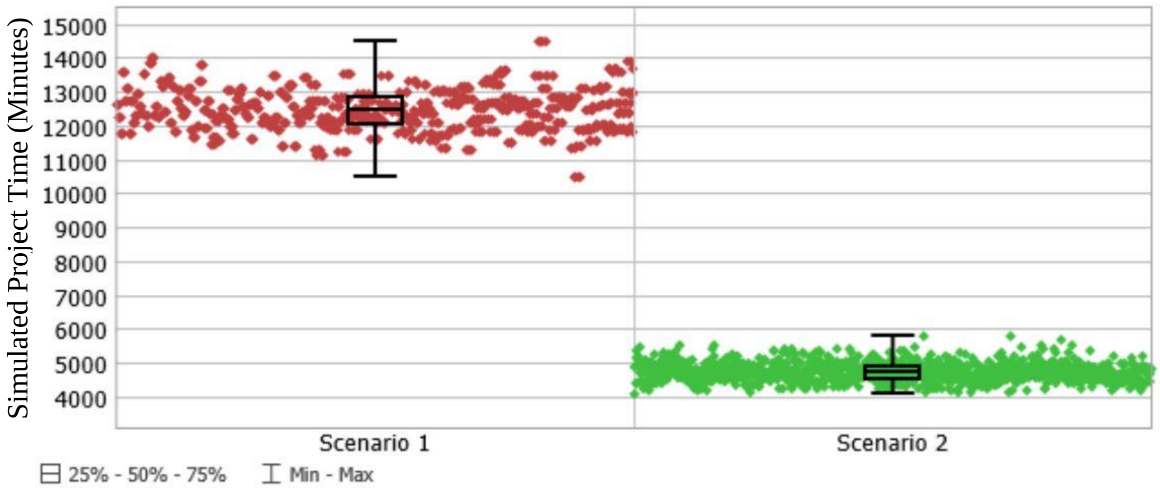


Figure 4-3. Nuclear Simulation Analysis Results: Impact on Project Fabrication Time

The average simulated project fabrication time decreased from 12,471 minutes in the existing nuclear workflow, to 4,740 minutes in the proposed workflow. This represents 62% reduction in total project time by allowing fitters to assist with geometric inspection across all quality control stages, including before tack, after tack, after weld, and before final shipment to site.

Table 4-6. Nuclear Simulation Analysis Results: Impact on Queue Time for Final Inspection

Scenario	Mean (99% Confidence) Queue Time (Minutes)	Sample Std Dev	Min	Max
Existing	2,268 < 2,290 < 2,312	264	1,464	2,913
Proposed	114 < 115 < 116	12	87	165

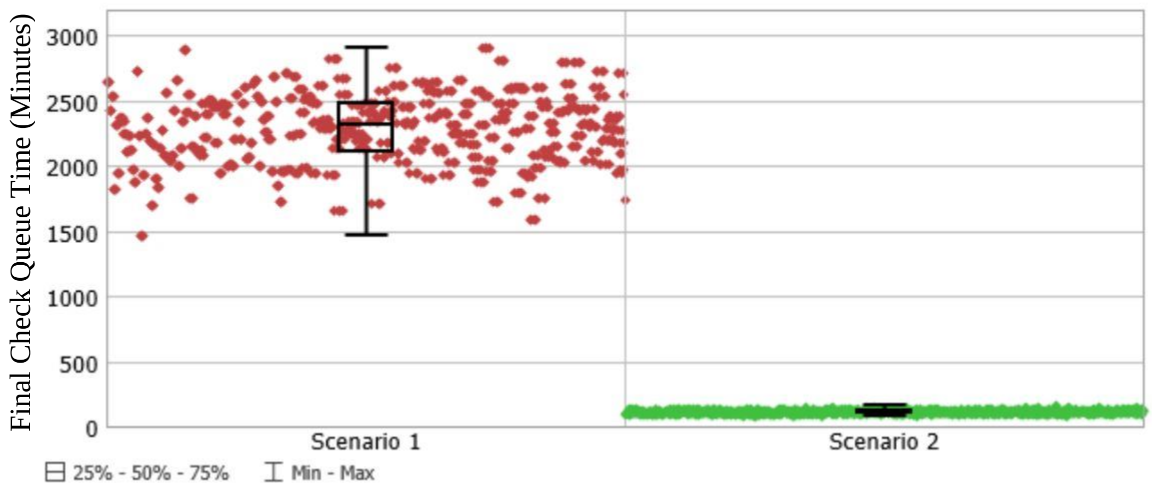


Figure 4-4. Nuclear Simulation Analysis Results: Impact on Queue Time for Final Inspection

The average queue time for final geometric inspection decreased from 2,290 minutes in the existing nuclear workflow, to 115 minutes in the proposed workflow. This represents 95% reduction in pipe spool wait times in the laydown area for QC personnel to inspect and release them. The results highlight the final inspection stage as a significant bottleneck during conventional pipe spool fabrication, and how much it contributes to the total project time. Note that the simulation greatly reduced the variance in the proposed workflow, due to a more streamlined processing of pipe spools as they enter the laydown area for final geometric inspection.

4.1.1 Nuclear Rework Time Sensitivity

The impact of rework time on proposed workflow of nuclear project is examined. Improvement multiplier of 0.28 is escalated by 0.05, 0.1, and 0.2, which increases rework time from 17 minutes to 20, 23, and 29 minutes, respectively. The scenario where no improvement is observed, meaning the original rework time of 60 minutes remains, is also included in this sensitivity analysis. Table 4-7 outlines the changing variables between baseline scenario of applying Kwiatek's result for the proposed workflow, and incremental increase to the rework improvement multiplier. The last column of the table indicates no improvement to rework activity time when fitters use 3D scanning technology during quality control as part of the fabrication workflow.

Table 4-7. Nuclear Simulation Analysis: Rework Time Sensitivity Parameters

Variables		Scenario				
		Baseline	B + 0.05	B + 0.1	B + 0.2	None
Inspection Time by Fitters (Minutes)	Before Tack	30	30	30	30	30
	After Tack	30	30	30	30	30
	After Weld	30	30	30	30	30
	Before Shipment	30	30	30	30	30
Inspection Time by QC (Minutes)	Before Tack	5	5	5	5	5
	After Tack	5	5	5	5	5
	After Weld	5	5	5	5	5
	Before Shipment	5	5	5	5	5
Failure Probability (%)	Before Tack	3.6	3.6	3.6	3.6	3.6
	After Tack	3.6	3.6	3.6	3.6	3.6
	After Weld	7.1	7.1	7.1	7.1	7.1
	Before Shipment	7.9	7.9	7.9	7.9	7.9
Rework Time (Minutes)		17	20	23	29	60

The variables are implemented into the nuclear simulation model, and their impact is tracked on the performance metric of total simulated project fabrication time. The results of this metric are summarized in Table 4-8 and presented in Figure 4-5. The table is statistics based on the 1,000 samples collected for each scenario, and the figure is taken from the FlexSim Experimenter results output, where Scenario 1 denotes baseline parameters of applying Kwiatek's improvement multiplier to the proposed workflow, Scenario 2 to 4 denotes incremental increase to the rework improvement multiplier, and Scenario 5 denotes no improvement in rework time for the proposed workflow.

Table 4-8. Nuclear Rework Time Sensitivity: Impact on Project Fabrication Time

Scenario	Mean (99% Confidence) Project Time (Minutes)	Sample Std Dev	Min	Max
Baseline	4,701 < 4,722 < 4,744	259	4,204	5,470
B + 0.05	4,731 < 4,755 < 4,779	288	4,167	5,962
B + 0.1	4,711 < 4,734 < 4,757	272	3,866	5,588
B + 0.2	4,730 < 4,754 < 4,777	287	4,091	5,887
None	4,819 < 4,843 < 4,868	298	4,138	5,846

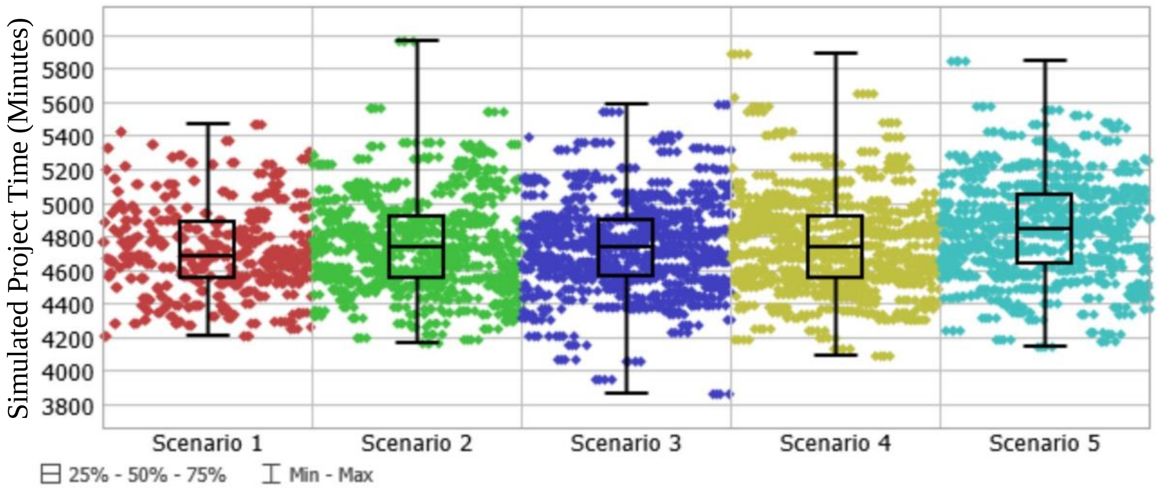


Figure 4-5. Nuclear Rework Time Sensitivity: Impact on Project Fabrication Time

The average project fabrication time increased from 4,722 minutes (Scenario 1) to 4,843 minutes (Scenario 5), as the rework time increased from 17 minutes (Scenario 1) to 60 minutes (Scenario 5). Figure 4-6 illustrates the linear relationship between increasing rework activity time and the project fabrication time.

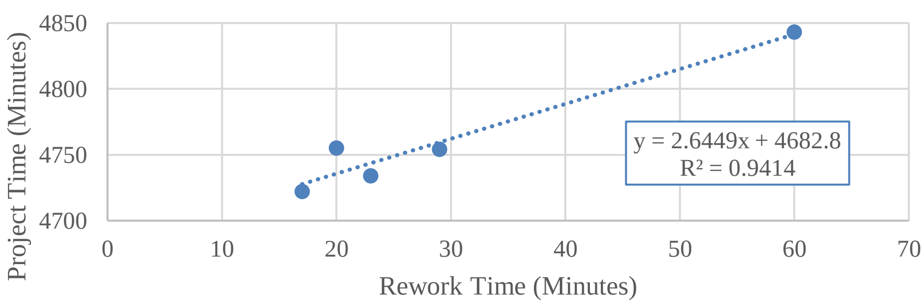


Figure 4-6. Nuclear Correlation between Rework Time and Project Fabrication Time

4.1.2 Nuclear Failure Probability Sensitivity

The impact of non-conformance failure probability on proposed workflow of nuclear project is examined. Improvement multiplier of 0.71 is escalated by 0.05, 0.1, and 0.2. The scenario where no improvement is observed is also included in this sensitivity analysis, meaning the original failure probability during quality control before tack, after tack, after weld, and before shipment, all remain the same. Table 4-9 outlines the changing variables between baseline scenario of applying Kwiatek's result for the proposed workflow, and incremental increase to the failure probability improvement multiplier. The last column of the table indicates no improvement to non-conformance failure probability when fitters use 3D scanning technology during quality control as part of the fabrication workflow.

Table 4-9. Nuclear Simulation Analysis: Failure Probability Sensitivity Parameters

Variables		Scenario				
		Baseline	B + 0.05	B + 0.1	B + 0.2	None
Inspection Time by Fitters (Minutes)	Before Tack	30	30	30	30	30
	After Tack	30	30	30	30	30
	After Weld	30	30	30	30	30
	Before Shipment	30	30	30	30	30
Inspection Time by QC (Minutes)	Before Tack	5	5	5	5	5
	After Tack	5	5	5	5	5
	After Weld	5	5	5	5	5
	Before Shipment	5	5	5	5	5
Failure Probability (%)	Before Tack	3.6	3.8	4.1	4.6	5
	After Tack	3.6	3.8	4.1	4.6	5
	After Weld	7.1	7.6	8.1	9.1	10
	Before Shipment	7.9	8.4	9.0	10.1	11
Rework Time (Minutes)		17	17	17	17	17

The variables are implemented into the nuclear simulation model, and their impact is tracked on the performance metrics of (1) number of rework instances, and (2) total simulated project fabrication time; the results on these metrics are summarized in Table 4-10 and Table 4-11, respectively, as well as presented in Figure 4-7 and Figure 4-9, respectively. The table is statistics based on the 1,000 samples collected for each scenario, and the figure is taken from the FlexSim Experimenter results output, where Scenario 1 denotes baseline parameters of applying Kwiatek's improvement multiplier to the proposed workflow, Scenario 2 to 4 denotes incremental increase to the non-conformance failure probability improvement multiplier, and Scenario 5 denotes no improvement to failure probability for the proposed workflow.

Table 4-10. Nuclear Failure Probability Sensitivity: Impact on Rework Instances

Scenario	Mean (99% Confidence) Number of Rework	Sample Std Dev	Min	Max
Baseline	16.52 < 16.88 < 17.23	4.27	8	29
B + 0.05	17.65 < 18.02 < 18.40	4.51	8	31
B + 0.1	19.47 < 19.86 < 20.25	4.74	8	36
B + 0.2	22.04 < 22.47 < 22.90	5.19	9	44
None	24.55 < 25.00 < 25.45	5.43	12	43

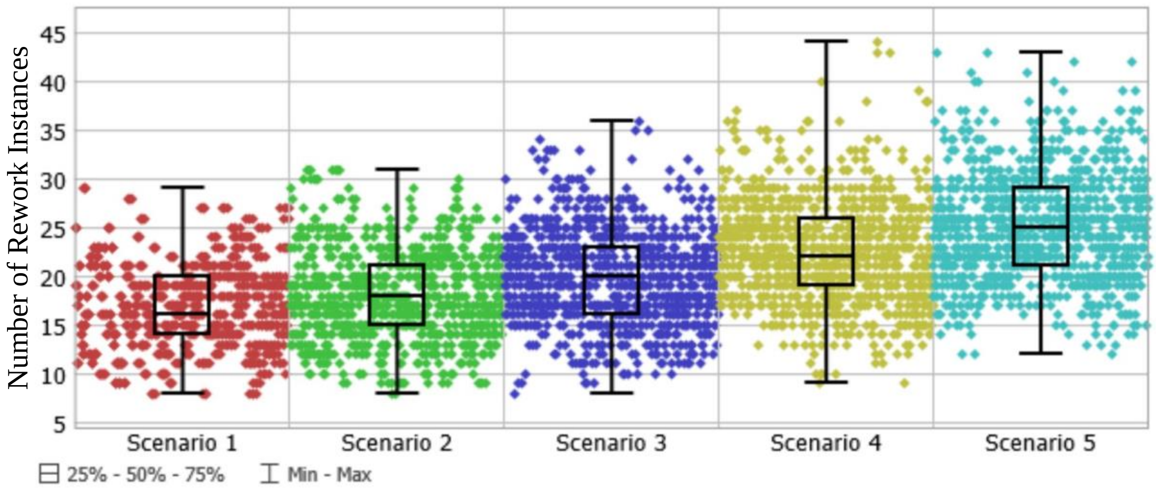


Figure 4-7. Nuclear Failure Probability Sensitivity: Impact on Rework Instances

The average number of rework instances increased from 16.88 (Scenario 1) to 25.00 (Scenario 5), as the failure probability improvement multiplier caused the failure probability before tack, after tack, after weld, and before shipment to increase from 3.6%, 3.6%, 7.1%, and 8.4%, respectively, to assumed no improvement in failure probability of 5%, 5%, 10%, and 11%, respectively. Figure 4-8 illustrates the linear relationship between increasing non-conformance failure probability and the number of rework instances in a project.

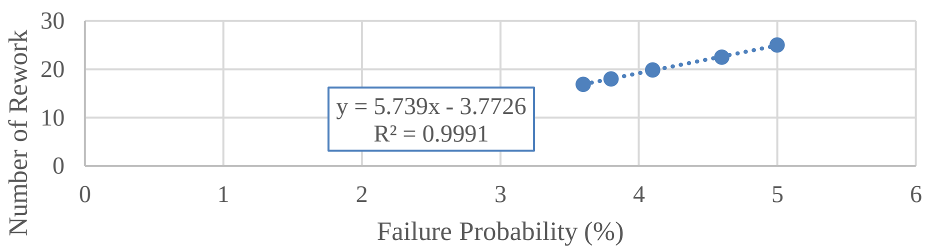


Figure 4-8. Nuclear Correlation between Failure Probability and Rework Instances

Table 4-11. Nuclear Failure Probability Sensitivity: Impact on Project Fabrication Time

Scenario	Mean (99% Confidence) Project Time (Minutes)	Sample Std Dev	Min	Max
Baseline	4,702 < 4,723 < 4,745	260	4,204	5,470
B + 0.05	4,738 < 4,761 < 4,785	280	4,121	5,828
B + 0.1	4,796 < 4,821 < 4,846	304	3,821	6,136
B + 0.2	4,861 < 4,887 < 4,912	308	4,037	6,143
None	4,951 < 4,976 < 5,002	311	4,149	6,287

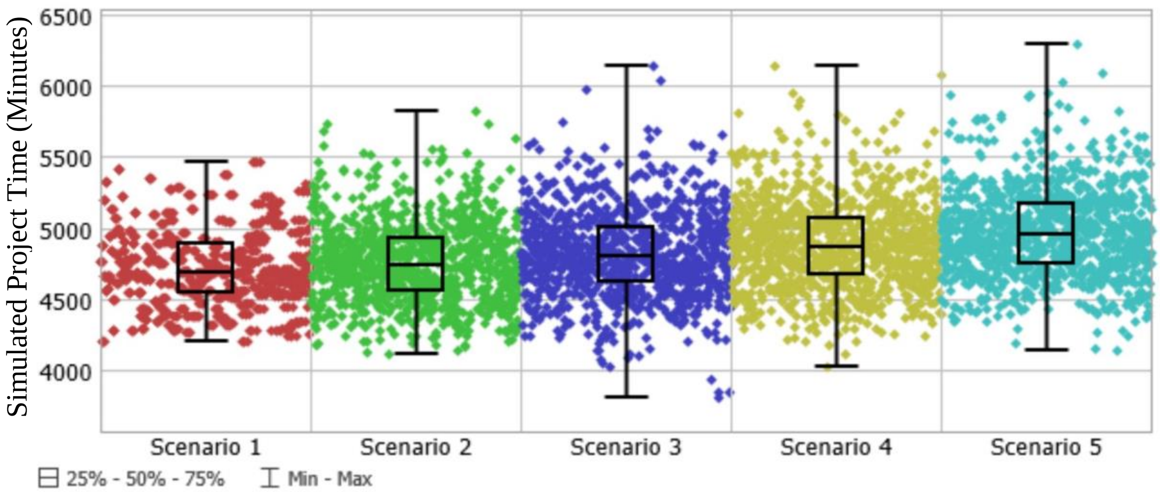


Figure 4-9. Nuclear Failure Probability Sensitivity: Impact on Project Fabrication Time

The average simulated project fabrication time increased from 4,723 minutes (Scenario 1) to 4,976 minutes (Scenario 5), highlighting the repercussion of performing multiple rework on pipe spools that failed quality control. Similar to the impact on number of rework instances, there is also a linear relationship between increasing non-conformance failure probability and the project fabrication time, as illustrated in Figure 4-10.

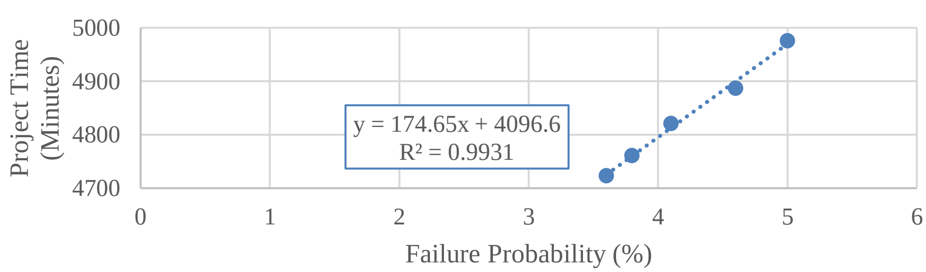


Figure 4-10. Nuclear Correlation between Failure Probability and Project Fabrication Time

4.1.3 Nuclear Quality Control Time Sensitivity

The impact of quality control time on proposed workflow of nuclear project is examined. The assumption of 30 minutes for inspection by the fitters is based on the average time by the research team to 3D scan pipe spools, register the scanned data into point clouds, and uploading the point cloud into the developed software application for discrepancy analysis. It is possible for the fitters to take a longer time performing these tasks, due to dynamic activity on the shop floor that could disrupt data acquisition, or unusual pipe spool geometry that requires multiple scans to capture complete surface information on the as-built assembly. Table 4-12 outlines the changing variables between Scenario 1 as the baseline parameters for the proposed workflow, and Scenario 2 and 4 as incremental increase to the fitters' inspection time. Scenario 3 and 5 represent increase in time by QC personnel to review the scanned data carried by the fitters, and to release the assembly to the next fabrication task.

Table 4-12. Nuclear Simulation Analysis: Quality Control Time Sensitivity Parameters

Variables		Scenario				
		1	2	3	4	5
Inspection Time by Fitters (Minutes)	Before Tack	30	33	33	36	36
	After Tack	30	33	33	36	36
	After Weld	30	33	33	36	36
	Before Shipment	30	33	33	36	36
Inspection Time by QC (Minutes)	Before Tack	5	5	10	5	10
	After Tack	5	5	10	5	10
	After Weld	5	5	10	5	10
	Before Shipment	5	5	10	5	10
Failure Probability (%)	Before Tack	3.6	3.6	3.6	3.6	3.6
	After Tack	3.6	3.6	3.6	3.6	3.6
	After Weld	7.1	7.1	7.1	7.1	7.1
	Before Shipment	7.9	7.9	7.9	7.9	7.9
Rework Time (Minutes)		17	17	17	17	17

The variables are implemented into the nuclear simulation model, and their impact is tracked on the performance metric of total simulated project fabrication time. The results of this metric are summarized in Table 4-13 and presented in Figure 4-11. The table is statistics based on the 1,000 samples collected for each scenario, and the figure is taken from the FlexSim Experimenter results output. Scenario 1 to 5 represent parameters as outlined in Table 4-12.

Table 4-13. Nuclear Quality Control Time Sensitivity: Impact on Project Fabrication Time

Scenario	Mean (99% Confidence) Project Time (Minutes)	Sample Std Dev	Min	Max
1	4,703 < 4,724 < 4,746	260	4,204	5,470
2	4,843 < 4,868 < 4,893	298	4,228	5,948
3	7,572 < 7,604 < 7,636	388	6,379	8,556
4	4,934 < 4,959 < 4,985	304	4,247	6,139
5	7,602 < 7,637 < 7,671	413	6,682	8,796

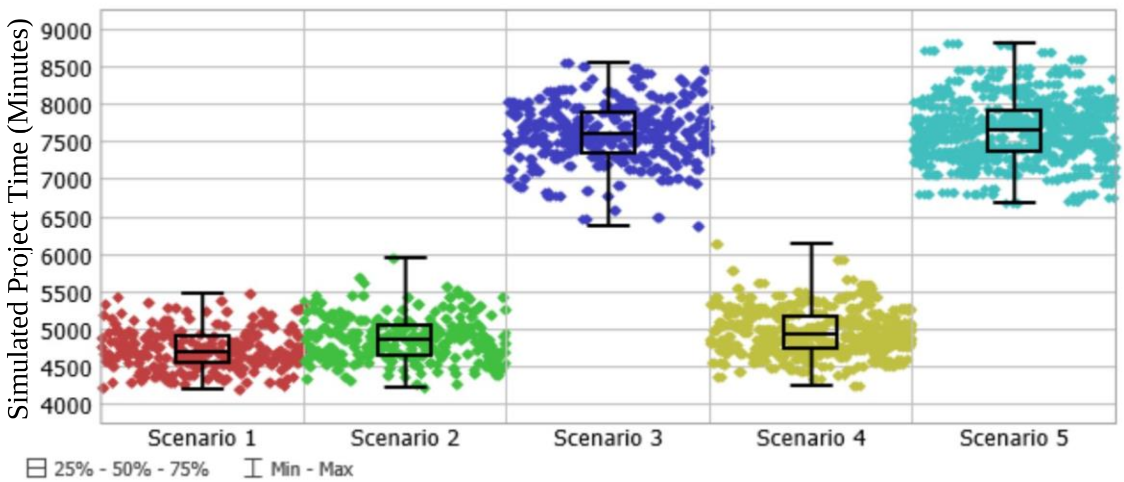


Figure 4-11. Nuclear Quality Control Time Sensitivity: Impact on Project Fabrication Time

With inspection time by QC personnel kept constant, the average simulated project fabrication time increased from 4,724 minutes (Scenario 1) to 4,959 minutes (Scenario 4); Figure 4-12 illustrates the linear relationship between increasing fitters' inspection time during quality control and the project fabrication time. Inspection time by QC personnel demonstrate a much higher impact, where an increase of QC time from 5 to 10 minutes correspond to over 50% escalation in overall project time.

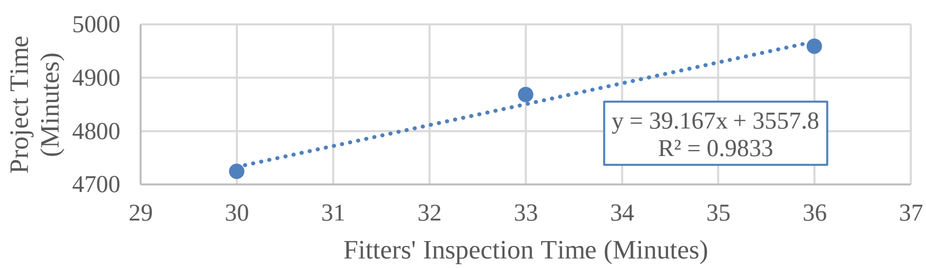


Figure 4-12. Nuclear Correlation between Fitters' Inspection Time and Project Time

4.2 Analysis on Small Bore Non-Nuclear Projects

Similar to nuclear projects, the difference between existing and proposed workflow for small bore non-nuclear projects is the distribution of geometric inspection responsibility from the QC personnel to fitters, taking advantage of the relative ease of technology operation and the worker composition ratio of 15 fitters to 1 QC. The task of data collection, which takes roughly 30 minutes, involves operating the 3D data acquisition hardware, uploading scanned data to developed software application, and overlaying the scanned point cloud over the point cloud from the design model to visually identify discrepancy. It is assumed it would take 5 minutes for the QC personnel to review the final results and release the spool for final shipment to site. Improvement multipliers of 0.28 and 0.71 from Kwiatek's results are applied to rework time and non-conformance failure probability, respectively. Table 4-14 outlines the changing variables between existing and proposed small bore non-nuclear pipe spool fabrication workflow.

Table 4-14. Small Bore Simulation Analysis: Existing vs. Proposed Workflow

Variables		Scenario	
		Existing	Proposed
Inspection Time by Fitters (Minutes)	After Tack	5	30
	After Weld	15	30
	Before Shipment	0	30
Inspection Time by QC (Minutes)	After Tack	0	0
	After Weld	0	0
	Before Shipment	30	5
Failure Probability (%)	After Tack	5	3.6
	After Weld	10	7.1
	Before Shipment	11	7.9
Rework Time (Minutes)		30	8

The variables are implemented into the nuclear simulation model, and their impact is tracked on three performance metrics, which are: (1) number of rework instances, (2) total simulated project fabrication time, and (3) queue time for final geometric inspection before shipment to site; the results on these metrics are summarized in Table 4-15, Table 4-16, and Table 4-17, respectively, as well as presented in Figure 4-13, Figure 4-14, and Figure 4-15, respectively. The tables are statistics based on the 1,000 samples collected for each scenario, and the figures are taken from the FlexSim Experimenter results output, where Scenario 1 denotes existing workflow, and Scenario 2 denotes proposed workflow.

Table 4-15. Small Bore Simulation Analysis Results: Impact on Rework Instances

Scenario	Mean (99% Confidence) Number of Rework	Sample Std Dev	Min	Max
Existing	23.74 < 24.18 < 24.62	5.26	11	39
Proposed	16.52 < 16.89 < 17.26	4.43	4	31

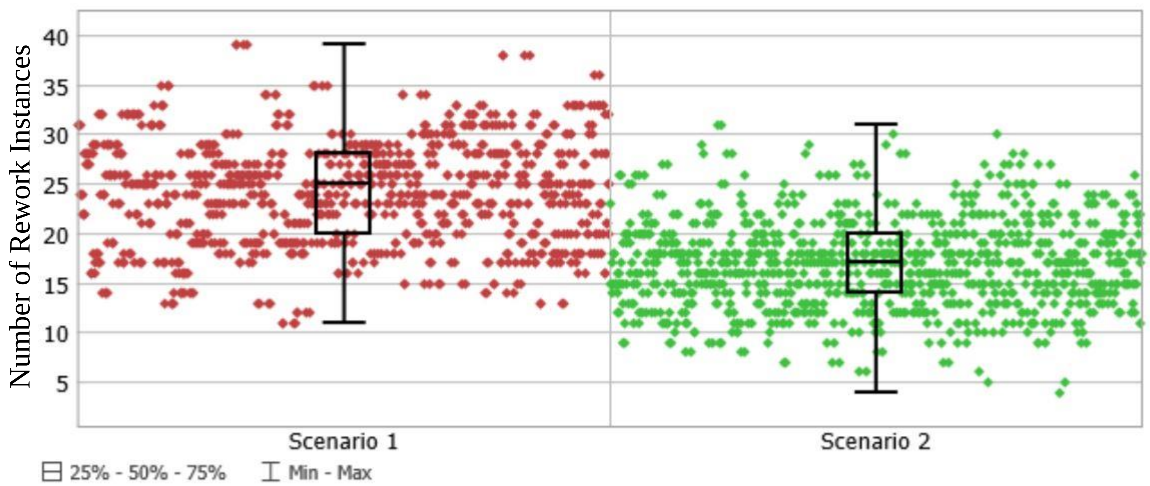


Figure 4-13. Small Bore Simulation Analysis Results: Impact on Rework Instances

The average number of rework instances decreased from 24.18 in the existing small bore non-nuclear workflow (Scenario 1), to 16.89 in the proposed workflow (Scenario 2). This 30% reduction in rework corresponds to the non-conformance failure probability improvement multiplier of 0.71 (29% reduction) taken from Kwiatek's experiment results.

Table 4-16. Small Bore Simulation Analysis Results: Impact on Project Fabrication Time

Scenario	Mean (99% Confidence) Project Time (Minutes)	Sample Std Dev	Min	Max
Existing	3,527 < 3,537 < 3,547	118	3,174	3,987
Proposed	2,175 < 2,186 < 2,196	131	1,882	2,627

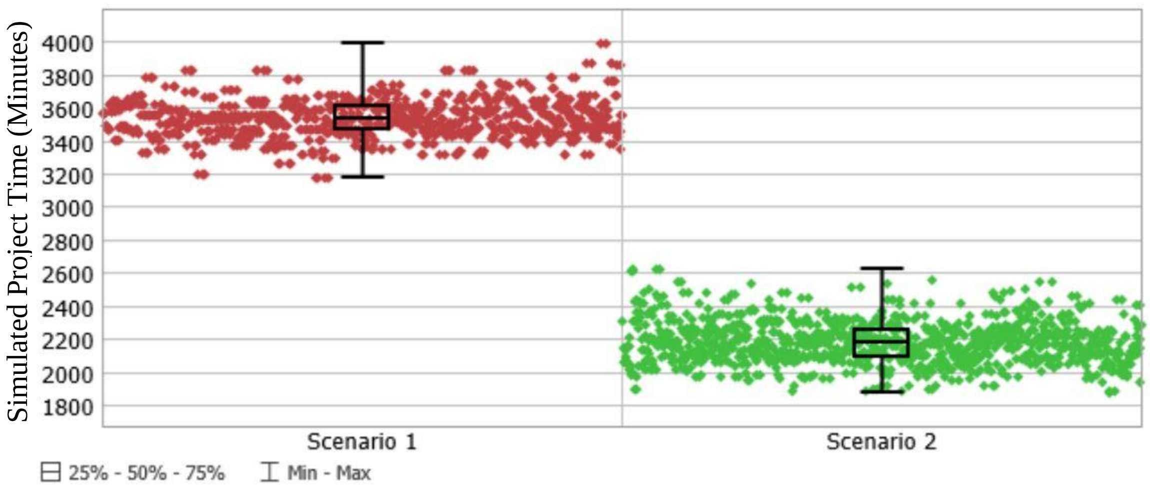


Figure 4-14. Small Bore Simulation Analysis Results: Impact on Project Fabrication Time

The average simulated project fabrication time decreased from 3,537 minutes in the existing small bore non-nuclear workflow, to 2,186 minutes in the proposed workflow. This represents 38% reduction in total project time by allowing fitters to assist with geometric inspection before final shipment to site, as well as self check after tack and after weld.

Table 4-17. Small Bore Simulation Analysis Results: Impact on Queue Time for Final Inspection

Scenario	Mean (99% Confidence) Queue Time (Minutes)	Sample Std Dev	Min	Max
Existing	902 < 907 < 913	63	689	1,064
Proposed	94.8 < 95.2 < 95.7	5.5	78.1	115

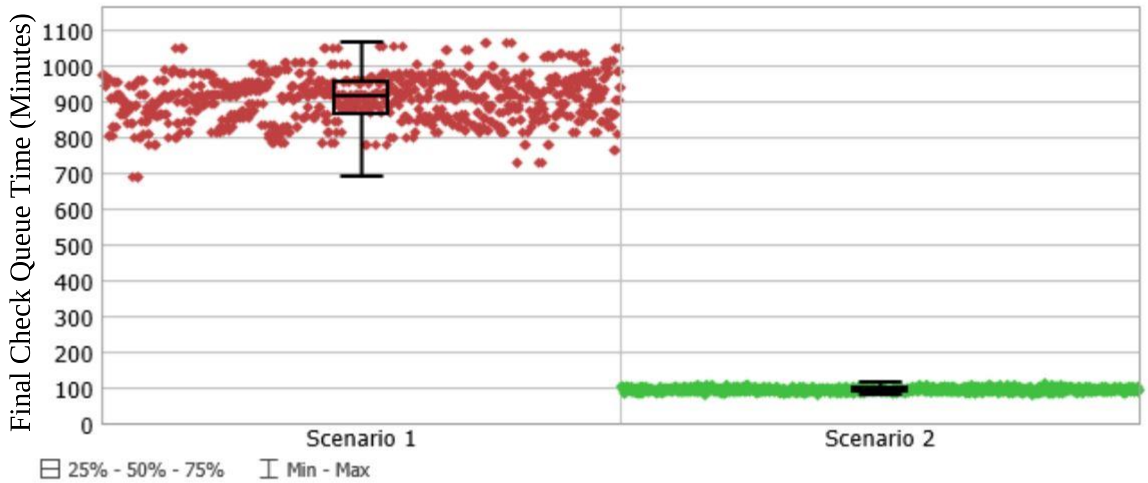


Figure 4-15. Small Bore Simulation Analysis Results: Impact on Queue Time for Final Inspection

The average queue time for final geometric inspection decreased from 907 minutes in the existing small bore non-nuclear workflow, to 95 minutes in the proposed workflow. This represents 90% reduction in pipe spool wait times in the laydown area for QC personnel to inspect and release them. The results highlight the final inspection stage as a significant bottleneck during conventional pipe spool fabrication, and how much it contributes to the total project time.

4.2.1 Small Bore Non-Nuclear Rework Time Sensitivity

The impact of rework time on proposed workflow of small bore non-nuclear project is examined. Improvement multiplier of 0.28 is escalated by 0.05, 0.1, and 0.2, which increases rework time from 8 minutes to 10, 11, and 14 minutes, respectively. The scenario where no improvement is observed, meaning the original rework time of 30 minutes remains, is also included in this sensitivity analysis. Table 4-18 outlines the changing variables between baseline scenario of applying Kwiatek's result for the proposed workflow, and incremental increase to the rework improvement multiplier. The last column of the table indicates no improvement to rework activity time when fitters use 3D scanning technology during quality control as part of the fabrication workflow.

Table 4-18. Small Bore Simulation Analysis: Rework Time Sensitivity Parameters

Variables		**Scenario**				
		Baseline	B + 0.05	B + 0.1	B + 0.2	None
Inspection Time by Fitters (Minutes)	After Tack	30	30	30	30	30
	After Weld	30	30	30	30	30
	Before Shipment	30	30	30	30	30
Inspection Time by QC (Minutes)	After Tack	0	0	0	0	0
	After Weld	0	0	0	0	0
	Before Shipment	5	5	5	5	5
Failure Probability (%)	After Tack	3.6	3.6	3.6	3.6	3.6
	After Weld	7.1	7.1	7.1	7.1	7.1
	Before Shipment	7.9	7.9	7.9	7.9	7.9
Rework Time (Minutes)		8	10	11	14	30

The variables are implemented into the small bore non-nuclear simulation model, and their impact is tracked on the performance metric of total simulated project fabrication time. The results of this metric are summarized in Table 4-19 and presented in Figure 4-16. The table is statistics based on the 1,000 samples collected for each scenario, and the figure is taken from the FlexSim Experimenter results output, where Scenario 1 denotes baseline parameters of applying Kwiatek's improvement multiplier to the proposed workflow, Scenario 2 to 4 denotes incremental increase to the rework improvement multiplier, and Scenario 5 denotes no improvement in rework time for the proposed workflow.

Table 4-19. Small Bore Rework Time Sensitivity: Impact on Project Fabrication Time

Scenario	Mean (99% Confidence) Project Time (Minutes)	Sample Std Dev	Min	Max
Baseline	2,162 < 2,172 < 2,182	121	1,860	2,504
B + 0.05	2,182 < 2,193 < 2,205	136	1,903	2,701
B + 0.1	2,173 < 2,183 < 2,194	129	1,773	2,650
B + 0.2	2,176 < 2,187 < 2,198	134	1,873	2,759
None	2,230 < 2,242 < 2,253	298	4,138	5,846

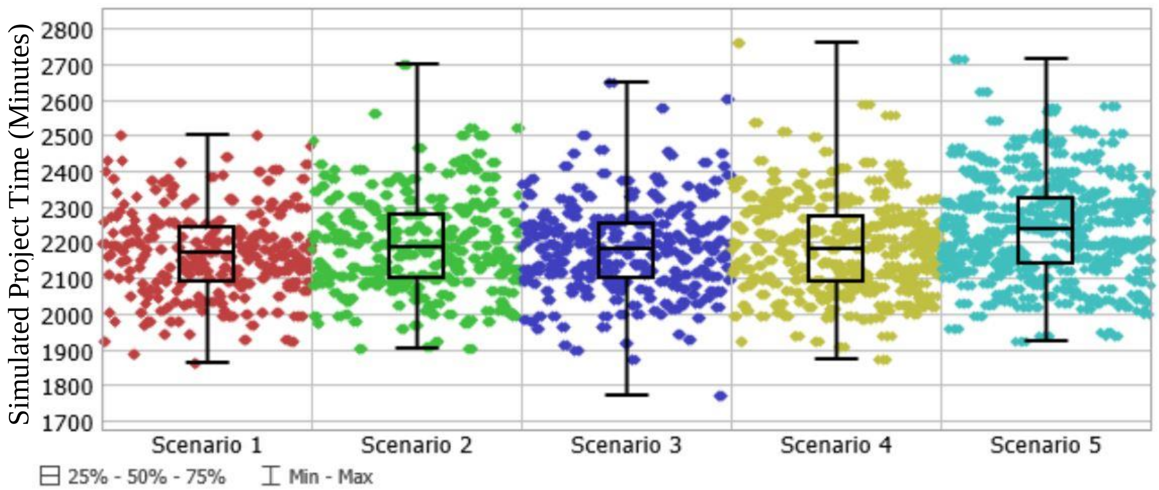


Figure 4-16. Small Bore Rework Time Sensitivity: Impact on Project Fabrication Time

The average project fabrication time increased from 2,172 minutes (Scenario 1) to 2,242 minutes (Scenario 5), as the rework time increased from 8 minutes (Scenario 1) to 30 minutes (Scenario 5). Figure 4-17 illustrates the linear relationship between increasing rework activity time and the project fabrication time.

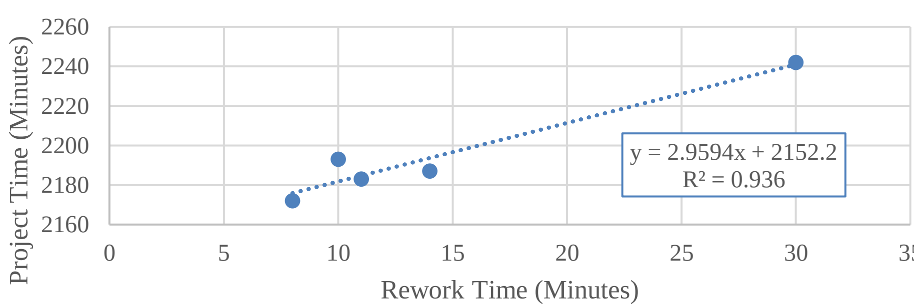


Figure 4-17. Small Bore Correlation between Rework Time and Project Fabrication Time

4.2.2 Small Bore Non-Nuclear Failure Probability Sensitivity

The impact of non-conformance failure probability on proposed workflow of small bore non-nuclear project is examined. Improvement multiplier of 0.71 is escalated by 0.05, 0.1, and 0.2. The scenario where no improvement is observed is also included in this sensitivity analysis, meaning the original failure probability during quality control after tack, after weld, and before shipment, all remain the same. Table 4-20 outlines the changing variables between baseline scenario of applying Kwiatek's result for the proposed workflow, and incremental increase to the failure probability improvement multiplier. The last column of the table indicates no improvement to non-conformance failure probability when fitters use 3D scanning technology during quality control as part of the fabrication workflow.

Table 4-20. Small Bore Simulation Analysis: Failure Probability Sensitivity Parameters

Variables		**Scenario**				
		Baseline	B + 0.05	B + 0.1	B + 0.2	None
Inspection Time by Fitters (Minutes)	After Tack	30	30	30	30	30
	After Weld	30	30	30	30	30
	Before Shipment	30	30	30	30	30
Inspection Time by QC (Minutes)	After Tack	0	0	0	0	0
	After Weld	0	0	0	0	0
	Before Shipment	5	5	5	5	5
Failure Probability (%)	After Tack	3.6	3.8	4.1	4.6	5
	After Weld	7.1	7.6	8.1	9.1	10
	Before Shipment	7.9	8.4	9.0	10.1	11
Rework Time (Minutes)		8	8	8	8	8

The variables are implemented into the small bore non-nuclear simulation model, and their impact is tracked on the performance metrics of (1) number of rework instances, and (2) total simulated project fabrication time; the results on these metrics are summarized in Table 4-21 and Table 4-22, respectively, as well as presented in Figure 4-18 and Figure 4-20, respectively. The table is statistics based on the 1,000 samples collected for each scenario, and the figure is taken from the FlexSim Experimenter results output, where Scenario 1 denotes baseline parameters of applying Kwiatek's improvement multiplier to the proposed workflow, Scenario 2 to 4 denotes incremental increase to the non-conformance failure probability improvement multiplier, and Scenario 5 denotes no improvement to failure probability for the proposed workflow.

Table 4-21. Small Bore Failure Probability Sensitivity: Impact on Rework Instances

Scenario	Mean (99% Confidence) Number of Rework	Sample Std Dev	Min	Max
Baseline	16.52 < 16.87 < 17.23	4.26	8	29
B + 0.05	17.66 < 18.04 < 18.41	4.53	8	31
B + 0.1	19.45 < 19.85 < 20.24	4.75	8	36
B + 0.2	22.04 < 22.47 < 22.90	5.20	8	47
None	24.53 < 24.98 < 25.42	5.35	11	43

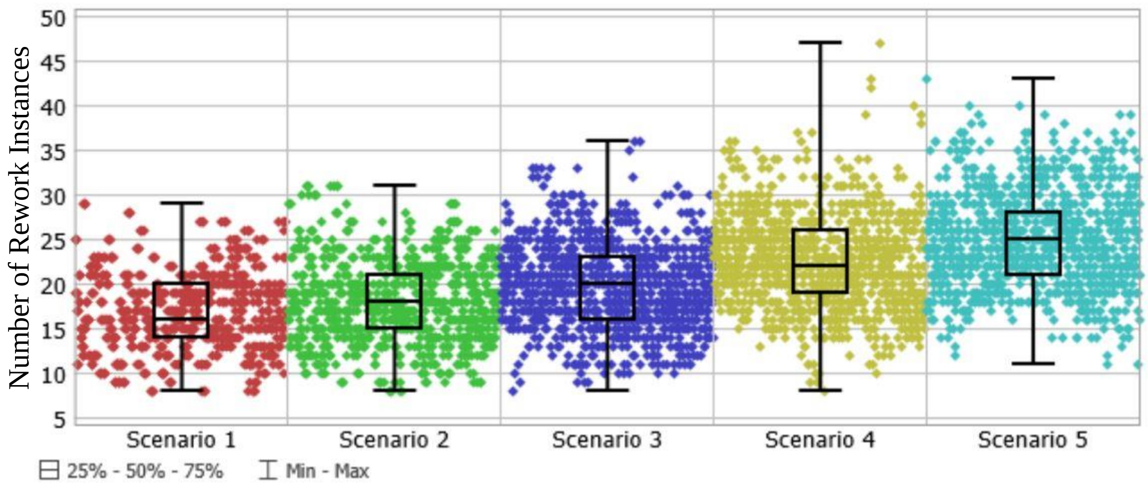


Figure 4-18. Small Bore Failure Probability Sensitivity: Impact on Rework Instances

The average number of rework instances increased from 16.87 (Scenario 1) to 24.98 (Scenario 5), as the failure probability improvement multiplier caused the failure probability after tack, after weld, and before shipment to increase from 3.6%, 7.1%, and 8.4%, respectively, to assumed no improvement in failure probability of 5%, 10%, and 11%, respectively. Figure 4-19 illustrates the linear relationship between increasing non-conformance failure probability and the number of rework instances in a project.

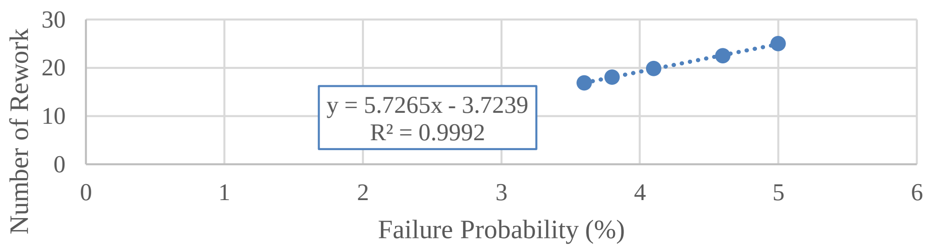


Figure 4-19. Small Bore Correlation between Failure Probability and Rework Instances

Table 4-22. Small Bore Failure Probability Sensitivity: Impact on Project Fabrication Time

Scenario	Mean (99% Confidence) Project Time (Minutes)	Sample Std Dev	Min	Max
Baseline	2,161 < 2,171 < 2,181	121	1,860	2,504
B + 0.05	2,184 < 2,196 < 2,201	132	1,851	2,720
B + 0.1	2,212 < 2,224 < 2,236	141	1,743	2,718
B + 0.2	2,239 < 2,251 < 2,263	143	1,857	3,046
None	2,286 < 2,298 < 2,310	143	1,944	2,904

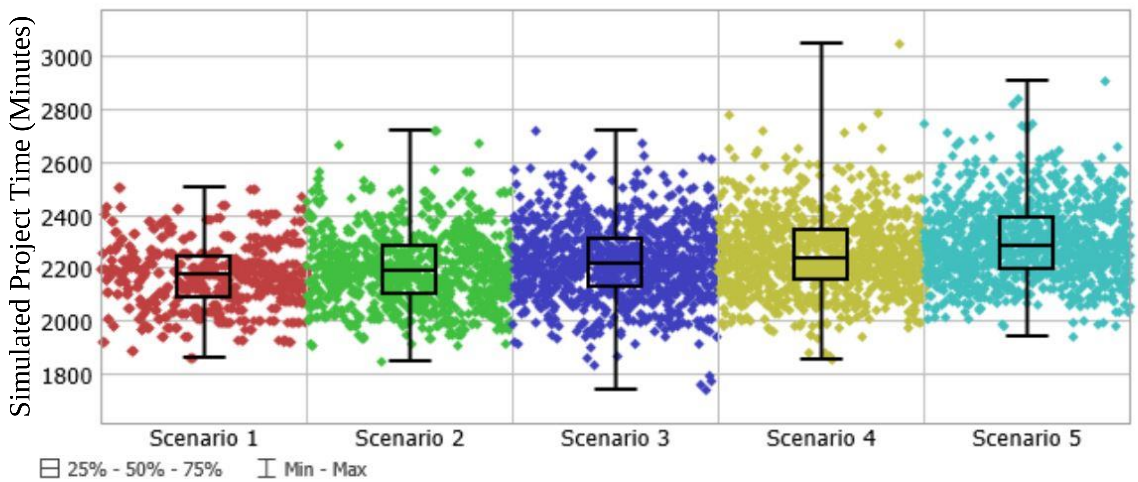


Figure 4-20. Small Bore Failure Probability Sensitivity: Impact on Project Fabrication Time

The average simulated project fabrication time increased from 2,171 minutes (Scenario 1) to 2,298 minutes (Scenario 5), highlighting the repercussion of performing multiple rework on pipe spools that failed quality control. Similar to the impact on number of rework instances, there is also a linear relationship between increasing non-conformance failure probability and the project fabrication time, as illustrated in Figure 4-21.

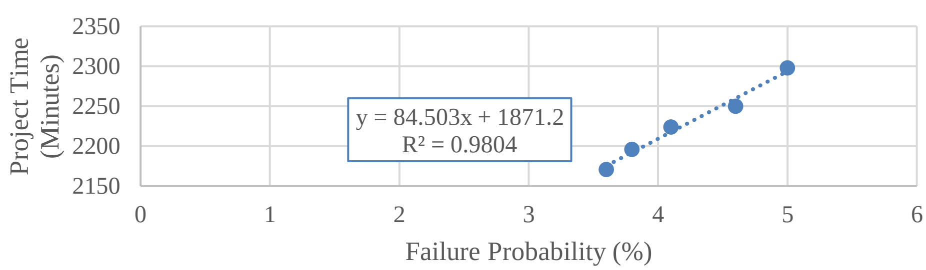


Figure 4-21. Small Bore Correlation between Failure Probability and Project Fabrication Time

4.2.3 Small Bore Non-Nuclear Quality Control Time Sensitivity

The impact of quality control time on proposed workflow of small bore non-nuclear project is examined. The assumption of 30 minutes for inspection by the fitters is based on the average time by the research team to 3D scan pipe spools, register the scanned data into point clouds, and uploading the point cloud into the developed software application for discrepancy analysis. It is possible for the fitters to take a longer time performing these tasks, due to dynamic activity on the shop floor that could disrupt data acquisition, or unusual pipe spool geometry that requires multiple scans to capture complete surface information on the as-built assembly. Table 4-23 outlines the changing variables between Scenario 1 as the baseline parameters for the proposed workflow, and Scenario 2 and 4 as incremental increase to the fitters' inspection time. Scenario 3 and 5 represent increase in time by QC personnel to review the scanned data carried by the fitters, and to finally release the assembly for shipment to site.

Table 4-23. Small Bore Simulation Analysis: Quality Control Time Sensitivity Parameters

Variables		Scenario				
		1	2	3	4	5
Inspection Time by Fitters (Minutes)	After Tack	30	33	33	36	36
	After Weld	30	33	33	36	36
	Before Shipment	30	33	33	36	36
Inspection Time by QC (Minutes)	After Tack	0	0	0	0	0
	After Weld	0	0	0	0	0
	Before Shipment	5	5	10	5	10
Failure Probability (%)	After Tack	3.6	3.6	3.6	3.6	3.6
	After Weld	7.1	7.1	7.1	7.1	7.1
	Before Shipment	7.9	7.9	7.9	7.9	7.9
Rework Time (Minutes)		8	8	8	8	8

The variables are implemented into the nuclear simulation model, and their impact is tracked on the performance metric of total simulated project fabrication time. The results of this metric are summarized in Table 4-24 and presented in Figure 4-22. The table is statistics based on the 1,000 samples collected for each scenario, and the figure is taken from the FlexSim Experimenter results output. Scenario 1 to 5 represent parameters as outlined in Table 4-23.

Table 4-24. Small Bore Quality Control Time Sensitivity: Impact on Project Fabrication Time

Scenario	Mean (99% Confidence) Project Time (Minutes)	Sample Std Dev	Min	Max
1	2,162 < 2,172 < 2,182	121	1,860	2,504
2	2,276 < 2,288 < 2,299	140	1,980	2,819
3	2,316 < 2,327 < 2,338	128	1,924	2,774
4	2,356 < 2,367 < 2,379	143	2,033	2,937
5	2,324 < 2,335 < 2,346	134	2,032	2,690

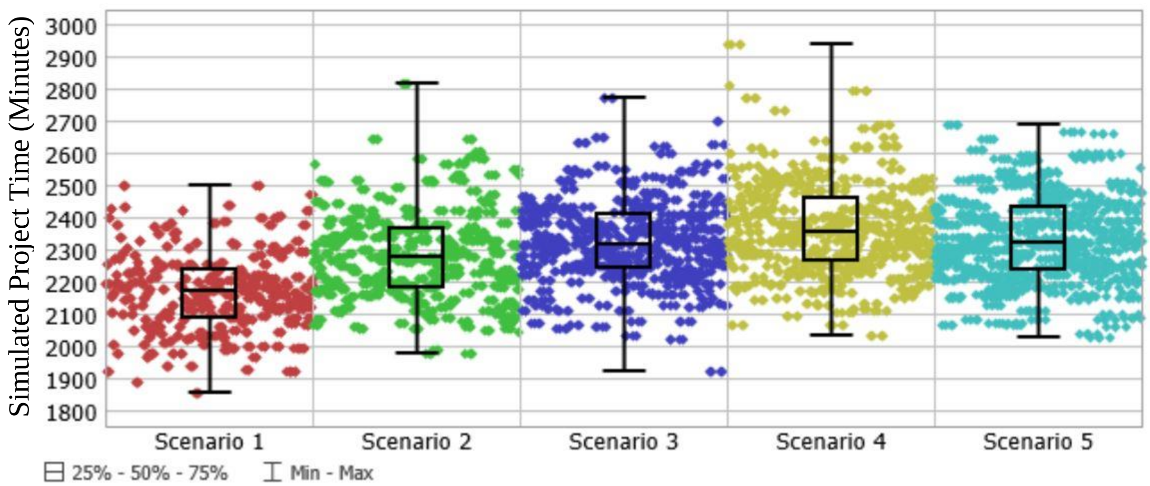


Figure 4-22. Small Bore Quality Control Time Sensitivity: Impact on Project Fabrication Time

With inspection time by QC personnel kept constant, the average simulated project fabrication time increased from 2,172 minutes (Scenario 1) to 2,367 minutes (Scenario 4); Figure 4-23 illustrates the linear relationship between increasing fitters' inspection time during quality control and the project fabrication time. Inspection time by QC personnel demonstrate no significant impact, where an increase of QC time from 5 to 10 minutes correspond to less than 2% change in project time.

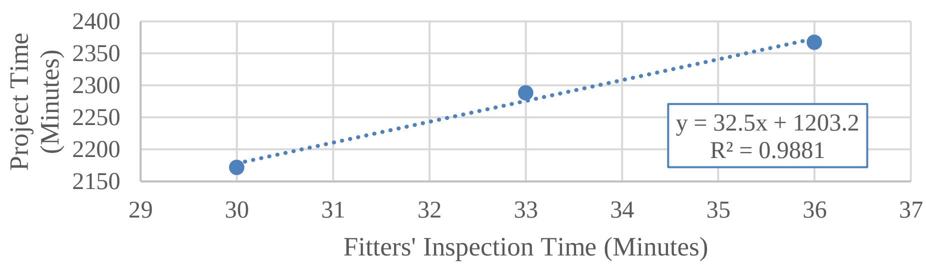


Figure 4-23. Small Bore Correlation between Fitters' Inspection Time and Project Time

4.3 Analysis on Large Bore Non-Nuclear Projects

Similar to small bore non-nuclear projects, the difference between existing and proposed workflow for large bore non-nuclear projects is the distribution of geometric inspection responsibility from the QC personnel to fitters, taking advantage of the relative ease of technology operation and the worker composition ratio of 15 fitters to 1 QC. The task of data collection, which takes roughly 30 minutes, involves operating the 3D data acquisition hardware, uploading scanned data to developed software application, and overlaying the scanned point cloud over the point cloud from the design model to visually identify discrepancy. It is assumed it would take 5 minutes for the QC personnel to review the final results and release the spool for final shipment to site. Improvement multipliers of 0.28 and 0.71 from Kwiatek's results are applied to rework time and non-conformance failure probability, respectively. Table 4-24 outlines the changing variables between existing and proposed small bore non-nuclear pipe spool fabrication workflow.

Table 4-25. Large Bore Simulation Analysis: Existing vs. Proposed Workflow

Variables		**Scenario**	
		Existing	Proposed
Inspection Time by Fitters (Minutes)	After Tack	5	30
	After Weld	20	30
	Before Shipment	0	30
Inspection Time by QC (Minutes)	After Tack	0	0
	After Weld	0	0
	Before Shipment	30	5
Failure Probability (%)	After Tack	5	3.6
	After Weld	10	7.1
	Before Shipment	11	7.9
Rework Time (Minutes)		45	13

The variables are implemented into the nuclear simulation model, and their impact is tracked on three performance metrics, which are: (1) number of rework instances, (2) total simulated project fabrication time, and (3) queue time for final geometric inspection before shipment to site; the results on these metrics are summarized in Table 4-26, Table 4-27, and Table 4-28, respectively, as well as presented in Figure 4-24, Figure 4-25, and Figure 4-26, respectively. The tables are statistics based on the 1,000 samples collected for each scenario, and the figures are taken from the FlexSim Experimenter results output, where Scenario 1 denotes existing workflow, and Scenario 2 denotes proposed workflow.

Table 4-26. Large Bore Simulation Analysis Results: Impact on Rework Instances

Scenario	Mean (99% Confidence) Number of Rework	Sample Std Dev	Min	Max
Existing	23.75 < 24.19 < 24.63	5.26	11	39
Proposed	16.51 < 16.88 < 17.26	4.50	5	33

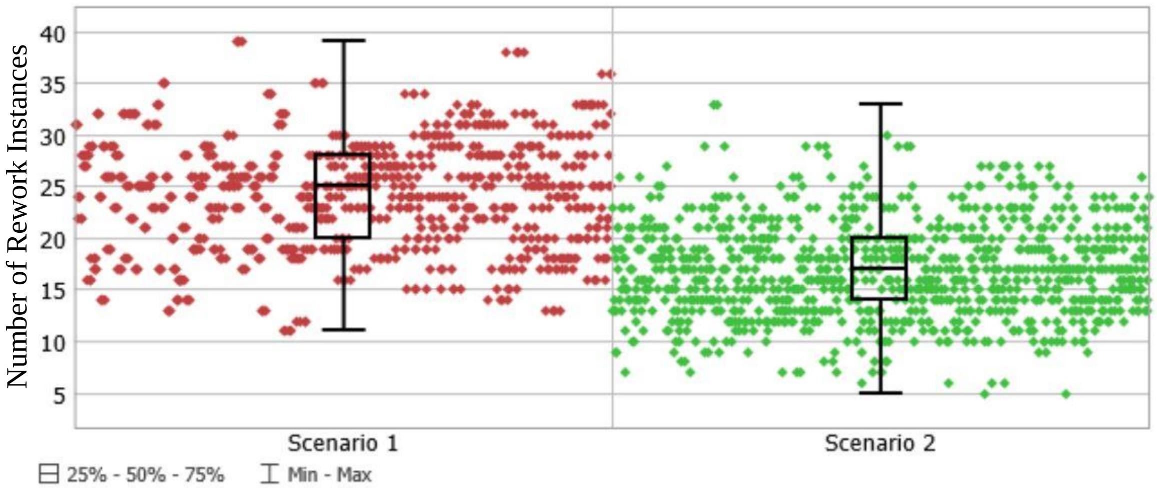


Figure 4-24. Large Bore Simulation Analysis Results: Impact on Rework Instances

The average number of rework instances decreased from 24.19 in the existing large bore non-nuclear workflow (Scenario 1), to 16.88 in the proposed workflow (Scenario 2). This 30% reduction in rework corresponds to the non-conformance failure probability improvement multiplier of 0.71 (29% reduction) taken from Kwiatek's experiment results.

Table 4-27. Large Bore Simulation Analysis Results: Impact on Project Fabrication Time

Scenario	Mean (99% Confidence) Project Time (Minutes)	Sample Std Dev	Min	Max
Existing	3,643 < 3,655 < 3,667	146	3,235	4,201
Proposed	2,784 < 2,799 < 2,813	175	2,376	3,510

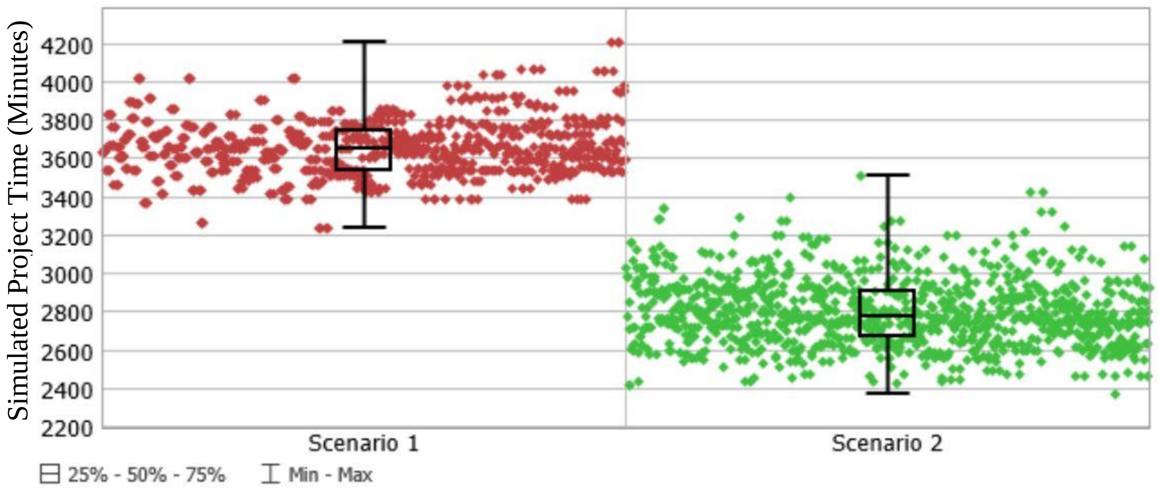


Figure 4-25. Large Bore Simulation Analysis Results: Impact on Project Fabrication Time

The average simulated project fabrication time decreased from 3,655 minutes in the existing large bore non-nuclear workflow, to 2,799 minutes in the proposed workflow. This represents 23% reduction in total project time by allowing fitters to assist with geometric inspection before final shipment to site, as well as self check after tack and after weld.

Table 4-28. Large Bore Simulation Analysis Results: Impact on Queue Time for Final Inspection

Scenario	Mean (99% Confidence) Queue Time (Minutes)	Sample Std Dev	Min	Max
Existing	620 < 625 < 631	69	497	820
Proposed	111.0 < 111.4 < 111.9	5.3	95.5	128.2

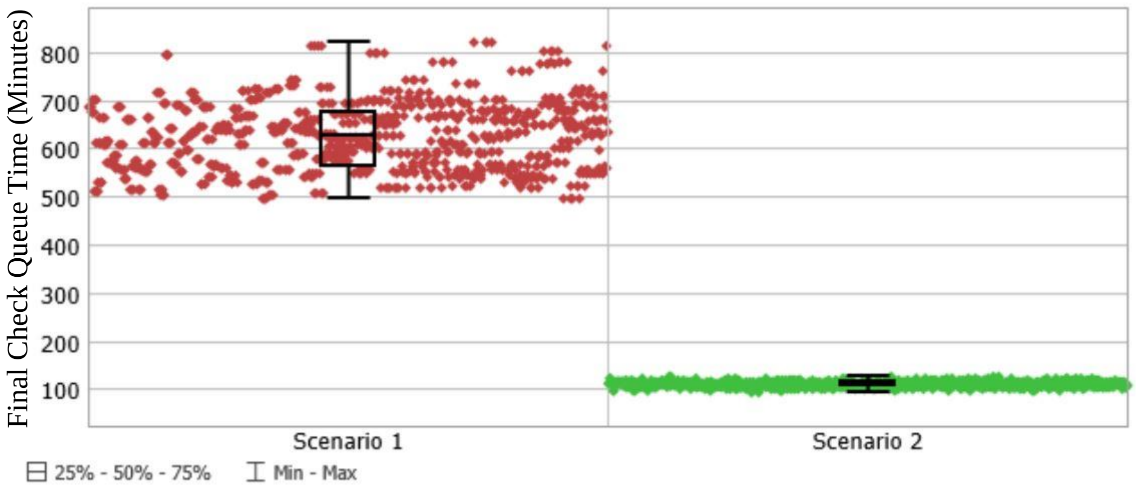


Figure 4-26. Large Bore Simulation Analysis Results: Impact on Queue Time for Final Inspection

The average queue time for final geometric inspection decreased from 625 minutes in the existing large bore non-nuclear workflow, to 111 minutes in the proposed workflow. This represents 82% reduction in pipe spool wait times in the laydown area for QC personnel to inspect and release them. The results highlight the final inspection stage as a significant bottleneck during conventional pipe spool fabrication, and how much it contributes to the total project time.

4.3.1 Large Bore Non-Nuclear Rework Time Sensitivity

The impact of rework time on proposed workflow of small bore non-nuclear project is examined. Improvement multiplier of 0.28 is escalated by 0.05, 0.1, and 0.2, which increases rework time from 13 minutes to 15, 17, and 22 minutes, respectively. The scenario where no improvement is observed, meaning the original rework time of 45 minutes remains, is also included in this sensitivity analysis. Table 4-29 outlines the changing variables between baseline scenario of applying Kwiatek's result for the proposed workflow, and incremental increase to the rework improvement multiplier. The last column of the table indicates no improvement to rework activity time when fitters use 3D scanning technology during quality control as part of the fabrication workflow.

Table 4-29. Large Bore Simulation Analysis: Rework Time Sensitivity Parameters

Variables		Scenario				
		Baseline	B + 0.05	B + 0.1	B + 0.2	None
Inspection Time by Fitters (Minutes)	After Tack	30	30	30	30	30
	After Weld	30	30	30	30	30
	Before Shipment	30	30	30	30	30
Inspection Time by QC (Minutes)	After Tack	0	0	0	0	0
	After Weld	0	0	0	0	0
	Before Shipment	5	5	5	5	5
Failure Probability (%)	After Tack	3.6	3.6	3.6	3.6	3.6
	After Weld	7.1	7.1	7.1	7.1	7.1
	Before Shipment	7.9	7.9	7.9	7.9	7.9
Rework Time (Minutes)		13	15	17	22	45

The variables are implemented into the large bore non-nuclear simulation model, and their impact is tracked on the performance metric of total simulated project fabrication time. The results of this metric are summarized in Table 4-30 and presented in Figure 4-27. The table is statistics based on the 1,000 samples collected for each scenario, and the figure is taken from the FlexSim Experimenter results output, where Scenario 1 denotes baseline parameters of applying Kwiatek's improvement multiplier to the proposed workflow, Scenario 2 to 4 denotes incremental increase to the rework improvement multiplier, and Scenario 5 denotes no improvement in rework time for the proposed workflow.

Table 4-30. Large Bore Rework Time Sensitivity: Impact on Project Fabrication Time

Scenario	Mean (99% Confidence) Project Time (Minutes)	Sample Std Dev	Min	Max
Baseline	2,773 < 2,787 < 2,800	162	2,354	3,243
B + 0.05	2,792 < 2,806 < 2,821	174	2,441	3,492
B + 0.1	2,787 < 2,800 < 2,814	167	2,270	3,360
B + 0.2	2,788 < 2,803 < 2,817	173	2,420	3,504
None	2,866 < 2,881 < 2,896	182	2,466	3,525

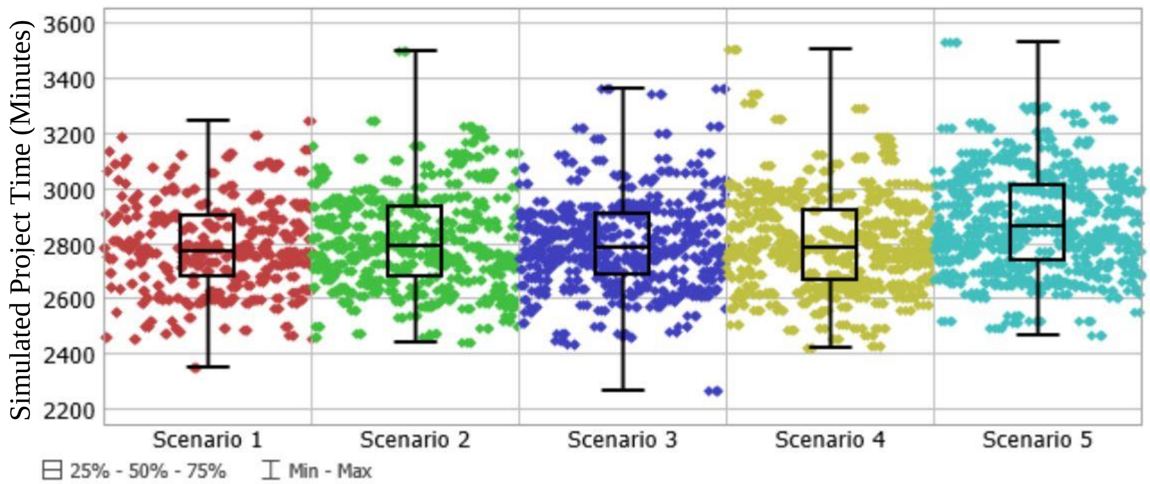


Figure 4-27. Large Bore Rework Time Sensitivity: Impact on Project Fabrication Time

The average project fabrication time increased from 2,787 minutes (Scenario 1) to 2,881 minutes (Scenario 5), as the rework time increased from 13 minutes (Scenario 1) to 45 minutes (Scenario 5). Figure 4-28 illustrates the linear relationship between increasing rework activity time and the project fabrication time.

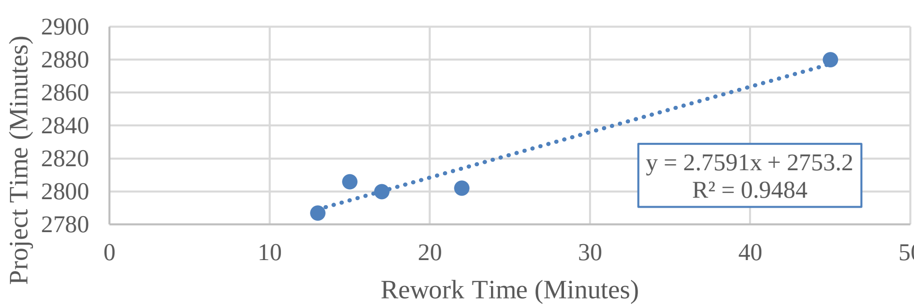


Figure 4-28. Large Bore Correlation between Rework Time and Project Fabrication Time

4.3.2 Large Bore Non-Nuclear Failure Probability Sensitivity

The impact of non-conformance failure probability on proposed workflow of large bore non-nuclear project is examined. Improvement multiplier of 0.71 is escalated by 0.05, 0.1, and 0.2. The scenario where no improvement is observed is also included in this sensitivity analysis, meaning the original failure probability during quality control after tack, after weld, and before shipment, all remain the same. Table 4-31 outlines the changing variables between baseline scenario of applying Kwiatek's result for the proposed workflow, and incremental increase to the failure probability improvement multiplier. The last column of the table indicates no improvement to non-conformance failure probability when fitters use 3D scanning technology during quality control as part of the fabrication workflow.

Table 4-31. Large Bore Simulation Analysis: Failure Probability Sensitivity Parameters

Variables		Scenario				
		Baseline	B + 0.05	B + 0.1	B + 0.2	None
Inspection Time by Fitters (Minutes)	After Tack	30	30	30	30	30
	After Weld	30	30	30	30	30
	Before Shipment	30	30	30	30	30
Inspection Time by QC (Minutes)	After Tack	0	0	0	0	0
	After Weld	0	0	0	0	0
	Before Shipment	5	5	5	5	5
Failure Probability (%)	After Tack	3.6	3.8	4.1	4.6	5
	After Weld	7.1	7.6	8.1	9.1	10
	Before Shipment	7.9	8.4	9.0	10.1	11
Rework Time (Minutes)		13	13	13	13	13

The variables are implemented into the large bore non-nuclear simulation model, and their impact is tracked on the performance metrics of (1) number of rework instances, and (2) total simulated project fabrication time; the results on these metrics are summarized in Table 4-32 and Table 4-33, respectively, as well as presented in Figure 4-29 and Figure 4-31, respectively. The table is statistics based on the 1,000 samples collected for each scenario, and the figure is taken from the FlexSim Experimenter results output, where Scenario 1 denotes baseline parameters of applying Kwiatek's improvement multiplier to the proposed workflow, Scenario 2 to 4 denotes incremental increase to the non-conformance failure probability improvement multiplier, and Scenario 5 denotes no improvement to failure probability for the proposed workflow.

Table 4-32. Large Bore Failure Probability Sensitivity: Impact on Rework Instances

Scenario	Mean (99% Confidence) Number of Rework	Sample Std Dev	Min	Max
Baseline	16.51 < 16.87 < 17.22	4.28	8	29
B + 0.05	17.67 < 18.04 < 18.41	4.48	8	31
B + 0.1	19.45 < 19.84 < 20.23	4.70	9	36
B + 0.2	22.06 < 22.49 < 22.92	5.21	9	44
None	24.54 < 24.98 < 25.42	5.32	10	40

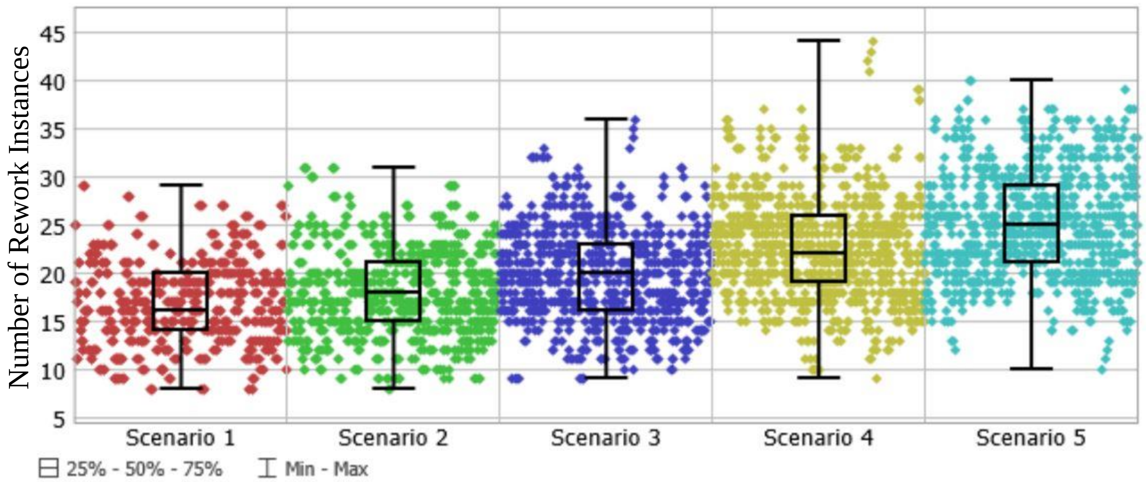


Figure 4-29. Large Bore Failure Probability Sensitivity: Impact on Rework Instances

The average number of rework instances increased from 16.87 (Scenario 1) to 24.98 (Scenario 5), as the failure probability improvement multiplier caused the failure probability after tack, after weld, and before shipment to increase from 3.6%, 7.1%, and 8.4%, respectively, to assumed no improvement in failure probability of 5%, 10%, and 11%, respectively. Figure 4-30 illustrates the linear relationship between increasing non-conformance failure probability and the number of rework instances in a project.

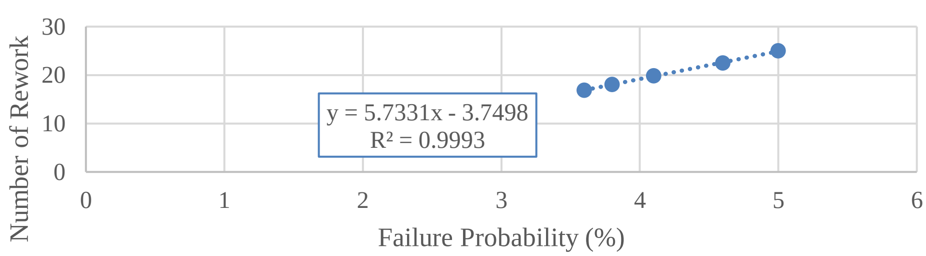


Figure 4-30. Large Bore Correlation between Failure Probability and Rework Instances

Table 4-33. Large Bore Failure Probability Sensitivity: Impact on Project Fabrication Time

Scenario	Mean (99% Confidence) Project Time (Minutes)	Sample Std Dev	Min	Max
Baseline	2,773 < 2,787 < 2,800	161	2,354	3,243
B + 0.05	2,795 < 2,809 < 2,822	162	2,407	3,422
B + 0.1	2,834 < 2,850 < 2,865	186	2,250	3,569
B + 0.2	2,868 < 2,883 < 2,898	183	2,380	3,728
None	2,928 < 2,944 < 2,959	184	2,472	3,679

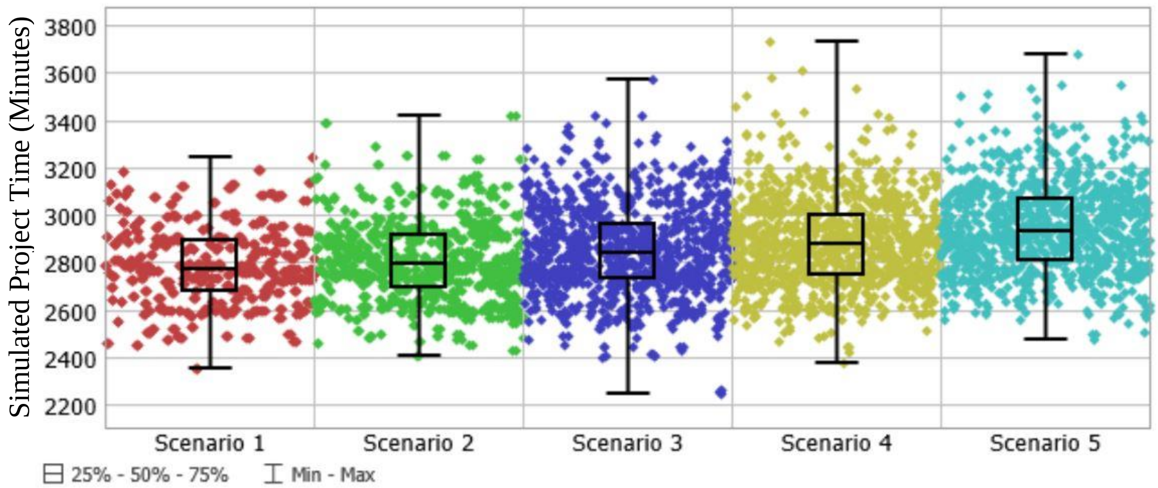


Figure 4-31. Large Bore Failure Probability Sensitivity: Impact on Project Fabrication Time

The average simulated project fabrication time increased from 2,787 minutes (Scenario 1) to 2,944 minutes (Scenario 5), highlighting the repercussion of performing multiple rework on pipe spools that failed quality control. Similar to the impact on number of rework instances, there is also a linear relationship between increasing non-conformance failure probability and the project fabrication time, as illustrated in Figure 4-32.

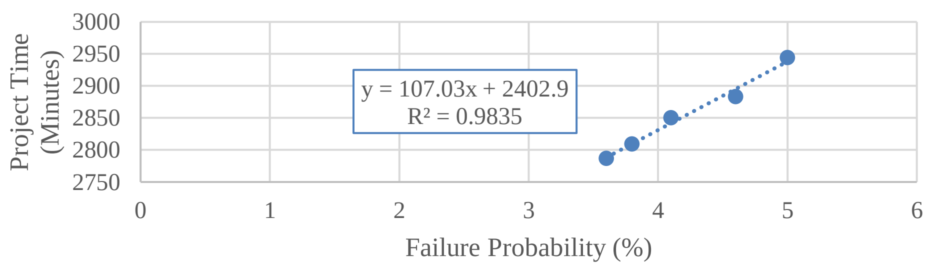


Figure 4-32. Large Bore Correlation between Failure Probability and Project Fabrication Time

4.3.3 Large Bore Non-Nuclear Quality Control Time Sensitivity

The impact of quality control time on proposed workflow of large bore non-nuclear project is examined. The assumption of 30 minutes for inspection by the fitters is based on the average time by the research team to 3D scan pipe spools, register the scanned data into point clouds, and uploading the point cloud into the developed software application for discrepancy analysis. It is possible for the fitters to take a longer time performing these tasks, due to dynamic activity on the shop floor that could disrupt data acquisition, or unusual pipe spool geometry that requires multiple scans to capture complete surface information on the as-built assembly. Table 4-34 outlines the changing variables between Scenario 1 as the baseline parameters for the proposed workflow, and Scenario 2 and 4 as incremental increase to the fitters' inspection time. Scenario 3 and 5 represent increase in time by QC personnel to review the scanned data carried by the fitters, and to finally release the assembly for shipment to site.

Table 4-34. Large Bore Simulation Analysis: Quality Control Time Sensitivity Parameters

Variables		**Scenario**				
		1	2	3	4	5
Inspection Time by Fitters (Minutes)	After Tack	30	33	33	36	36
	After Weld	30	33	33	36	36
	Before Shipment	30	33	33	36	36
Inspection Time by QC (Minutes)	After Tack	0	0	0	0	0
	After Weld	0	0	0	0	0
	Before Shipment	5	5	10	5	10
Failure Probability (%)	After Tack	3.6	3.6	3.6	3.6	3.6
	After Weld	7.1	7.1	7.1	7.1	7.1
	Before Shipment	7.9	7.9	7.9	7.9	7.9
Rework Time (Minutes)		13	13	13	13	13

The variables are implemented into the nuclear simulation model, and their impact is tracked on the performance metric of total simulated project fabrication time. The results of this metric are summarized in Table 4-35 and presented in Figure 4-33. The table is statistics based on the 1,000 samples collected for each scenario, and the figure is taken from the FlexSim Experimenter results output. Scenario 1 to 5 represent parameters as outlined in Table 4-34.

Table 4-35. Large Bore Quality Control Time Sensitivity: Impact on Project Fabrication Time

Scenario	Mean (99% Confidence) Project Time (Minutes)	Sample Std Dev	Min	Max
1	2,773 < 2,787 < 2,800	161	2,354	3,243
2	2,886 < 2,902 < 2,917	189	2,516	3,578
3	2,907 < 2,921 < 2,935	167	2,421	3,478
4	2,966 < 2,982 < 2,997	188	2,551	3,696
5	2,914 < 2,929 < 2,942	173	2,535	3,379

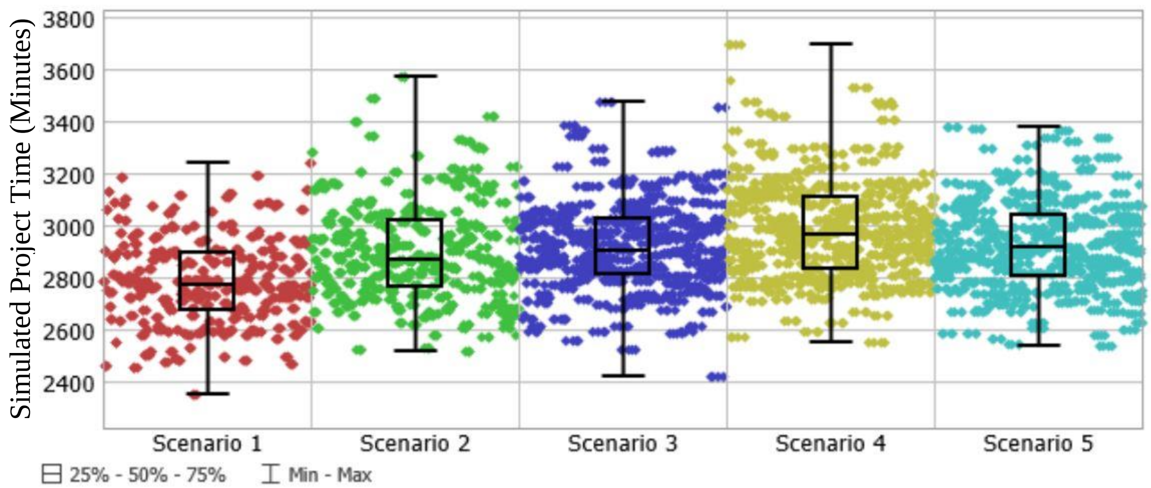


Figure 4-33. Large Bore Quality Control Time Sensitivity: Impact on Project Fabrication Time

With inspection time by QC personnel kept constant, the average simulated project fabrication time increased from 2,787 minutes (Scenario 1) to 2,982 minutes (Scenario 4); Figure 4-34 illustrates the linear relationship between increasing fitters' inspection time during quality control and the project fabrication time. Inspection time by QC personnel demonstrate no significant impact, where an increase of QC time from 5 to 10 minutes correspond to less than 2% change in project time.

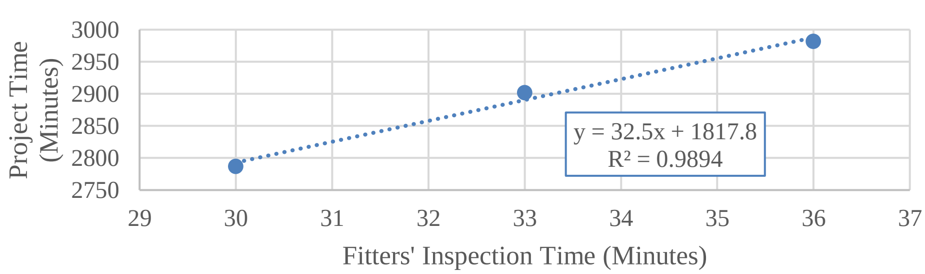


Figure 4-34. Large Bore Correlation between Fitters' Inspection Time and Project Time

4.4 Risk Mitigation and Economic Analysis on Proposed Workflows

Risk refers to uncertainty about and severity of the events and consequences (or outcomes) of an activity with respect to something that humans value (Aven and Renn 2009). In order to express uncertainty, probabilities are used as an effective tool to quantify it. Therefore, the assessment of risk can be calculated as the product of probability of an event and the loss (or consequence) associated with it, as expressed in Equation (3):

$$Risk_i = Probability_i \times Impact_i \tag{3}$$

For this analysis, estimate is carried out to assess the risk associated with existing conventional workflows, and risk associated with proposed workflows. The assessment is performed for all three technology implementation use cases, namely: (1) nuclear projects, (2) small bore non-nuclear projects, and (3) large bore non-nuclear projects. Numerous interviews and meetings with the partner's senior management were held, and through these discussions the research team learned that there are often disputes and misunderstandings between the site installation team and the pipe spool fabricator. Regardless of the organization representing the site stakeholder, whether they are another one of the partner's business units or direct clients who ordered the prefabricated assemblies, responsibility of rework when spool misalignment occurs is usually at the centre of exchange between the two parties.

The proposed 3D scanning and 3D feedback workflow have demonstrated the ability for craft workers to check their work, change the fabrication process in real time, and perform effective rework as necessary, ultimately allowing the fabricator to ship spools that meet tolerance. However, there is also a potential for the developed technology tool to be used as a documentation archive for the purpose of dispute mitigation, thus eliminating back charges to the fabrication shop for alleged costs incurred by the site contractor. Project coordinators and project mangers often spend hours disproving these back charges for pipe spool geometric non-conformance, and in some cases they have to send craft workers on-site to bill materials individually, and perform rework on-site or back in the facility if required. These expenses are significant but have yet to be quantified. The ensuing analysis will assess the impact of these risk events in terms of cost, by estimating the difference in risk between the existing workflow and the proposed workflow. The degree of risk mitigation between the two workflows will serve as the basis of overall benefit when conducting preliminary economic analysis on the cost and benefit of implementing the innovation technology, as a tool for: (1) fabrication in-process quality control, and (2) documentation of as-built pipe spools before shipment to site.

There are several important costs that need to be accounted for in the proposed workflows. Some technologies have already been introduced in earlier sections, however, to review the 3D data acquisition hardware that work with the developed software application, there are two types of 3D scanners, namely the DotProduct DPI-8S, and the FARO Focus Laser Scanner. With the DotProduct hand-held 3D scanner, the worker can walk around awkward position of the entire assembly and maneuver around the environment in order to capture as much information as possible. On the other hand, the FARO Focus Laser Scanner, though stationary, is a reliable system that offers accurate measurements of up to ±1mm. Again, readers may refer to Appendix A for detailed technical specifications of the 3D data acquisition hardware used in this research.

Costs can be broadly categorized into two groups based on the frequency of occurrence, which are: (1) start-up cost, and (2) annual cost. Start-up cost represent the initial investment required to prepare and implement the proposed workflow, which include purchasing the hardware for 3D scanning, as well as developing proper integration between the software application and the in-house information management system. This would enable effective near real-time feedback during fabrication, and as-built documentation archive. Annual cost represent recurring expense required to keep the proposed workflow in operation. This involves the maintenance of hardware, which include software updates and priority support from the manufacturer, hardware upgrades, and access to factory re-calibration, if required. Another critical annual cost is the training of using 3D workflow during fabrication. Though user interface of the software application was designed to be as intuitive and straightforward as possible, however, with variable turnover rate of the craft workers, as well as periodic update of the hardware and software to the latest technology, it is recommend for the software development team to host annual workshops in order to demonstrate the workflow of using 3D scanning and 3D feedback, as well as to provide support through different projects for troubleshooting. Table 4-36 outlines and summarizes the breakdown of costs to implement the technologies required for proposed workflow.

Table 4-36. Cost of Technology Implementation

Type of Cost	Description	Unit Rate	Number of Units	Total Cost	Sum
Start-up Cost	DotProduct Scanner	$5,000	60	$300,000	$700,000
	FARO Scanner	$50,000	5	$250,000	
	IT Integration	$150,000	1	$150,000	
Annual Cost	DotProduct Maintenance	$500	60	$30,000	$42,000
	FARO Maintenance	$2,000	5	$10,000	
	3D Workflow Training	$2,000	1	$2,000	

4.4.1 Nuclear Projects

Nuclear projects are subject to risks with significantly higher impact than other types of projects, due to the strength of materials required, strict quality control procedure which may involve third-party nuclear inspectors, as well as the time it takes to fabricate according to the intricate design. Risk assessment of nuclear projects with existing and proposed workflow are summarized in Table 4-37 and Table 4-38, respectively. It is assumed there are 100 spools to be fabricated.

Table 4-37. Risk Assessment of Nuclear Projects with Existing Workflow

Event		Probability of Occurrence	Cost/Spool	Total Impact ($)	Risk ($)
Site Approval		90.0%	$0	$0	$0
Site Disapproval	Within Tolerance	9.0%	$500	$50,000	$4,500
	Site Rework	0.9%	$10,000	$1,000,000	$9,000
	Total Rework	0.1%	$1,000,000	$100,000,000	$100,000
	Total	100%		Total Risk	$113,500

Table 4-38. Risk Assessment of Nuclear Projects with Proposed Workflow and Technology

Event		Probability of Occurrence	Cost/Spool	Total Impact ($)	Risk ($)
Site Approval		90.00%	$0	$0	$0
Site Disapproval	Within Tolerance	9.90%	$100	$10,000	$990
	Site Rework	0.09%	$10,000	$1,000,000	$900
	Total Rework	0.01%	$1,000,000	$100,000,000	$10,000
	Total	100%		Total Risk	$11,890

The total risk reduction achieved by adopting the proposed workflow and implementing the technology is $101,610, mitigated by the lower probability of error, and faster time by the fabricator to respond to site team proving pipe spool geometric conformance. Another benefit is the reduction in project fabrication time, and according to the simulation results as presented in Table 4-5, the total time reduced from 12,471 to 4,740 minutes. Assuming there are 26 workers (15 fitters, 10 welders, 1 QC), and each having a cost rate of $65/hr, this reduction translates to $217,757 of savings in labour cost. Lastly, it is assumed that there would be two nuclear projects every year, which could be for refurbishment of existing nuclear generating stations, or modules for a new nuclear facility. On the next page, Table 4-39 outlines the calculation of cost and benefit of nuclear projects with proposed workflow and implementing the technology. Based on the table, Figure 4-35 illustrates the annual cost and benefit, while Figure 4-36 illustrates the annual cumulative cost and benefit.

Table 4-39. Economic Analysis of Nuclear Projects with Proposed Workflow and Technology

Description		Year 1	Year 2	Year 3	Year 4	Year 5	Year 6
Annual	Cost	$(742,000)	$(42,000)	$(42,000)	$(42,000)	$(42,000)	$(42,000)
	Benefit	$638,733	$638,733	$638,733	$638,733	$638,733	$638,733
	Net	$(103,267)	$596,733	$596,733	$596,733	$596,733	$596,733
Cumulative	Cost	$(742,000)	$(784,000)	$(826,000)	$(868,000)	$(910,000)	$(952,000)
	Benefit	$638,733	$1,277,466	$1,916,199	$2,554,932	$3,193,665	$3,832,398
	Net	$(103,267)	$493,466	$1,090199	$1,686,932	$2,283,665	$2,880,398

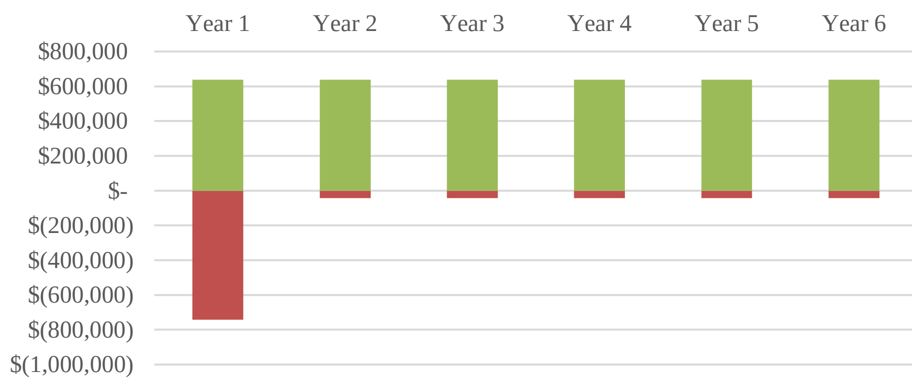


Figure 4-35. Annual Cost and Benefit of Nuclear Projects with Proposed Workflow and Technology

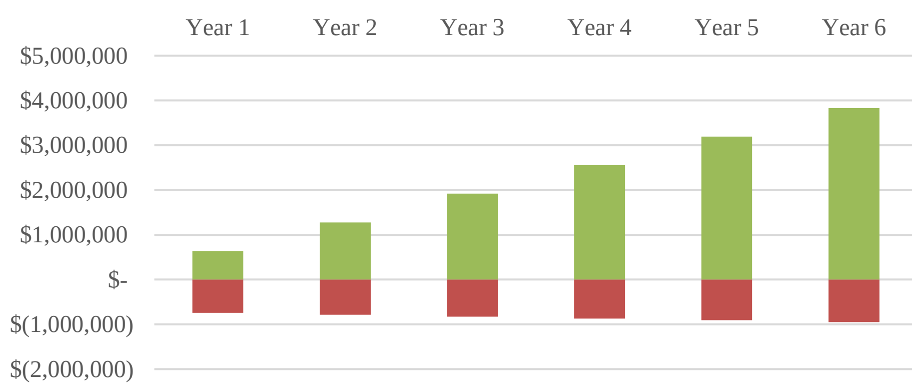


Figure 4-36. Annual Cumulative Cost and Benefit of Nuclear Projects with Proposed Workflow and Technology

The payback period for implementing the innovation technology in proposed nuclear workflow is 1.2 years, which demonstrate the relatively significant benefit over time despite the initial investment.

4.4.2 Small Bore Non-Nuclear Projects

Small bore non-nuclear projects are relatively straightforward to fabricate, given the standard components usually used as part of the assemblies. Small bore spools are also much easier to maneuver for fitting and welding. Risk assessment of small bore projects with existing and proposed workflow are summarized in Table 4-40 and Table 4-41, respectively. It is assumed there are 100 spools to be fabricated.

Table 4-40. Risk Assessment of Small Bore Projects with Existing Workflow

Event		Probability of Occurrence	Cost/Spool	Total Impact ($)	Risk ($)
Site Approval		90.0%	$0	$0	$0
Site Disapproval	Within Tolerance	9.0%	$500	$50,000	$4,500
	Site Rework	0.9%	$5,000	$500,000	$4,500
	Total Rework	0.1%	$20,000	$2,000,000	$2,000
	Total	100%		Total Risk	$11,000

Table 4-41. Risk Assessment of Small Bore Projects with Proposed Workflow and Technology

Event		Probability of Occurrence	Cost/Spool	Total Impact ($)	Risk ($)
Site Approval		90.00%	$0	$0	$0
Site Disapproval	Within Tolerance	9.90%	$100	$10,000	$990
	Site Rework	0.09%	$5,000	$500,000	$450
	Total Rework	0.01%	$20,000	$2,000,000	$200
	Total	100%		Total Risk	$1,640

The total risk reduction achieved by adopting the proposed workflow and implementing the technology is $9,360, mitigated by the lower probability of error, and faster time by the fabricator to respond to site team proving pipe spool geometric conformance. Another benefit is the reduction in project fabrication time, and according to the simulation results as presented in Table 4-16, the total time reduced from 3,537 to 2,186 minutes. Assuming there are 26 workers (15 fitters, 10 welders, 1 QC), and each having a cost rate of $65/hr, this reduction translates to $38,053 of savings in labour cost. Lastly, it is assumed that there would be seven small bore non-nuclear projects every year, which could be for utilities such as water supply or natural gas transport. Table 4-42 on the next page outlines the calculation of cost and benefit of small bore projects with proposed workflow and implementing the technology. Based on the table, Figure 4-37 illustrates the annual cost and benefit, while Figure 4-38 illustrates the annual cumulative cost and benefit.

Table 4-42. Economic Analysis of Small Bore Projects with Proposed Workflow and Technology

Description		Year 1	Year 2	Year 3	Year 4	Year 5	Year 6
Annual	Cost	$(742,000)	$(42,000)	$(42,000)	$(42,000)	$(42,000)	$(42,000)
	Benefit	$331,892	$331,892	$331,892	$331,892	$331,892	$331,892
	Net	$(410,108)	$289,892	$289,892	$289,892	$289,892	$289,892
Cumulative	Cost	$(742,000)	$(784,000)	$(826,000)	$(868,000)	$(910,000)	$(952,000)
	Benefit	$331,892	$663,784	$995,677	$1,327,569	$1,659,461	$1,991,353
	Net	$(410,108)	$(120,216)	$169,677	$459,569	$749,461	$1,039,353

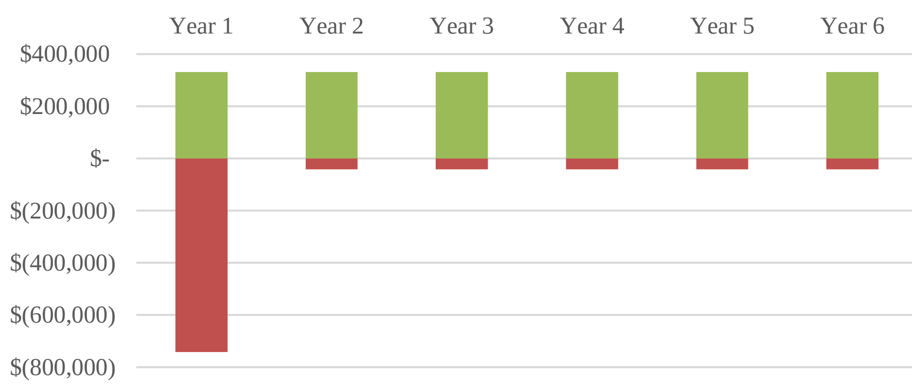


Figure 4-37. Annual Cost and Benefit of Small Bore Projects with Proposed Workflow and Technology

Figure 4-38. Annual Cumulative Cost and Benefit of Small Bore Projects with Proposed Workflow and Technology

The payback period for implementing the innovation technology in proposed small bore non-nuclear workflow is 2.4 years, which is a relatively fast investment recovery period.

4.4.3 Large Bore Non-Nuclear Projects

Large bore non-nuclear projects tend to use custom components Risk assessment of large bore projects with existing and proposed workflow are summarized in Table 4-43 and Table 4-44, respectively. It is assumed there are 100 spools to be fabricated.

Table 4-43. Risk Assessment of Large Bore Projects with Existing Workflow

Event		Probability of Occurrence	Cost/Spool	Total Impact ($)	Risk ($)
Site Approval		90.0%	$0	$0	$0
Site Disapproval	Within Tolerance	9.0%	$500	$50,000	$4,500
	Site Rework	0.9%	$10,000	$1,000,000	$9,000
	Total Rework	0.1%	$100,000	$10,000,000	$10,000
Total		100%		Total Risk	$23,500

Table 4-44. Risk Assessment of Large Bore Projects with Proposed Workflow and Technology

Event		Probability of Occurrence	Cost/Spool	Total Impact ($)	Risk ($)
Site Approval		90.00%	$0	$0	$0
Site Disapproval	Within Tolerance	9.90%	$500	$50,000	$990
	Site Rework	0.09%	$10,000	$1,000,000	$900
	Total Rework	0.01%	$100,000	$10,000,000	$1,000
Total		100%		Total Risk	$2,890

The total risk reduction achieved by adopting the proposed workflow and implementing the technology is $20,610, mitigated by the lower probability of error, and faster time by the fabricator to respond to site team proving pipe spool geometric conformance. Another benefit is the reduction in project fabrication time, and according to the simulation results as presented in Table 4-27, the total time reduced from 3,655 to 2,799 minutes. Assuming there are 26 workers (15 fitters, 10 welders, 1 QC), and each having a cost rate of $65/hr, this reduction translates to $24,111 of savings in labour cost. Lastly, it is assumed that there would be four large bore non-nuclear projects every year, which could be for processing facilities such as chemical plants or oil refineries. Table 4-45 on the next page outlines the calculation of cost and benefit of large bore projects with proposed workflow and implementing the technology. Based on the table, Figure 4-39 illustrates the annual cost and benefit, while Figure 4-40 illustrates the annual cumulative cost and benefit.

Table 4-45. Economic Analysis of Large Bore Projects with Proposed Workflow and Technology

Description		Year 1	Year 2	Year 3	Year 4	Year 5	Year 6
Annual	Cost	$(742,000)	$(42,000)	$(42,000)	$(42,000)	$(42,000)	$(42,000)
	Benefit	$178,883	$178,883	$178,883	$178,883	$178,883	$178,883
	Net	$(563,117)	$136,883	$136,883	$136,883	$136,883	$136,883
Cumulative	Cost	$(742,000)	$(784,000)	$(826,000)	$(868,000)	$(910,000)	$(952,000)
	Benefit	$178,883	$357,765	$536,648	$715,531	$894,413	$1,073,296
	Net	$(563,117)	$(426,235)	$(289,352)	$(152,469)	$(15,587)	$121,296

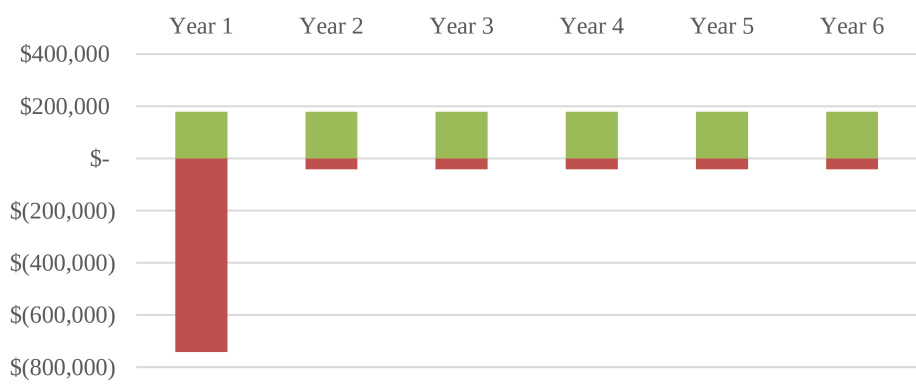


Figure 4-39. Annual Cost and Benefit of Large Bore Projects with Proposed Workflow and Technology

Figure 4-40. Annual Cumulative Cost and Benefit of Large Bore Projects with Proposed Workflow and Technology

The payback period for implementing the innovation technology in proposed large bore workflow is 5.1 years, which takes longer than nuclear and small bore non-nuclear projects.

4.4.4 General Fabricator

In the interest of understanding the net benefit to a pipe spool fabricator as they potentially engage in all three types of projects, the summation of their costs and benefits are taken into consideration. This analysis is feasible since the hardware technology is not limited by the projects, and the initial investment of start-up cost would be presumably applied to all projects within the prefabrication facility. Therefore the accumulated benefits may present a more reasonable assertion to the advantage of implementing 3D scanning and 3D feedback workflow for fabrication in-process quality control, as well as documentation for response with on-site installation team.

Similar to the analyses introduced earlier, and for consistent results, it is assumed that there would be two nuclear projects, seven small bore non-nuclear projects, and four large bore non-nuclear projects every year, and each project require 100 spools to be fabricated. The worker composition and cost rate for each worker remain the same as the previous analyses. Table 4-46 below outlines the calculation of cost and benefit of a fabricator implementing the innovation technology into the proposed workflow for all three project types. Based on the table, Figure 4-41 on the next page illustrates the annual cost and benefit, while Figure 4-42 illustrates the annual cumulative cost and benefit.

Table 4-46. Economic Analysis of Fabricator Implementing Proposed Workflow and Technology

Description		Year 1	Year 2	Year 3	Year 4	Year 5	Year 6
Annual	Cost	$(742,000)	$(42,000)	$(42,000)	$(42,000)	$(42,000)	$(42,000)
	Benefit	$1,149,508	$1,149,508	$1,149,508	$1,149,508	$1,149,508	$1,149,508
	Net	$407,508	$1,107,508	$1,107,508	$1,107,508	$1,107,508	$1,107,508
Cumulative	Cost	$(742,000)	$(784,000)	$(826,000)	$(868,000)	$(910,000)	$(952,000)
	Benefit	$1,149,508	$2,299,016	$3,448,524	$4,598,031	$5,747,539	$6,897,047
	Net	$407,508	$1,515,016	$2,622,524	$3,730,031	$4,837,539	$5,945,047

Figure 4-41. Annual Cost and Benefit of Fabricator Implementing Proposed Workflow and Technology

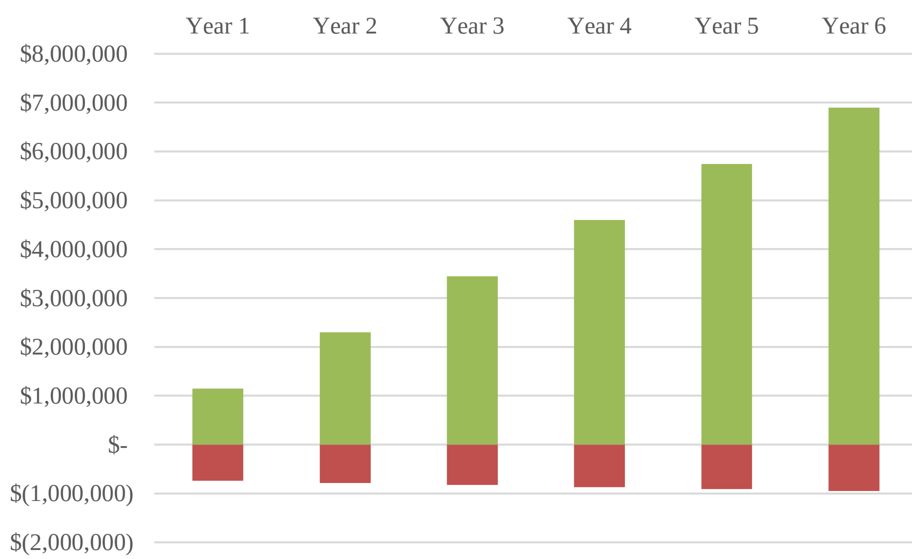


Figure 4-42. Annual Cumulative Cost and Benefit of Fabricator Implementing Proposed Workflow and Technology

The payback period for a fabricator to implement the innovation technology into their standard workflow is 0.6 years, which indicates a net positive return on investment almost instantaneously.

Chapter 5
Conclusions and Discussions

The construction industry has not been experiencing the same level of productivity increase as the manufacturing industry, due to their divergent production methods: while traditional construction projects are unique, craft-based, and typically done on-site, manufacturing is able to mass produce standardized products on assembly lines in a controlled environment. These fundamental differences preclude innovative technologies from being adopted at the same time and at the same rate between the two industries. Efforts to improve construction productivity take advantage of the more established and mature manufacturing processes and techniques, such as modularization and off-site assembly. Furthermore, recent rapid advancement of ICT allow the feedback loop of data sensors and computer analysis to continuously optimize work processes and deliver quality products. 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. Rework of items that have failed quality checks leads to significant waste of resources, resulting in reduced overall productivity represented by additional time and manpower spent on correcting the errors. The solution set to this problem ultimately needs to address lost productivity due to rework, and generate value from its operation in the industrial fabrication workflow.

The use of 3D data acquisition and 3D feedback is proposed to be part of the quality control process of pipe spool fabrication, which takes place during fitting and before shipment to site. The existing workflow and the proposed workflow are assessed using discrete-event simulation, and three technology implementation scenarios are investigated, which are: (1) nuclear projects, (2) small bore non-nuclear projects, and (3) large bore non-nuclear projects. They represent different quality control processes for their particular requirements, as well as their specific activity process times given the nature of their components and assemblies. The analysis aims to quantify the costs and benefits accrued under these implementation scenarios, and assess the degree of risk mitigation that would be achieved by implementing the revised fabrication workflows for pipe spool assembly. This chapter summarizes the findings from the completed analyses, discusses the limitations of this research, and proposes recommendations for future work.

5.1 Conclusions

Conclusions are drawn from the analysis of the simulation models, which are created based on the existing fabrication workflow and the proposed fabrication workflow. The impact of 3D scanning and 3D feedback are further assessed for their risk mitigation of geometric non-conformance, as well as economic justification of their implementation into standard work processes during quality control.

5.1.1 Summary of Simulation Analysis Results

The existing and proposed workflows for all three technology implementation scenarios are analyzed based the impact of 3D capability on improving worker productivity. They were evaluated based on the tracked performance metrics of: (1) the total number of rework instances for each simulation run, (2) the total simulated project fabrication time, and (3) the queue time for final geometric inspection before shipment to site.

In terms of rework instances, each of the three models exhibited a similar pattern when subjected to reduced rework probability. They all experienced a 30% reduction in rework from existing to proposed workflow, which corresponds to the non-conformance failure probability improvement multiplier of 0.71 (29% reduction) taken from Kwiatek's experiment results (2018).

The tasks of data collection for quality control are distributed among the fitters, which involves operating the 3D data acquisition hardware, uploading scanned data to developed software application, and overlaying the scanned point cloud over the point cloud from the design model to visually identify discrepancy. While each of the three models demonstrated a general trend of reduction in project fabrication time, the rate of improvement is different. Nuclear projects experienced the greatest impact in project fabrication time with an average of 62% reduction, while small bore non-nuclear projects experienced 38% reduction, and large bore non-nuclear project experienced 23% reduction.

Similarly, as the fitters help QC personnel with pipe spool quality control, each of the three models showed a similar pattern of reduction in queue time for final geometric inspection. Again, nuclear projects experienced the greatest impact with an average of 95% reduction, while small bore non-nuclear projects experienced 90% reduction, and large bore non-nuclear project experienced 82% reduction. The results highlight the final inspection stage as a significant bottleneck during conventional pipe spool fabrication, and how much it contributes to the total project time.

Three input variables were adjusted in each simulation model to observe their impact on the proposed fabrication workflow; these variables are: (1) rework time, (2) failure probability, and (3) quality control time. They were evaluated based on the tracked performance metrics related to productivity improvement and rework reduction.

In terms of rework time, each of the three models exhibited marginal impact in project fabrication time as the rework time was increased. The nuclear, small bore non-nuclear, and large bore non-nuclear projects experienced an average of 0.7%, 0.7%, and 0.5% increase in simulated project fabrication time, respectively, as rework time increased from 17 to 29 minutes (71% increase), 8 to 14 minutes (75% increase), and 13 to 22 minutes (70% increase), respectively. Also, rework time as a variable and project fabrication time as its dependent variable show a largely linear relationship. The results suggest that rework activity is not a major bottleneck in the proposed fabrication workflows, and even if 3D feedback provides little to no benefit to improving rework time, the distribution of quality control tasks to fitters is enough to improve overall fabrication productivity.

With regards to non-conformance failure probability, each of the three models demonstrated identical impact in rework instances. The same increase in failure probability was applied to all stages of quality control, that is, before tack, after tack, after weld, and before shipment for nuclear projects, and after tack, after weld, and before shipment for non-nuclear projects. All three models experienced an increase of 48% in rework instances, as failure probability for after tack, after weld, and before shipment increased from 3.6% to 5% (40% increase), 7.1% to 10% (41%), and 7.9% to 11% (40%), respectively. Furthermore, each of the three models also demonstrated similar impact in project fabrication time. The nuclear, small bore non-nuclear, and large bore non-nuclear projects experienced an average of 5.4%, 5.8%, and 5.6% increase in simulated project fabrication time, respectively, as failure probability increased at the same rate as described previously. Non-conformance probability as a variable show a linear relationship with both rework instances and project time as its dependent variables.

Lastly, in terms of quality control time by fitters, each of the three models exhibited considerable impact in project fabrication time. The nuclear, small bore non-nuclear, and large bore non-nuclear projects experienced an average of 5%, 9%, and 7% increase in simulated project fabrication time, respectively, as quality control time by fitters increased from 30 to 36 minutes (20% increase) for all three models. They also show a largely linear relationship between the two variables. The results suggest the process of quality control as a key contributor to overall fabrication time and productivity.

5.1.2 Summary of Risk Mitigation and Economic Analysis Results

The existing and proposed workflows for all three technology implementation scenarios are further assessed for their risk of geometric non-conformance, and the degree of risk mitigation between the two workflows serve as the basis of overall benefit when estimating the cost and benefit for preliminary economic analysis. Another benefit taken into consideration is the reduction in project fabrication time, which contribute to lower labour cost for every project. Initial investment for the start-up of the proposed workflow include 3D scanner hardware purchase and development of a fully integrated system between the software application and the fabricator's in-house information management system. Recurring cost include annual maintenance of the hardware, as well as workshops and trainings for the fitters on how to properly operate the 3D scanners and navigate the developed software application.

Nuclear projects experienced a risk reduction per project from $113,500 with the existing workflow, to $11,890 with the proposed workflow. The $101,610 difference in risk between the two workflows translates to 90% reduction, which is quite significant. Assuming there are two nuclear projects every year, the payback period of implementing the proposed workflow is 1.2 years, with a cumulative net benefit of almost $2.9 million after six years.

Small bore non-nuclear projects experienced a risk reduction per project from $11,000 with the existing workflow, to $1,640 with the proposed workflow. The $9,360 difference between the two workflows translates to 85% reduction in risk. Assuming there are seven small bore non-nuclear projects every year, the payback period of implementing the proposed workflow is 2.4 years, with a cumulative net benefit of over $1 million after six years.

Large bore non-nuclear projects, experienced a risk reduction per project from $23,500 with the existing workflow, to $2,890 with the proposed workflow. The $20,610 difference between the two workflows translates to 88% reduction in risk. Assuming there are four large bore non-nuclear projects every year, the payback period of implementing the proposed workflow is 5.1 years, with a cumulative net benefit of over $120,000 after six years.

In the interest of understanding the net benefit to a pipe spool fabricator as they potentially engage in all three types of projects, the summation of their costs and benefits are taken into consideration. The payback period of implementing the proposed workflow is 0.6 years, with a cumulative net benefit of almost $6 million after six years. The result support the economic justification of applying the proposed workflows into the standard fabrication processes and quality control practices.

5.2 Limitations

There are several limitations with the research itself, where the majority of data and information in this thesis are based on observations of the partner's existing work processes, and more specifically at their prefabrication facilities in Edmonton, AB and Cambridge, ON. While they represent over half of their prefabrication capacity, they may not reflect the work processes at the other two facilities, or any other industrial prefabrication shops for that matter. There may be specific work processes and quality control procedures for specialized productions, such as rebar fabrication. Nonetheless, the methodology presented in this thesis, particularly the approach to simulation modelling, simulation analysis, risk assessment, and economic analysis, may be generalized for any prefabrication projects of industrial construction, based on its complexity and activity process time. Figure 5-1 illustrates the matrix of scenarios constructed based on the two factors, and how it applies to this thesis.

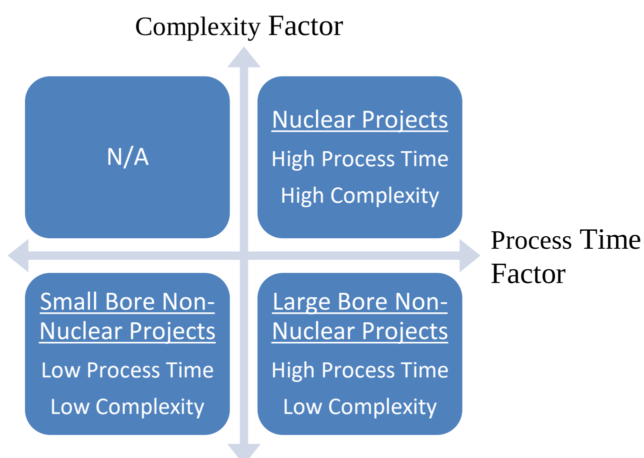


Figure 5-1. Simulation Scenario Matrix for Industrial Prefabrication

In terms of realizing the potential benefit of the proposed workflow in practice, there are challenges with applying 3D feedback during fabrication. Since 3D design models are required to generate point clouds for software application's discrepancy analysis, those models are critical to the visualization of any as-built geometric non-conformance. The level of collaboration or clear contract stipulation between the fabricator and the designer determine the success of 3D feedback workflow. Furthermore, prior to the implementation of the proposed workflow in nuclear projects, there needs an understanding within the nuclear industry to accept: (1) the accuracy and precision of the 3D data acquisition hardware, (2) the robustness of the point clouds that are generated based on the scanned data and 3D design models, and (3) the integrity of the algorithms within the software application.

5.3 Recommendations

Based on the research conducted and presented heretofore in this thesis, several recommendations are made for future work related to 3D feedback in the prefabrication of industrial construction:

- The software application should be subject to a more comprehensive field trial with end users, especially by the fitters, to assess current functionalities of the software application in practice, as well as to acquire feedback on its overall user interface, user experience, and learning curve.
- The research data, specifically the improvement factors related to non-conformance failure probability and rework time, are based on a small scale experiment of pipe spool assembly that can be completed relatively easily by one person (Kwiatek et al. 2019). A real fabrication project by craft workers in a shop environment could be used as an experiment, to evaluate the real benefit of applying 3D feedback workflow during fabrication, and compare against its baseline performance with the existing workflow.
- This thesis focused on the quality control processes during active fabrication, that is, during fitting and after welding, as well as before final shipment to site. There is another quality control step in the beginning of the project, which was explained in Section 3.3.1, that takes place during material receipt. There would be value in applying the proposed workflow at that stage of fabrication, and assess the impact of 3D feedback on subsequent and overall fabrication productivity, as defective materials are eliminated as possible contributor to overall spool geometric non-conformance.
- Despite favourable perception of technology use at work from a survey conducted by Kwiatek (2018), the data should not be generalized across the industry. Technical uncertainty and complexity are social constructions that vary from setting to setting, and the actual worker perception and consequently organization structural change are likely to be unanticipated. It is a system of multi-faceted interactions that include technical, social, organizational, cultural, and operational factors. To investigate the implementation of 3D feedback workflow in the prefabrication of industrial construction, an appropriate field methodology should be designed to provide a holistic perspective to reduce bias.
- Potential transformations in power dynamics of intra-organization relations (i.e. craft workers and supervisors) and inter-organization leverage (i.e. customer-supplier dyad) should be explored, in an effort to understand the social ramification of innovation deployment in the architecture, engineering, and construction industry.

Appendix A
Technical Specifications of 3D Data Acquisition Hardware

In this research project, three distinct 3D data acquisition hardware were assessed for their effective use case scenarios. These scanners are as follows:

1. FARO: Focus^{M} 70
2. DotProduct: DPI-8S
3. Occipital: Structure Sensor

It was determined by the research team that the FARO Focus Laser Scanner and the DotProduct DPI-8S provide the best tandem of 3D scanning hardware for geometric verification.

FARO

Focus Laser Scanner

The Most Compact Lightweight and Intuitive Laser Scanner Product Line

Laser Scanners for Short, Medium and Long Range Applications

FARO® Focus Laser Scanners are specifically designed for both indoor and outdoor measurements in industries such as Architecture, Engineering, Construction, Public Safety and Forensics or Product Design. All devices capture real world information used in the digital world to analyze, collaborate and execute decisions to improve and maintain the overall project and product quality.

The Focus^S Laser Scanner series offers advanced functionality. In addition to increased distance, angular accuracy, and range, the Focus^S and Focus^S Plus scanners' on-site compensation function ensures high-quality measurements, while external accessory bays and HDR functionality make the scanner extremely flexible.

Features

Accuracy

Highest accuracy and range by using a combination of the most advanced sensor technologies.

Rescanning of Distant Targets

The Scan Group feature identifies multiple areas to be rescanned with higher resolution to either perform accurate target detection or to capture smaller areas of interest with greater detail.

IP Rating 54 and Extended Temperature Range

With the sealed design and certified with the industry standard Ingress Protection (IP) Rating, IP54, the Focus can be used in wet weather conditions at temperatures from -20°C to 55°C[8].

Compact and Portable

Focus Laser Scanners are the smallest and lightest devices in their performance class.

Focus^S and Focus^S Plus

On-Site Compensation

With the on-site compensation functionality, users can verify and adjust the Focus^S compensation immediately before scanning, ensuring high-quality scan data and traceable documentation.

On-Site Registration

During on-site data capture, the laser scanner immediately transmits scan data wirelessly to FARO SCENE for real-time scan processing and registration, providing efficiency and time savings.

Benefits

- Confidence in documented data-quality by traceable calibration and market-leading on-site compensation.
- Scan in challenging environments while providing protection from dust, debris and water splashes. Mount the Focus^S scanner in an inverted position, such as under a ceiling of a hall.
- The Focus Laser Scanner portfolio offers the most economic 3D scanning solution for all requirements and budgets.
- Minimum training effort is ensured by the intuitive and easy to operate touch-screen interface as well as hands-on and online tutorials.
- Efficient integration into existing software infrastructures and workflows are provided by interfaces to various standard CAD systems.

www.faro.com

Performance Specifications

	Focus^S Plus 350	Focus^S Plus 150	Focus^S 350	Focus^S 150	Focus^S 70	Focus^M 70
Ranging Unit						
Unambiguity Interval	614m for up to 0.5 mil pts/sec 307m at 1 mil pts/sec 153m at 2 mil pts/sec		614m for up to 0.5 mil pts/sec 307m at 1 mil pts/sec			614m for up to 0.5 mil pts/sec
Range[1]						
90% Reflectivity (white)	0.6-350m	0.6-150m	0.6-350m	0.6-150m	0.6-70m	0.6-70m
10% Reflectivity (dark-gray)	0.6-150m	0.6-150m	0.6-150m	0.6-150m	0.6-70m	0.6-70m
2% Reflectivity (black)	0.6-50m	0.6-50m	0.6-50m	0.6-50m	0.6-50m	0.6-50m
Range Noise[2] (mm)						
@10m 90% (white)	0.1		0.3			0.7
@10m 10% (dark-gray)	0.3		0.4			0.8
@10m 2% (black)	0.9		1.3			1.5
@25m 90% (white)	0.2		0.3			0.7
@25m 10% (dark-gray)	0.5		0.5			0.8
@25m 2% (black)	1.6		2.0			2.1
Max. Measurement Speed (mil. pts/sec)	Up to 2		Up to 1			Up to 0.5
Ranging Error[3] (mm)	±1					±3
Angular Accuracy[4]	19 arcsec for vertical/horizontal angles					not specified
3D Point Accuracy[5]	2 @10m 3.5 @25m		2 @10m 3.5 @25m			not specified

Additional Performance Specifications	
Color Unit	
Color Resolution	Up to 165-megapixel color
HDR Camera	Exposure bracketing 2x, 3x, 5x
Parallax	Minimized due to co-axial design
Deflection Unit	
Field of View	300°vertical[6] / 360° horizontal
Step Size	0.009 (40,960 3D-pixel on 360°) vertical / 0.009 (40,960 3D-pixel on 360°) horizontal
Max. Scan Speed	97Hz (vertical)
Laser (Optical Transmitter)	
Laser Class	Laser Class 1
Wavelength	1550nm
Beam Divergence	0.3mrad (1/e)
Beam Diameter at Exit	2.12mm (1/e)
Data Handling and Control	
Data Storage	SDHC™, SDXC™, 32GB; max. 512GB card
Scanner Control	Via touch screen display and WLAN connection, Access by mobile devices with HTML5
Interface Connection	
WLAN	802.11n (150Mbit/s), as access point or client in existing networks

Additional Features	
Dual Axis Compensator	Performs a leveling of each scan with an accuracy of 19 arcsec valid within ±2°
Height Sensor	Via an electronic barometer, the height relative to a fixed point can be detected and added to a scan
Compass[7]	The electronic compass gives the scan an orientation
GNSS	Integrated GPS & GLONASS
On-Site Compensation*	Creates current quality report and improves compensation automatically
Accessory Bay*	The accessory bay connects versatile accessories to the scanner
Inverse Mounting	Yes
Real-time, On-site Registration in SCENE*	Connects to SCENE, real-time scan processing and registration, overview map
Electronic Automation Interface*	Available as option, only at point of sale
Digital Hash Function	Scans are cryptographically hashed and signed by the scanner
Rescanning of Distant Targets	Defined areas recaptured in higher resolution at a greater distance
Retake Photos	Select individual photographs with unwanted objects and retake them

*Not integrated with the Focus^M 70

General Specifications	
Power Supply	19V (external supply), 14.4V (internal battery)
Power Consumption	15W idle, 25W scanning, 80W charging
Battery Service Life	4.5 hours
Temperature	Operating: 5° - 40° C | Extended Operating[8]: -20° - 55° C | Storage: -10°- 60°C
Ingress Protection (IP) Rating Class	IP54
Humidity Resistance	Non-condensing
Weight	4.2 kg (including battery)
Size/Dimensions	230 x 183 x 103mm
Maintenance / Calibration	Recommended annual

CLASS 1 LASER PRODUCT

1. For a Lambertian scatterer. **2.** Ranging noise is defined as a standard deviation of values about the best-fit plane for measurement speed of 122,000 points/sec. **3.** Ranging error is defined as a systematic measurement error at around 10m and 25m. **4.** On-site compensation required. **5.** For distances larger 25m add 0.1mm/m of uncertainty. **6.** 2x150°, homogeneous point spacing is not guaranteed. **7.** Ferromagnetic objects can disturb the earth magnetic field and lead to inaccurate measurements. **8.** Low temperature operation: scanner has to be powered on while internal temperature is at or above 15°C, high temperature operation: additional accessory required.

All accuracy specifications are one sigma, after warm-up and within operating temperature range; unless otherwise noted. Subject to change without prior notice.

For more information, call 800.736.0234 or visit www.faro.com

FARO Technologies, Inc. | 250 Technology Park | Lake Mary, FL 32746

GSA Contract Holder

SFDC_04MKT_476 Revised: 03/05/2020

DOT PRODUCT

DPI-8X SR Powered by Phi.3D and Dot3D Software

Handheld 3D Data Capture on a Tablet

DotProduct develops high performance easy-to-use solutions for capturing 3D data. Our technology is designed for mobile professionals who need high quality spatial data, instantly. Our Phi.3D and Dot3D software turns an Android tablet into a fully mobile 3D-capture and -processing solution that delivers the results before you leave the worksite.

Next Generation Mobile 3D Scanning Software

- Capture and register 3D spatial data on the processing power of a tablet – no PC or cloud service required!
- Define the coordinate system on the tablet, append multiple datasets in the field, pull measurements on the fly, and easily implement targets for the highest level of accuracy.

Truly Mobile

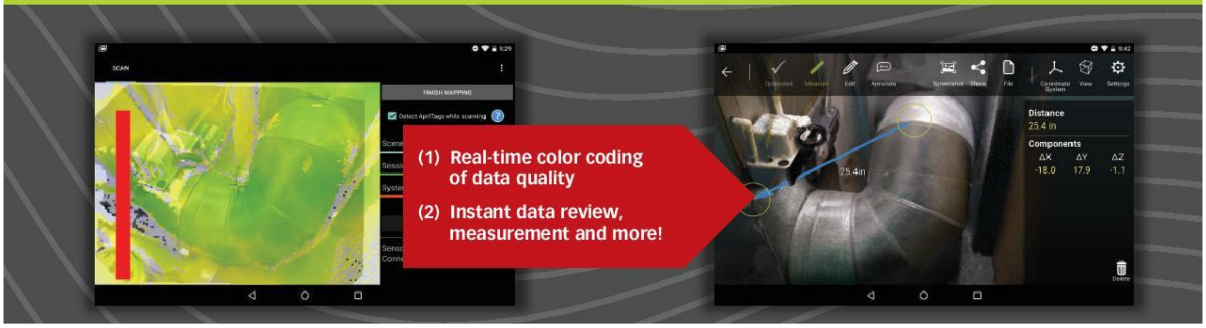
Forget lugging around a laptop and cumbersome cables

- Capture and process 3D spatial data directly on the tablet!
- Safely capture difficult areas with one or two hands.
- Crop, measure, annotate and more with Dot3D Edit.
- Get into hard-to-reach, occluded areas, inaccessible with other technologies.

Real-Time Results

- No surprises: leave the jobsite knowing you've collected the right data you need for your project.
- Phi.3D technology provides users with real-time data quality feedback as the data is being acquired.
- Instantly review point cloud datasets right on the tablet.

New Technology – Familiar and Proven Work Flows



Georeference, Measure, Crop, and Annotate in the Field

- Set the coordinate system on the tablet in seconds.
- Measure vertical, horizontal, and point-to-point distances directly from the data on the job site.
- Crop, annotate, and take precise measurements in the new Dot3D Edit software on Android or Windows.

Append Multiple Data Sets Together Automatically

- Use the Append to Scan function to add new data to previously captured 3D spatial data. New data can be captured and appended on-the-fly without the need for additional targets or control.
- Utilize the Append to Add function to connect multiple distinct data sets into the same coordinate system on the fly.

Direct Export to Industry Formats

- Use DPI-8X SR captured data with CAD and point cloud software you work with today. No need to change your current workflow.
- Export in PTS, PTX, PLY, PTG, E57, LAS, LAZ, POD, or DP format for effecient storage and rapid data export. Native DP files integrate directly with Autodesk ReCap, Leica Cyclone, Trimble Realworks, Z+F LaserControl, ClearEdge3D, AVEVA LFM, Bloom Cloud Engine, CloudCompare, InfiPoints, PointCab, Pointfuse, 3D Reconstructor, Rhino, Sequoia, Undet, Visual Statement, WorldViz, and more.

The DotProduct DPI-8X SR Handheld 3D Scanner contains:	
1	8" Android Tablet computer with at least 16GB of storage (DotProduct reserves the right to provide greater than 16GB depending on availability)
1	License of DotProduct Phi.3D software, preloaded and licensed to that tablet computer and camera. One year of support and upgrades included
1	PrimeSense Carmine 1.09 red, green, blue and depth sensor
1	One-year license of Dot3D Edit software (Android or Windows)
1	DPI-8X SR dual-grip housing for Android tablet and sensor
3	USB to micro USB connectors for connecting camera to tablet
1	Carrying case
1	Tablet charger

Test Facility Results

(measured distance in final post-processed model)

Range	Typical Accuracy	Minimum Accuracy
< 1 m (3.3 ft)	99.8%	99.6%
1 m to 2 m (6.6 ft.)	99.5%	99.2%
> 2 m (6.6 ft.)	Not Specified	Not Specified

DPI-8X SR Compatible Accessories

DPI Extension Kit, DPI Light Kit, AccuScale-DP Scale Bar Kit, InfiPoints DP, Pointfuse for DP

DPI-8X SR Handheld 3D Scanner Performance

The data quality of the DPI-8X SR depends on range, temperature, ambient lighting conditions, reflectivity of the area of interest, operator skill and other factors. System accuracy is improved by using survey targets. System performance is degraded by long collection times, accumulation of frame-to-frame drift and lack of scene fitness induced by geometry and texture limitations.

DPI-8X SR (Short Range) Range of Capture

The working range of the DPI-8X SR is from 0.3 m to 2 m (1 ft – 7 ft).

Illustrations, descriptions and technical specifications are not binding and may change.

DPI-8X SR Product Specifications - General	
Imager Type	Compact, near infrared structured light and RGB 3D depth imaging system
User Interface	Android operating system
Data Storage	Onboard 16 GB flash drive
Data Transfer	USB 2.0/3.0, microUSB connector
Battery Life	2-3 hours of continous scanning, extendable with 2nd tablet
DPI-8X SR Product Specifications - Physical	
Mass	1.36 kg (3 lbs.)
Dimensions	25 cm x 15 cm x 8 cm (10 in x 6 in. x 3 in.)
Temperature	Tested operating range: 15 °C to 32 °C (60 °F to 85 °F)
Lighting	Not operational in direct sunlight
Humidity	Non-condensing

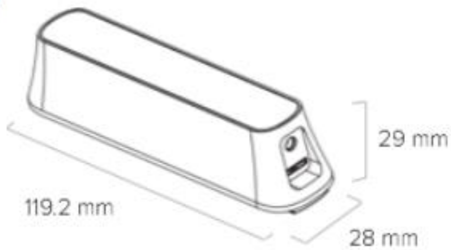
DOT PRODUCT

Please feel free to contact us for more details about our calibration and test procedures.

DotProduct LLC | 11 Elkins St. | Suite 310 | Boston, MA 02127 USA | +1 617 415-7222 | www.dotproduct3d.com

Structure Sensor by Occipital
Technical Specifications

Dimensions



Weight

95g

Maximum Recommended Range

3.5m+

Minimum Recommended Range

40cm

Precision

0.5mm at 40cm (0.15%),
30mm at 3m (1%)

Resolution

VGA (640 x 480),
QVGA (320 x 240)

Framerate

30 / 60 frames per second

Battery Life

3-4 hours of active sensing,
1000+ hours of standby

Illumination

Infrared structured light projector, uniform infrared LEDs

Field of View

Horizontal: 58 degrees,
Vertical: 45 degrees

Operating Temperature

0° to 35° C (32° to 95° F)

Appendix B

The Partner's Quality Control Procedure

	Quality Control Procedure	Procedure No. QCP 309.44	Page 1 of 14
	CONTROL OF NONCONFORMING ITEMS	Rev. No: 11 Date Issued: 23 Oct. 2017	
Prepared By:	Approved By: Original signed by		

1.0 PURPOSE:

1.1 This procedure provides instructions for the control of nonconforming material or components.

2.0 SCOPE:

2.1 This procedure is applicable to all work performed by the partner.

3.0 REFERENCES:

Quality Assurance Manual for Nuclear Class Items, Section 15
CSA N286Quality Assurance Manual for EPC Projects; Subsection 3.11
Quality Control Manual; Subsection 3.6
ISO 9001 MPM; Section 18.0

4.0 DEFINITIONS

4.1 **Nonconformance: A** deficiency in characteristic, documentation or procedure that renders the quality of material, component or activity unacceptable or indeterminate.

4.2 **Counterfeit:** Item that has been intentionally manufactured or altered to imitate a legitimate product without the legal right to do so.

4.3 **Fraudulent:** Items that are intentionally misrepresented with intent to deceive. Fraudulent items include item(s) provided with incorrect identification, falsified or inadequate certification. Fraudulent items also include items sold by entities that have acquired the legal right to manufacture a specified quantity of an item (such as an integrated circuit), but produce a larger quantity than authorized and sell the overage as legitimate inventory.

4.4 **Suspect:** Items that are suspected of being counterfeit or fraudulent based on visual inspection, testing or other information that may indicate nonconformance to Government or Industry accepted Specifications or National Consensus Standards. Suspect items must be investigated to determine whether the item is counterfeit or fraudulent.

4.5 **Item:** An all-inclusive term used in place of any of the following: appurtenance, assembly, component, equipment, material, module, part, structure, subassembly, subsystem, system, or unit.

5.0 GENERAL:

5.1 A nonconformance is a deficiency in characteristic, documentation or procedure that renders the quality of material, component or activity unacceptable or indeterminate.

5.2 Material received that is found to contain issues with quantities, missing documentation or damage shall not require a Nonconformance Report (NCR). Such issues shall be recorded on an Overage, Shortage & Damage (OS&D) Report (form G 066) in accordance with QCP 405.7.

5.3 If the Materials Manager, Purchasing Manager or Project Manager cannot resolve the issue with the supplier using an OS&D, then an NCR shall be raised.

5.4 When identification & traceability of material is lost during any stage of manufacturing an NCR shall be issued. The disposition shall include the requirement that prior to remarking the material; as a minimum the material shall be tested or supporting documentation shall be reviewed to verify the identification of the material.

5.5 Non-conformances shall be dispositioned in one of six ways as follows:

- Use-as-is
- Repair
- Re-work*
- Scrap
- Return & Replace
- Other

* Re-work: applies only to Non-ASME Section III items

5.6 When a nonconformance occurs, a Quality Control Inspector (QCI) is responsible for:

- Logging into the NCR data base.
- Raising a Nonconformance Report (Form Q001)
- Detailing the nonconformance including the applicable defect code. (Refer to Table T309.44-1 Non-Conformance Report Defect Codes)
- Identifying the item, component or batch of components with a red Nonconformance/hold tag (Refer to attachment #1)

Note: NCR number is automatically allocated by the NCR database.

5.6.1 When identifying the item, component or batch of components with a red Nonconformance/Hold Tag, the tag shall be attached to the item container (holding the batch), or the segregated storage area, and shall include the following information as applicable:

- Job Number
- Drawing/spool/item number
- NCR number
- Description of the nonconformance

5.6.2 When practical, segregate nonconforming items by placing them in a clearly identified Hold Area. When segregation is not practical, the affected area shall be clearly marked with a halogen free marker on the item and identified on the NCR tag.

5.6.3 Recording the NCR number at the operation in the Traveler where the nonconformance occurred or, if there is no traveler, on the applicable drawing, or on the Material Receiving Report.

5.6.4 The NCR shall be forwarded for review to:

- The Quality Control Supervisor (QCS) for non-nuclear contracts, or
- Quality Manager for nuclear contracts.

5.7 No work may proceed on the affected area of the nonconforming item until the NCR is issued with an approved disposition. Only QC personnel may remove a hold tag.

6.0 The partner's non-nuclear quality programs:

6.1 Red ribbons may be used in addition to tagging to identify nonconforming items.

6.2 The QCS completes his review in the database and submits the nonconformance to the Project Manager (PM).

6.3 The PM shall review the NCR and provide a disposition. The PM may obtain the assistance of other personnel, as required.

6.4 The QCS shall review the disposition and if acceptable route the NCR for disposition approval. If the proposed disposition is not acceptable, return the NCR to the PM to change the proposed disposition.

6.5 The QCS shall indicate the required approvals for the NCR by placing an "x" in the appropriate boxes, and shall also indicate if a Corrective Action is required. If Corrective Action is required, the QCS shall initiate a Corrective Action Report in accordance with QCP 309.74.

6.6 The QCS shall then print a hard copy of the NCR and obtain approval signatures by personnel identified on the NCR form.

6.7 For Code related NCR's dispositioned Use-As-Is or Repair

6.7.1. When the partner is responsible for the design, the PM shall forward the NCR to the Design Service, for approval of the NCR disposition.

6.7.2. The Design Service shall review the partner's proposed disposition. The Design Service shall provide technical justification and may provide changes to the disposition. Once the Design Service has accepted the disposition, they shall return the NCR with technical justification to the PM.

6.7.3. If the customer is responsible for design, the PM shall forward the NCR to the customer for disposition. The customer shall return the dispositioned NCR with technical justification to the PM.

6.7.4. The PM shall then forward the accepted dispositioned NCR to the QCS.

6.7.5. The QCS shall obtain AI acceptance of the disposition.

6.8 For NCR's dispositioned Repair.

6.8.1 The QCS shall attach a copy of the dispositioned NCR to the drawing and present it to the Superintendent.

6.8.2 In cases where a traveler is being used to control the job, the QCS shall place a copy of the dispositioned NCR in with the Traveler and return the Traveler to the Superintendent.

6.8.3 The shop shall execute the repair as described in the NCR.

6.9 For NCR's dispositioned Rework

6.9.1 The PM shall return the NCR to the QCS.

6.9.2 The QCS shall attach a copy of the dispositioned NCR to the drawing and present it to the Superintendent.

6.9.3 In cases where a traveler is being used to control the job, the QCS shall place a copy of the dispositioned NCR in with the Traveler and return the Traveler to the Superintendent.

6.10 For NCR's dispositioned Rework or Repair, the applicable components shall be re-inspected in the same manner as originally inspected as a minimum.

6.11 For NCR's dispositioned Scrap

6.11.1 The PM shall requisition more material and return the NCR to the QCS for closing. The PM shall contact the Quality Specialist to initiate any new travelers required, referencing the NCR #, to remake parts.

6.11.2 The QCS shall have the material or component conspicuously and permanently marked, or positively controlled, until physically rendered unusable.

6.12 For NCR's Dispositioned Return & Replace:

6.12.1 The PM shall forward a copy of the dispositioned NCR to the Purchasing Manager.

6.12.2 The Purchasing Manager or delegate will contact the Supplier to exchange and replace the defective material or item.

6.12.3 The Purchasing Manager shall review and accept the disposition, and return the NCR to the QCS for closing.

6.12.4 The QCS shall forward a copy of the dispositioned NCR to the Receiver, who shall follow the NCR disposition.

6.13 For NCR's dispositioned Other:

6.13.1 'Other' can be used when a use-as-is, repair, rework, scrap or return and replace disposition is not applicable. Examples of when 'Other' could be selected include:

- a preliminary disposition (e.g. further analysis is required)
- a proposed disposition (e.g. final customer disposition is required for Customer supplied items).
- to address documentation issues.

6.13.2 In the event 'Other' is used as a preliminary or proposed disposition, upon determination of the final disposition (e.g. customer disposition has been received), the NCR shall be revised and the disposition changed from 'Other' to the final disposition (i.e. repair, use-as-is, rework, return or replace, or scrap) and the NCR processed in accordance paragraphs 5.8, 5.9, 5.10, 5.11, 5.12. or 5.13 as applicable.

7.0 The partner's nuclear quality program:

7.1 The Quality Manager completes his review and submits the nonconformance to the Manufacturing Specialist. When 10CFR Part 21 and/or 10CF50.55e apply, the QM shall complete form N040 and attach it to the NCR. If assistance from the Design Service is required, the QM forward the NCR to the TSM who shall request it. In addition, the QM shall indicate on the NCR that the assessment to 10CFR Part 21 and/or 10CF50.55e was performed.

7.2 In the event that the initial screening indicates a condition that may be reportable under 10CFR21 and/or 10CF50.55e requirements, further evaluation shall be performed in accordance with QCP 405.9 - 10CFR21 Reporting of Defects and Noncompliance.

7.3 The Manufacturing Specialist shall review the NCR, provide a disposition and submit it to the Quality Manager. The Manufacturing Specialist may obtain the assistance of other personnel, as required.

7.4 The Quality Manager shall review the disposition and if acceptable route the NCR for disposition approval. If the proposed disposition is not acceptable, return the NCR to the Manufacturing Specialist to change the proposed disposition.

7.5 The Quality Manager shall indicate the required approvals for the NCR by placing an "x" in the appropriate boxes, and shall also indicate if a Corrective Action is required. If Corrective Action is required, the QM shall initiate a Corrective Action Report in accordance with QCP 309.74.

7.6 The Quality Manager shall then print a hard copy of the NCR, submit it to the QCS, who shall obtain approval signatures by personnel identified on the NCR form.

7.7 NCR's dispositioned Use-As-Is or Repair

7.7.1 When the partner is responsible for the design, the Technical Services Manager (TSM) shall forward the NCR to the Design Service, for approval of the NCR disposition.

7.7.2 The Design Service shall review the partner's proposed disposition. The Design Service shall provide technical justification and may provide changes to the disposition. Once the Design Service has accepted the disposition, they shall return the NCR to the TSM.

7.7.3 If the customer is responsible for design, the PM shall forward the NCR to the customer for disposition. The customer shall return the dispositioned NCR with technical justification to the PM.

7.7.4 The PM shall then forward the accepted dispositioned NCR to the QCS.

7.7.5 The QCS shall obtain approval of the NCR from the ANI and then forward it to the Manufacturing Specialist.

7.7.6 For NCR's dispositioned Repair, the Manufacturing Specialist shall prepare a Traveler (new traveler, revision or addendum) which shall describe the repair operations, inspection and test operations and any NDE required. After obtaining approval of the PM and the QM, the Manufacturing Specialist shall forward the NCR and Traveler to the QCS.

7.7.7 The QCS shall obtain approval of the Traveler from the ANI and then forward it to Document Control for issuance.

7.7.8 The shop shall execute the repair as described in the Traveler.

7.7.9 The items shall be re-inspected in the same manner as originally inspected as a minimum.

7.8 For NCR's dispositioned Scrap

7.8.1 When the NCR disposition is scrap, the Manufacturing Specialist shall requisition more material and return the NCR to the QCS for closing.

7.8.2 The Manufacturing Specialist shall initiate new travelers if required, referencing the NCR #, and providing necessary operations to remake the parts.

7.8.3 The QCS shall have the scrap material or component conspicuously and permanently marked, or positively controlled, until physically rendered unusable.

7.9 For NCR's dispositioned Return & Replace:

7.9.1 The Manufacturing Specialist shall forward a copy of the dispositioned NCR to the Purchasing Manager.

7.9.2 The Purchasing Manager will contact the Supplier to exchange and replace the defective material or item.

7.9.3 The Purchasing Manager shall review and accept the disposition, and return the NCR to the QCS for closing.

7.9.4 The QCS shall forward a copy of the dispositioned NCR to the Receiver, who shall follow the NCR disposition.

7.10 For NCR's dispositioned Rework: (Note: Re-work applies only to Non-ASME Section III items)

7.10.1 The PM shall return the NCR to the QCS.

7.10.2 The QCS shall attach a copy of the dispositioned NCR or Traveler addendum (if required) to the Traveler and present it to the Superintendent

7.10.3 In cases where a traveler is being used to control the job, the QCS shall place a copy of the dispositioned NCR in with the Traveler and return the Traveler to the Superintendent.

For NCR's dispositioned Rework, if required the Manufacturing Specialist shall prepare a Traveler addendum listing the required rework and re-inspection operations. After obtaining approval of the PM and the QM, the Manufacturing Specialist shall forward the NCR and Traveler addendum to Document Control for issuance.

The QCS shall obtain approval of the Traveler from the ANI and then forward it to Document Control for issuance.

The shop shall execute the rework as described in the Traveler.

The items shall be re-inspected in the same manner as originally inspected as a minimum.

7.11 For NCR's dispositioned Other:

7.11.1 'Other' can be used when a use-as-is, repair, rework, scrap or return and replace disposition is not applicable. Examples of when 'Other' could be selected include:

- a preliminary disposition (e.g. further analysis is required)
- a proposed disposition (e.g. final customer disposition is required for Customer supplied items).
- to address documentation issues.

7.11.2 In the event 'Other' is used as a preliminary or proposed disposition, upon determination of the final disposition (e.g. customer disposition has been received), the NCR shall be revised and the disposition changed from 'Other' to the final disposition (i.e. repair, use-as-is, rework, return or replace, or scrap) and the NCR processed in accordance paragraphs 6.7, 6.8, 6.9 or 6.10 as applicable.

8.0 Closing the NCR:

8.1 When the NCR disposition is either "Use-As-Is, Repair or Rework" and the repair or rework and required inspections and tests are complete, the QCS shall sign off the NCR and/or the Traveler, and present them to the Customer, ANI or AI as applicable for their review and acceptance.

8.2 When the NCR disposition is "Scrap", the QCS shall sign off the NCR, after verifying the material or component has been conspicuously and permanently marked, or positively controlled, until physically rendered unusable, and shall then advise the Material Manager who shall send it to a scrap bin or area for scrap.

8.3 When the NCR disposition is "Return and Replace", the QCS shall sign off the NCR, mark the material or component "Return to Supplier" and advise the Materials Manager.

8.4 If the NCR number has been noted on an MRR, the QCS shall also sign off on the MRR signifying the NCR is closed.

8.5 After the NCR has been closed by the QCS the hold tag can be removed by the QC Inspector.

9.0 Revisions to Nonconformance Reports:

9.1 A revision to a nonconformance will be made by the originator of the NCR or by their Supervisor / Manager.

9.2 A revision to an NCR can be for several reasons, ie. additional information under the description of nonconforming condition or a revision to the disposition once approved.

9.3 When the NCR is originally raised, no revision level is identified. If it is necessary to revise NCR, then the first revision is indicated by the number 1 (one) in the revision (Rev.) field. If there are further revisions, then the revision number increases numerically by one.

9.4 Revisions to NCRs shall be reviewed and approved in the same manner as the original.

9.5 If for any reason a closed NCR requires a change, that NCR shall remain closed and a new NCR shall be initiated.

10.0 SUPPLIER NONCONFORMANCES:

10.1 The partner's quality assurance programs shall require that supplier nonconformance reports be submitted to the partner for review and acceptance.

10.2 Supplier Nonconformance Reports shall be forwarded to the purchasing agent or to Document Control, who shall forward to the QCS.

10.3 The QCS shall raise a NCR in the database referring to the supplier NCR. These NCRs shall be processed in accordance with Section 5.0 or Section 6.0 of this procedure as applicable.

10.4 Once the disposition is approved, the NCR shall be returned to Document Control who shall return it to the supplier.

10.5 At the completion of all work by the supplier and prior to shipment, the supplier shall submit a copy of their closed nonconformance with supporting documentation as applicable to the partner which will be reviewed by the QCS before closing the partner's NCR.

11.0 CUSTOMER NCRS AND CARS:

11.1 Customer Nonconformance Reports and Corrective Action Reports shall be evaluated by the Quality Manager. If accepted, a corresponding NCR or CAR shall be issued to track and document within the partner's quality system.

11.2 Customer Corrective Action Reports will be handled in accordance with QCP 309.74 Corrective Action.

12.0 COUNTERFEIT, FRAUDULENT AND SUSPECT ITEMS (CFSI):

12.1 The nonconformance process shall be followed for CFSIs with the addition of the following requirements.

12.2 The QC Inspector, when initiating the NCR shall assign a defect code of 2h; Counterfeit Material or Item.

12.3 The Manufacturing Specialist shall use the "Other" disposition and disposition the NCR with an action to evaluate and investigate the item to determine if in fact the item is counterfeit or fraudulent. At this stage the item is deemed to be suspect.

12.4 During the investigation, the Manufacturing Specialist shall work with the Original Equipment Manufacturer (OEM) to establish the authenticity if the item. The distribution chain shall not be utilized due to the suspect nature of the supply chain and the item.

12.5 If during the investigation, the item has been verified as being authentic, the Manufacturing Specialist shall forward the objective evidence to the QCS and the NCR shall be closed. If the item has been verified as being Counterfeit or Fraudulent, the Manufacturing Specialist shall revise the disposition actions to notify the customer of the Counterfeit / Fraudulent Item and hold the item until authorization to scrap the item is received from the Quality Director.

12.6 The customer shall be notified by the Quality Director that a Counterfeit or Fraudulent Item has be discovered. Specific customer notification requirements are as follows;

12.7 Ontario Power Generation (OPG) requires notification of defects and nonconformance when a known or suspected defect is discovered that affects, or may affect product that have already been delivered to OPG. Such notification shall be on the partner's letterhead signed by the Quality Director. The notification shall include the following details as a minimum and be sent by email to scqs.suppliers@opg.com:

- A clear description of the defect or nonconformance.
- An assessment of the impact of the defect or nonconformance to product form, fit, or function. Also, address the potential impact on safety if known.
- Identify OPG catalogue identification number(s) that are affected including OPG purchase order and line numbers, ship date, quantity, manufacturer product identification / traceability (eg. Serial number, lot number, batch number, etc…)
- Immediate short-term actions to be taken to remedy the situation at OPG (address the availability and replacement of item(s) and delivery time)
- Long-term corrective action plan to address the root cause for the defect or nonconformance including completion / implementation commitments.

12.8 United States Nuclear Regulatory Commission does not require any addition reporting requirements. The process for reporting of defects to comply with 10CFR Part 21 is sufficient.

12.9 The Quality Director shall post the documents related to the CFSI event to the partner's intranet site in the CFSI page.

13.0 RECORDS:

13.1 The completed NCR together with any 10CFR Part 21 Screening forms, if applicable, shall be filed with the Quality Coordinator, who shall forward a copy to the QAR Clerk.

13.2 The Quality Coordinator shall maintain a log of NCRs issued including the NCR number, date raised, and date closed.

14.0 RECORD OF REVISION:

Rev. No.	Revision Date	Revision Description
0	13 April 2011	Initial release.
1	23 June 2011	New para's 4.2, 4.3, 6.5.5 Revised para 6.6.3
2	4 Oct 2011	Para’s 2.1, 3.0, 4.6.1, 4.6.2, 4.6.3, 4.8, 6.5.2 revised Para 5.1 added new – subsequent para’s renumbered Attachment 1 – deleted
3	27 Oct 2011	Para 9.1 added new – subsequent para’ renumbered. Table T309.44-1 revised - D45 added.
4	11 May 2012	Added para’s 4.7, 6.4, 6.5. Revised para 12.1.
5	3 Oct 2013	QA Manual 10CFR50 Appendix B Supplement added to Para 3.0; Para 4.7 revised.
6	2 Jan 2014	Previous section 6.8 deleted and subsequent para’s renumbered. Para’s 4.8, 6.1, 6.2, 6.6, 6.7.5, 6.8, 6.8.1. 6.8.2, 6.8.3, 6.9.1, 6.9.2, 6.9.3, 6.10.1, 9.2, 9.3, 9.5, Attachment 2 and Attachment 3 revised. Para’s 6.7.6, 6.7.7, 6.7.8 and 6.7.9 added new.
7	26 May 2014	Added “code related” to para. 5.5 Changed “approval” to “acceptance” in paragraph 5.5.5 Defect codes revised Para’s 4.8, 6.1, 6.2, 6.7.5, 6.7.6, 6.8.1, 6.8.2, 6.9.1, and 9.3 revised to change MS to Manufacturing Specialist for clarification. Para 6.4, 6.5 revised to add and/or 10CFR50.55e.
8	29 Oct 2014	General Revision
9	10 May 2015	Revised section 4.5 Added section 5.14, 6.10, 6.11
10	12 April 2017	Para 10.2 revised to remove reference to QCP 309.55 added QCP 309.74 Para 8.5 added new – per CR # 349 & 353 Para 11.2 revised – removed last sentence. Para 11.3 – deleted.
11	23 Oct. 2017	General revision

Table T309.44-1 Non-Conformance Report Defect Codes

DEFECT CODES

1. Procurement Issue

a. Purchase Order Error

2. Material Issue (Vendor)

a. Missing MTR/Documentation
b. Incorrect MTR
c. Damaged Material/Item - Incoming
d. Material Defect
e. Wrong material/Improper Specification
f. Contamination
g. Identification/Traceability
h. Counterfeit Material or Items
i. Dimensional/Out of Tolerance
j. Improper Material Substitution

3. Fabrication/Construction Issue

a. Damaged Material/Item –Production
b. Improper Material Substitution
c. Dimensional/Out-of-Tolerance
d. Use of detrimental / unapproved product
e. Unqualified Welder/Welding Operator
f. Wrong WPS Used
g. Fitting Error
h. Weld Defect
i. Wrong Material/Consumable Used
j. Lack of Process/Procedural Compliance
k. Drawing Error
l. Machining Error
m. Loss of FME
n. PWHT Error
o. Pressure Test Failure
p. Paint Defect

4. Engineering/Document Control Issue

a. Drawing or Drafting Error
b. Non-current Revision
c. Process Compliance

5. Free Issue Material (Customer)

a. Damaged Material/Item
b. Does Not Meet Code/Specification/Standard/Contract
c. Insufficient/Incomplete Documentation

6. Regulatory

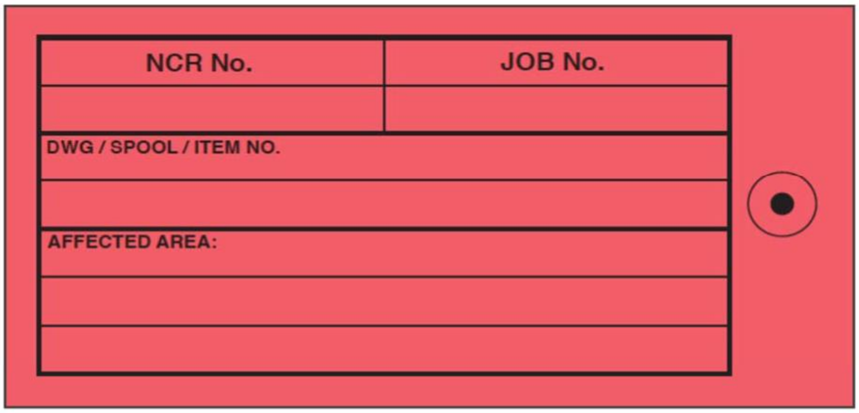
a. Regulatory Non Conformance

7. Miscellaneous

a. Defects not covered by those above

Attachment #1 – Nonconformance/Hold Tag

Back



Front

Tag is Red

Appendix C
Sampled NCR: Description

84 NCR were sampled out of the 693 geometric-related non-conformance. Each NCR was reviewed for the root cause of their non-conformance, affected module, remedy proposal, as well as specific details and instructions on the remedy.

Code	NCR #	Module	Description	Proposal	Disposition Details
2C	0211	Q223	Damage was observed to temporary plugs on valve S/N 19089911 on module X23. The bottom plug (see attached photos) is more severe than the top, but they've both been damaged. The damaged valve is item no. 8, Commodity Code APP-PV14-Z0D-104, in drawing SV3-Q223-PXS-PLW-03 Rev 3.	Other	Note that valve S/N 19089911 is installed in module SV3-Q223. Plugs, as shown in photo, are bent. The affect on fit, form or function of the plugs is unknown by the partner. It appears to the partner that these parts are easily replaceable. Customer to advise.
2C	0597	Q240	During CFM/PFM inspection of B40 material, the following valves were found to have non-conforming conditions: The partner Drawing: VS3-Q240-RNS-PLW-01 Rev. 0 WECTEC Drawing: APP-RNS-PLW-14 Rev. 7 •APP-PV01-ZOD-116 (BN477) – Gouge on valve body 1" X 1/8" in size, 1/16" deep (see attached picture).	Other	For Valve BN477 – Mechanical damage resulting in a gouge 1"x1/8"x 1/16", was found on the valve body. The partner proposes a repair to be completed at site by an authorized agency after the installation of the valve.

Defect Code	NCR #	Module	Description	Proposal	Disposition Details
2C	1132	Q601	For X01: Due to an operating error, the tool broke an insert causing a gouge in the hole. Gouge marks found in one of the 2.625'' dia. holes. The finished diameter is now out of tolerance nominal size is 2.625'' +.031'' actual diameter is 2.665''. Depth of the deepest gouge is aprox. 0.050''	Repair	As per APP-Q601-GNR-850104: "Attachment 1: Disposition and Q601 Justification Disposition: The design authority has reviewed the non-conforming condition and approves a "Repair" disposition. The fabricator shall perform base metal repair to remove sharp edges from the gouges in Mk 501, followed by weld build-up (NF-4130) to restore the base metal to the requirements of Ref. 1 which are as follows; Maximum bolt hole diameter for bolt sizes greater than 2" is the bolt diameter plus 3/16" per Table NF- 4721(a)-1 of Ref. 1. The bolt size of the ring girder stud (connecting the ring girder to the Q601 attachment plate, Mk 501) is 2.5" diameter. Therefore the bolt hole diameter per table NF-4721(a)-1 of Ref. 1 is 2.6875". The fabricator shall perform weld repair on all gouges resulting in a hole diameter greater than 2.6875." Base metal repair shall be performed to remove sharp edges for all gouges resulting in a hole diameter less than 2.6875". Weld repair shall be performed if base metal repair results in a hole diameter greater than 2.6875" in accordance with approved welding procedures. Justification: Performing base metal repair and/or weld repair (where required) of the area damaged by the drill bit will restore the part to the as designed condition and comply with the requirements of Ref. 1. Impact to Q601: APP-Q601-S3C-002 (Ref. 4) analyzes the Q601 attachment plate (MK 501; see Ref. 2 &

Defect Code	NCR #	Module	Description	Proposal	Disposition Details
2D	0075	Q233	Excessive kerf depth was found on the edge of plate # b3052-4 during material verification. Depth of kerf was measured at approximately 5/32". Drawing SF3000 Rev. 0 has a dimensional tolerance of only 1/8"; therefore depth of the kerf exceeds drawing tolerances. This plate (b3052-4) is to be used in traveler TRV-A00002G33-019. See attached pictures for reference.	Re-work	The defect found in plate b3052-4 will be removed during the continuation of fabrication operations. This plate becomes part SF3000 which is used to construct box beam S3020. When S3020 is fabricated to become SA3019, the cutting operation will remove approximately 4 15/16" which will fully remove the kerf. Dimensional inspection following the cutting of SA3019 on traveler TRV-A00002G33-068 will confirm that the kerf is removed.

Defect Code	NCR #	Module	Description	Proposal	Disposition Details
2D	0105	Q240	Non-conforming conditions for set -2 of the grating- Panel MK 23-2 - 8 11/16” dim.is 9 9/16” (depth of cutout) Panel MK 28-2 - 4 1/16” dim. is 4 ¾” (depth of cutout) Panel MK 29-2 - 4 1/16” dim is 4 ¾” (depth of cutout) Panel MK 30-2 - 1’ 6 ¼” dim is 1’ 7 ¼” (dim. of open area on side with toe plate) Panel MK 34-2 - 5’ 1” dim is 5’ 1 5/16” (distance from outside edge to start of cutout) -1’ 6 5/16” dim is 1’ 7” (depth of cutout) Panel MK 35-2 - 3’ 0” dim is 3’ ½” (width of grate) -5 ½” dim is 6” (depth of cutout) Panel MK 36-2 - 8” dim is 7 5/16” (distance from outside edge to start of cutout) Panel MK 41-2 - 1’ 3 ¼” dim is 1’ 2 5/8” (width of grate) Panel MK 40-2 - 1’ 2 ¼” dim is 1’ 2 5/8” (width of grate) Panel MK 39-2 - 1’ 10” dim is 1’ 9 ½” (distance from outside edge to start of cutout) Dimensional tolerance: +/- ¼” per MBG 531-09 Square tolerance: ¼” per MBG 531-09 Drawings Q240-GRTG-02-2 R.0, Q240-GRTG-02-3 R.0 Refernce WEC APP-Q240-SS-217 R.1, item #s Mk. GR. 21 through GR. 42.	Use as is	This is for SV3. Condition #1. A review of the individual panels and how they fit on the frame was completed. No clashes or interferences were found, the results can be viewed on the following attachments: Summary of individual panels & Q240 Unit 1 Grating Pics. Disposition is Use as is. Condition #2. A review of the installed panels was performed and yielded the following attachment. Grating layout on Module Q240. I would suggest that the layout of the panels on the module is acceptable. Use as is.

Defect Code	NCR #	Module	Description	Proposal	Disposition Details
2D	0161	Q240	Valve S/N"s BN222 and BN223 (both APP-PV01-Z0D-116 valves) are missing the required hole in their wedge disc plate. This hole is to provide internal equalized pressure in the stem body cavity, as per note 6 of drawing SV3-Q240-RNS-PLW-01 Rev. 1. Note number 5 on Westinghouse drawing number APP-RNS-PLW-014 Rev. 7 also explains the requirement for this disc plate hole to be present and installed on the upstream side. Section 8.0, note 8, of APP-PV01-Z0D-116 Rev. 5 (PV01 Datasheet 116) also explains the requirement for a hole to be drilled into the wedge disc plate. See attached pictures of missing wedge disc plate holes, as well as what the acceptable condition should look like. Reference documents: SV3-Q240-RNS-PLW-01 Rev. 1, APP-RNS-PLW-014 Rev. 7, and APP-PV01-Z0D-116 Rev. 5 (PV01 Datasheet 116). Applicable Traveler/Module: A00002X40-005/Q240 (X40)	Other	The customer has provided us with a letter which permits us to continue work (see attached). The final disposition will be provided by the customer at a later date. The disposition is other.
2D	0163	Q223	During Fit-up Inspection of BOM# 2271-2 it was noted that the N-E hole was out of tolerance as per WI30 Rev 4 Para 4.2 "Drilled hole diameter tolerance is + 1/32", -0" unless otherwise specified" The N-E hole at its smallest diameter was measured to be 2.063" and its required to be 2.125". This plate is tacked on in place on the A23 frame. A0000-2A23-002 VS2	Re-work	An addendum will be added to TRV-A00002A23-002 to instruct the shop to increase the size of the hold on plate 2271-2. QC shall inspect the plate after removal of material.

Code	NCR #	Module	Description	Proposal	Disposition Details
2D	0396	Q305	Module A05 The partner Drawing: VS2-Q305-CVS-PLW-106-00 Rev.2 WECTEC Drawing: APP-CVS-PLW-106 Rev.3 During CFM/PFM inspection of A05 material, spool VS2-CVS-PLW-106-1R was found to have the following non-conforming conditions: •Valve orientation wrong. DWG states (STEM E 25deg UP), Valve is 25deg West, Down.	Repair	An Addendum will be added to TRV-A00002A05-004 to repair the non-conforming parts per N&D APP-CVS-GNR-850015. The stem will be rotated to reflect APP-CVS-PLW-106 Rev 3 and VS2-Q305-CVS-PLW-106-00 Rev 2 orientation. This is for VS2.
2D	0441	Q240	Two APP-PV01-Z0D-116 valves, serial #s BL273 and BL258 were identified upon receipt at shop as being damaged. OS&D 819 was generated to document this condition. N&D #s APP-Q240-GNR-850031 R.0 & APP-Q240-GNR-850032 R.0 were subsequently generated. See attached N&Ds that contain OS&D 819.	Other	As per the N&D #s APP-Q240-GNR-850084 R.0 & APP-Q240-GNR-850085 R.0, scope of this non-conforming condition shall be transferred to site. This is for VS2.
2D	0593	Q223	The partner Drawing: VS3-Q223-PXS-PLW-02 Rev. 0 WECTEC Drawing: APP-Q223-V0-001 Rev. 9 Spool VS3-PXS-PLW-02Y-1 : Various thru-holes on flange have sharp burring on both sides. Raised flange face side has mechanical damage (0.450'' X 0.180'' X 0.015'').	Repair	Disposition to NCR given in N&D APP-Q223-GNR-850090. "The design authority has reviewed the non-conforming condition and approves a "Repair" disposition. The gouge at the edge of the flange face shall be ground to remove any sharp edges... In addition, all burring shall be removed at bolt hole locations." N&D APP-Q223-GNR-850090 is attached. Unit: VS3
2D	0594	Q223	The partner Drawing: VS3-Q223-PXS-PLW-02 Rev. 0 WECTEC Drawing: APP-Q223-V0-001 Rev. 9 SV3-PXS-PLW-02Y-2B : Drawing VS3-Q223-PXS-PLW-02 Rev. 0 specifies that this hand wheel should be facing east. Actual spool has hand wheel rotated 180 degrees, facing west.	Use as is	N&D APP-Q223-GNR-850110 allows for the valve and handwheel to remain in the current orientation. This valve orientation is acceptable; disposition "use-as-is". Unit: VS3

Defect Code	NCR #	Module	Description	Proposal	Disposition Details
2D	0624	KB36	During CFM/PFM it was noticed that on all three flange faces on APP-PCS-PLW-111 the serrations on the flange face have been blasted away in some areas. This is in violation of ASME B16.5-1996 / ASME B16.5a-1998 addenda clause 6.4.4.3 See attached for locations of blasted areas on flange surface The partner DWG: SV4-KB36-PCS-PLW-03 Rev 1 Wec Tec DWG: APP-PCS-PLW-111 Rev 2	Re-work	The 3 flange faces of SV4-PCS-PLW-111-1 shall be machined as to produce a surface finish of 3.2 - 6.3 microns with 45 - 55 grooves/in. Maximum removal shall not exceed 1/32". These flanges are installed into an ASME B31.1 spool. This is for SV3.
2D	0662	Q305	TRV-A00002A05-015 Rev.0 Op# 95 Drawing #: •VS2-Q305-CAS-PLW-83A-00 (WEC REF. DWG: APP-CAS-PLW-83A R.3) •VS2-Q305-CAS-PLW-PNEU-83A-1 R.3WEC REF. DWG: APP-Q305-V0-001 & 002 R.7) Item •CAS-PL-V034 (part of Item 1, commodity code CAS-PLW-83A-1) Condition expected: Ball valve should be able to close properly Condition found: Handel of ball valve is obstructed when trying to close it Please see attached	Repair	The partner will repair valve CAS-PL-V03 by removing the valve handle and rotating it 180 degrees, thus allowing the ball valve to close properly.

Defect Code	NCR #	Module	Description	Proposal	Disposition Details
2D	0829	KB36	N&D No.: APP-KB36-GNR-850124 Rev. 0 N&D Title: KB36 SV4-PCS-PLW-10M Coating During CFM/PFM materials inspection, it was observed that SV4-PCS-PLW-10M-1 was coated and shall not be per APP-G10PX-003 as it is alloy steel. A similar condition existed on previous units please reference APP-KB36-GNR-850016.	Re-work	As per N&D APP-KB36-GNR-850124, pipe shall have paint removed by blasting in accordance with WI-025. All open ends and valves shall be capped or bagged as to prevent damage and or FME violation. This is accordance with specification in APP-G1-PX-003. This is for SV4.
2D	1040	KB36	TRV-A00002Y36-016, R.0 Op. 130 Module KB36 (Y36) - Hydrotest 6 UNIT: SV4 An indentation to spool SV4-FPS-PLW-61E-1 for module Y36 was noticed that was inadvertently missed during receiving of materials. Depth of indentation was measured to be approx. 0.050". This would be a vendor supplied issue since the damage is under the vendor applied paint and that there is no paint damage apparent to the area in question. Spool indentation was discovered post hydrotest. See attached photo.	Other	As per attached UT report, indentation is above minimum wall - therefore the defect is a dent. The depression is blended smoothly with surrounded area. Nominal inside diameter is 6.065". Depression depth of 0.050" is less than 1% of nominal inside diameter. The depression has passed MT examination. As per APP-GW-P0-008 Appendix B, Section B.1 - this indentation is acceptable. Disposition: Meets Requirements. This is for SV4.

Code	NCR #	Module	Description	Proposal	Disposition Details
2I	0393	Q305	Module A05 The partner Drawing: VS2-Q305-CVS-PLW-100-00 Rev.1 WECTEC Drawing: APP-CVS-PLW-100 Rev.3 During CFM/PFM inspection of A05 material, spool VS2-CVS-PLW-100-1A was found to have the following non-conforming conditions: * Item 1 & 3 have the same commodity code (CVS-PLW-100-1A). * Elbow "to be welded at site" is already welded (see attached drawing). * Spool VS2-CVS-PLW-100-1A extends longer than drawing depicts (see attached drawing). * More details required for the flange orientation on drawing. During CFM/PFM inspection of A05 material, spool VS2-CVS-PLW-100-1B was found to have the stem on the attached valve CVS-PL-V083 facing the incorrect direction. The drawing requires the stem to be facing East, 22.5° to the South. The actual orientation of the stem is West, 22.5° to the North.	Repair	Non-Conforming conditions: Item 1 & 3 have the same commodity code (CVS-PLW-100-1A) and more details required for the flange orientation on drawing. Proposal- The partner's drawing VS2-Q305-CVS-PLW-100-00 will be re-vised to Rev 2 to update the commodity codes for items 1 & 3 as well as a flange detail will be added. Non-Conforming conditions: Spool VS2-CVS-PLW-100-1A extends longer than drawing depicts. Proposal- Based on drawing VS2-Q305-CVS-PLW-100-00 spool VS2-CVS-PLW-100-1A extends the correct distance and will be reinspected to confirm. Non-Conforming conditions: Elbow "to be welded at site" is already welded and during CFM/PFM inspection of A05 material, spool VS2-CVS-PLW-100-1B was found to have the stem on the attached valve CVS-PL-V083 facing the incorrect direction. The drawing requires the stem to be facing East, 22.5° to the South. The actual orientation of the stem is West, 22.5° to the North. Proposal- An Addendum will be raised to grind remove weld to be completed at site and to repair spool VS2-CVS-PLW-100-1B by rotating valve CVS-PL-V083. This if for VS2.

Code	NCR #	Module	Description	Proposal	Disposition Details
2I	0400	Q305	Module X05 The partner Drawing: SV3-Q305-CAS-PLW-083A-00 Rev.2 WECTEC Drawing: APP-CAS-PLW-83A Rev.3 During CFM/PFM inspection of X05 material, spool SV3-CAS-PLW-083A was found to have the following non-conforming conditions: Condition Expected: Valve CAS-PL-V034 Stem Up Condition Found: Valve CAS-PL-V034 Stem East	Repair	An Addendum will be added to TRV-A00002X05-005 to repair the non-conforming spool. This is for SV3.
2I	0434	KB36	As per N&D APP-PCS-GNR-850002, WECTEC has identified the following condition for item SV3-PCS-PLW-10M-1: Pipe spool A as fabricated is 5. 1/2" long instead of 5. 15/16" as shown on the drawing APP-PCS-PLW-10M. Pipe spool C as fabricated is 7. 1/2" long instead of 8. 3/16" as shown on the drawing APP-PCS-PLW-10M See attached markup of the as-built drawing.	Re-work	As per N&D APP-PCS-GNR-850002, spool SV3-PCS-PLW-10M-1 shall undergo the following rework: Spool shall be cut at WEC weld 4, 5, 7 and 8 as described in the attached N&D. The sections between WEC welds 5 and 7, and 4 and 8 shall be scrapped and replaced with longer pieces to bring the overall dimension into conformance. Joints shall be prepared as per the ASME B31.1 joint detail and re-welded using an appropriate WPS for A335 P11 material. The welds shall be visually inspected following welding. Production drawings shall be updated to reflect this repair. This pipe conforms to ASME B31.1 specification. This is for SV3.

Defect Code	NCR #	Module	Description	Proposal	Disposition Details
2I	0449	KB36	DWG; SV3-KB36-PCS-PLW-02 B.O.M item 7C commodity code PCS-PLW-111-2 Ref. DWG; APP-KB36-V0-001 As per Manufacturing specialist request, inspection was performed on spool item 7C commodity code PCS-PLW-111-3 and was found to be out of tolerance. The Drawing indicates that it should be 12" from the face of the flange to the center of the elbow. The actual measurement is 15", therefore rendering it out of tolerance See Attach picture for additional information	Re-work	Extension of non-conformance description: SV3-PCS-PLW-111-1 also has a non-conforming dimension. Dimension from center of tee to flange face (the 3' 7 13/16" dimension) is actually 3'-11 13/16". Disposition. As per APP-KB36-GNR-850027, the non-conforming spools SV3-PCS-PLW-111-1 and SV3-PCS-PLW-111-2 (see NCR A00002-000-0447-00 for identification non-conformance) shall be re-worked so that they are in conformance. Rework shall be as follows for SV3-PCS-PLW-111-1: 1.Identification markings shall be transferred to areas outside of that which is identified in step 2. 2.Spool shall be cut at the tee, WEC weld 9. Pipe material shall be removed as to bring the final dimension into conformance. Allowances for fit-up and weld shrinkage shall be observed. Machine weld prep of both halves. 3.Perform PT on machined surfaces. 4.Fit and tack weld joint 5.Perform VI. 6.Weld complete. 7.Perform VI on final weld. Rework shall be as follows for SV3-PCS-PLW-111-2: 1.Identification markings shall be transferred to areas outside of that which is identified in step 2. 2.Spool shall be cut 1.5 inches from weld joint 11. Pipe material shall be removed as to bring the final dimension into conformance. Allowances for fit-up and weld shrinkage shall be observed. Machine weld prep of both halves. 3.Perform PT on machined surfaces. 4.Fit and tack weld joint 5.Perform VI.

Code	NCR #	Module	Description	Proposal	Disposition Details
2I	0497	Q305	Traveler: TRV-A00002X05-004 Rev. 1 Operation: 45 The partner Drawing: SV3-Q305-CVS-PLW-100-00 Rev. 5 Westinghouse Drawing: APP-CVS-PLW-100 Rev. 9 Affected Items: spool SV3-CVS-PLW-100-1B, spool SV3-CVS-PLW-100-1C, Valve CVS-PL-V045 (APP-PV14-Z0D-101) The Westinghouse drawing above shows the valve (CVS-PL-V045) item #12 to be a length of 15 3/4". However, the actual measured length of the valve is 14 1/2". Splitting the difference of measured length to each side of the valve fit up will leave the overall length of the line short by 5/8". The required overall length of the line should be 3'-6 9/16".	Repair	This is for SV3. Addendum 6 on TRV-A00002X05-004 has been raised to do the repairs to spool PLW-100 as per N&D APP-Q305-GNR-850029.
2I	0500	Q305	Traveler: TRV-A00002A05-004 Rev. 0 Operation: 45 The partner Drawing: VS2-Q305-CVS-PLW-100-00 Rev. 3 Westinghouse Drawing: APP-CVS-PLW-100 Rev. 9 Affected Items: spool VS2-CVS-PLW-100-1BR, spool VS2-CVS-PLW-100-1C, Valve CVS-PL-V045 (APP-PV14-Z0D-101) The Westinghouse drawing above shows the valve (CVS-PL-V045) item #12 to be a length of 15 3/4". However, the actual measured length of the valve is 14 1/2". Splitting the difference of measured length to each side of the valve fit up will leave the overall length of the line short by 5/8". The required overall length of the line should be 3'-6 9/16".	Repair	L049 has been received with additional material as it was spooled through to the length for the middle of CVS-PL-V045. The partner proposes a rework to cut L049 1 1/4" longer than drawing APP-CVS-PLW-100 calls for. This will result in spool in CVS-PL-V045 being out of drawing location by 5/8" but overall spool CVS-PLW-100 will be correct dimensions.

Defect Code	NCR #	Module	Description	Proposal	Disposition Details
2I	0546	KB36	Customer Reference: APP-PCS-PLW-111 As per manufacturing specialist request, inspection has yielded the following conditions. Condition 1: According to isometric drawing, VS2-PCS-PLW-111-1 is suppose to have a dimension of 3' - 7 13/16" between the face of flange (at item 10) to center of tee (item 5). Actual dimension is 3' - 11 13/16". Condition 2: VS2-PCS-PLW-111-3 is mislabelled VS2-PCS-PLW-111-2. Condition 3: According to isometric drawing, VS2-PCS-PLW-111-3 is supposed to have dimension of 12" from the face of flange (at item 10) to the center of elbow (item 6). Actual dimension is 15". This is for VS2. See attached photos.	Re-work	The non conforming spools shall be re-worked so that they are in conformance. Rework shall be as follows for VS2-PCS-PLW-111-1: 1.Identification markings shall be transferred to areas outside of that which is identified in step 2. 2.Spool shall be cut at the tee, WEC weld 9. Pipe material shall be removed as to bring the final dimension into conformance. Allowances for fit-up and weld shrinkage shall be observed. Machine weld prep of both halves. 3.Perform PT on machined surfaces. 4.Fit and tack weld joint 5.Perform VI. 6.Weld complete. 7.Perform VI on final weld. 8. Remark as VS2-PCS-PLW-111-1R1 then remove all markings for VS2-PCS-PLW-111-1. Rework shall be as follows for VS2-PCS-PLW-111-2: 1.Identification markings shall be transferred to areas outside of that which is identified in step 2. 2.Spool shall be cut 1.5 inches from weld joint 11. Pipe material shall be removed as to bring the final dimension into conformance. Allowances for fit-up and weld shrinkage shall be observed. Machine weld prep of both halves. 3.Perform PT on machined surfaces. 4.Fit and tack weld joint 5.Perform VI. 6.Weld complete. 7.Perform VI on final weld 8. Remark as VS2-PCS-PLW-111-3R1 then remove all markings for VS2-PCS-PLW-111-2. Note that this condition is identical as that found in APP-KB36-GNR-

Code	NCR #	Module	Description	Proposal	Disposition Details
2I	0627	KB36	During CFM/PFM it was noticed that on SV4- APP-PCS-PLW-111 the referenced dimension in the NCR drawing attachment (APP-PCS-PLW-111 Rev 2) actually measures 4’. The actual dimension is exceeding the specified (3’ 7 - 13/16’’) with tolerance (1/8’’) by 4 -1/16’’ The partner DWG: SV3-KB36-PCS-PLW-03 Rev 1 Wec Tec DWG: APP-PCS-PLW-111 Rev 2	Re-work	SV4-PCS-PLW-111-1 shall be reworked to bring dimensions into conformance via the following steps: 1. Markings shall be transferred so as to maintain traceability. 2. Butt weld at Wec weld 9 shall be cut and material shall be cut to bring the 3' 7 13/16" dimension into conformance. 3. The joint shall then be re-welded at Wec weld 9. Visual inspection shall be performed at the weld. 4. The spool shall be relabeled as SV4-PCS-PLW-111-1R1. This is an ASME B31.1 pipe. This is for SV3.
2I	0630	KB36	Traveler: A00002X36-006 Rev 1 Operation# 140 The partner drawings # SV3-KB36-PCS-PLW-01 Rev 4, SV3-KB36-PCS-PLW-01-02X Rev 3 The partner Item # 10 (PIPE SPOOL SMLS, S80/S40, A335P11/A234WP11) Commodity code# SV4-PCS-PLW-10T-1 WEC drawing# APP-KB36-V0-001 Rev 6 See attached BF SHAW Drawing (Pg 5), Item: H, 2” 90 3,000# SW elbow Item: A1, 2” XS. Condition effects Weld # 8 Condition Found: It was noticed that when fabrication was going to install Item# 10 (SV4-PCS-PLW-10T-1) that the 2” run of pipe was found to be out by 2.5° East. The location of the pipe was also verified to be out of center by 3 ¼” East, from the centerline of support Item # 18 on dwg# SV3-KB36-PCS-PLW-01-02X.	Re-work	Location of 2" pipe is 3 1/4" east of location at support PCS-PH-12R0195. No deviation in elevation is present. The socket weld at WEC weld 8 shall be removed and pipe section 4 shall be rotated at WEC weld 8 to bring location at support PCS-PH-12R0195 into tolerance. WEC Weld 8 shall be re-welded and visually inspected. Pipe is fabricated to ASME B31.1. This is for SV3.

Code	NCR #	Module	Description	Proposal	Disposition Details
2I	0689	Q223, Q233	Per WECTEC N&D # APP-PXS-GNR-850021: VS3-PXS-PLW-02X-2 has a std. flange (10.5” raised face) in lieu of a special flange (13.7” raised face). In addition to that, SV4-PXS-PLW-010-1B has a special flange (13.7” raised face) in lieu of a std. flange (10.5” raised face). These need to be swapped to meet design requirements. This is not a condition caused by the partner but rather received as this is CFM/PFM material. This will affect VS3-Q223 and SV4-Q233 modules.	Repair	assembly drawings shall be revised to capture material changes. An addendum shall be issued to instruct on the fabrication activities for swapping the flanges. -The ISI/PSI markings shall be removed from Flange with Serial Number AP615 in accordance with all purchase order, design/fabrication specification, code and regulation requirements. Care shall be taken to maintain minimum wall thickness at these areas. -If any markings are identified on Flange with Serial Number AP615 identifying it as VS3-PXS-PLW-02X, they shall be removed in accordance with all purchase order, design/fabrication specification, code and regulation requirements. Care shall be taken to maintain minimum wall thickness at these areas. - Flange with Serial Number AP615 shall be beveled in accordance with all purchase order, design/fabrication specification, code and regulation requirements. (Including APP-GW-VFY-001) -Inspection of the weld prep shall be done in accordance with all purchase order, design/fabrication specification, code and regulation requirements. -Markings shall be added to the flange to identify the flange as SV4-PXS-PLW-010-1BR1 in accordance with all purchase order, design/fabrication specification, code and regulation requirements. -This is the authorization for installation of SV4-PXS-PLW-010-1BR1 into module SV4-1124-Q233. The “remarks” section on the N-5 Data Report for the PXS system of SV4-1124-Q233 shall identify the modification performed on SV4-PXS-PLW-010-1B in accordance with APP-PXS-GNR-850021. -The CMTRs and test reports are attached herein for Flange with serial number AP615.

Defect Code	NCR #	Module	Description	Proposal	Disposition Details
2I	0690	Q223	Per N&D APP-Q223-GNR-850082: Dimensions of 8” squib valve weld neck flange are defined by ANSI B16.5 Class 2500 Forged Flanges. The flange raised face diameter is 13.72” as shown in APPPV7B-V6-001. The actual diameter is measured to be 10.5”. The squib valve flange is on module VS3-Q223 and spool VS3-PXS-PLW-02X-2 as shown in APP-PXS-PLW-02X drawing. However, it is marked as VS3-PLX-PLW-02X-2.	Repair	Disposition Repair per WECTEC N&D # APP-PQ223-GNR-850082. Piping assembly drawings shall be revised to capture material changes. An addendum shall be issued to instruct on the fabrication activities for swapping the flanges. To address the incorrect marking of the piping assembly: -The code data plate and etching below the plate are shown in the attached photo. The temporary markings contain a typographical error, and the wrong marking shall be removed using an approved cleaning procedure in accordance with all purchase order, design/fabrication specification, code and regulation requirements. The incorrect marking may be corrected using an approved marking procedure; or the entire temporary marking may be removed. To address the incorrect flange installed on VS3-PXS-PLW-02X-2: -Remove Weld 11 as shown on isometric APP-PXS-PLW-02X between the pipe and the flange in accordance with all purchase order, design/fabrication specification, code and regulation requirements. -The severed flange with S/N AP615 will be tagged in accordance with approved procedures and reworked in accordance with N&D APP-PXS-GNR-850021. -The ISI/PSI markings shall be removed in accordance with all purchase order, design/fabrication specification, code and regulation requirements. Care shall be taken to maintain minimum wall thickness at these areas. After these markings are removed, the wall thickness shall be verified using approved procedures in accordance with all purchase order, design/fabrication specification, code and regulation requirements. -The remaining portion of VS3-PXS-PLW-02X-2 (piping portion) shall be beveled in accordance with all purchase order, design/fabrication specification, code and regulation requirements. (Including APP-GW-VFY-001)

Code	NCR #	Module	Description	Proposal	Disposition Details
2I	0697	KB36	Traveler#: TRV-A00002A36-008 Rev 0 Operation #: 5 Drawing # :VS2-KB36-PCS-PLW-04 Rev 0 Drawing Item #: 1 WEC Reference Drawing # APP-PCS-PLW-112 Rev 2 Non-conforming condition: It was noticed that spool VS2-PCS-PLW-112-1 was found to be dimensionally out of tolerance as shown on the attached WEC reference drawing. Expected dimension: 2' 1 – 1/2" with a tolerance of +/- 0.3125" Actual dimension: 2' - 7/8" Note: that Dim was taken from flange face centers.	Re-work	Identification markings shall be copied to either side of WEC Weld 18 (18R) and the spool shall be cut at WEC weld 18 (18R). Tee and pipe shall be re-prepared and the spool shall be re-fit to correct the position at the PCS-MP-01B flange. The weld shall be re-welded using an appropriate WPS and visually inspected in accordance with ASME B31.1 acceptance criteria. This is for VS2.
2I	0698	KB36	Traveler#: TRV-A00002A36-006 Rev 0 Operation #: 10 Drawing # :VS2-KB36-PCS-PLW-01 Rev 1 Drawing Item #: 9 WEC Reference Drawing # APP-PCS-PLW-10D Rev 2 Non-conforming condition: It was noticed that spool VS2-PCS-PLW-10D-1 was found to be dimensionally out of tolerance as shown on the attached WEC reference drawing. Expected dimension: 2' 1 – 1/2" with a tolerance of +/- 0.3125" Actual dimension: 2' 2- 1/8" Note: that Dim was taken from flange face centers.	Re-work	Following copying identification markings on either side of WEC Weld 15 (15R), the spool shall be cut at WEC weld 15 (15R). The pipe side of WEC weld 15 (15R) shall be cut, re-prepared, and the spool shall be re-fit to correct the position at the PCS-MP-01B flange. The weld shall be re-welded using an appropriate WPS and visually inspected in accordance with ASME B31.1 acceptance criteria. This is for VS2.
2I	0699	Q223	TRV-A00002B23-006 Rev. 0, Op. 15 – Fabrication to pick material. Drawing: VS3-Q223-PXS-PLW-01 Rev. 0 During the picking of material operation for B23, fabrication found a customer supplied spool to have non-conforming dimensions. Spools VS3-PXS-PLW-02X-1 and VS3-PXS-PLW-02U-2 are not level with each other, causing the two flange faces to be offset. See attached pictures for more details and measurements.	Repair	The partner proposes a Repair disposition. In order to correct the alignment issue of parallel spools VS3-PXS-PLW-02U-2 and VS3-PXS-PLW-02X-1, WEC weld 4 on APP-PXS-PLW-02X shall be cut, the angular deviation corrected and the spool re-welded. The proposed action will level the parallel spools and correct the angle of the offset flange face. The improved fit-up will benefit installation of the Squib Valves at site. Unit: VS3

Code	NCR #	Module	Description	Proposal	Disposition Details
2I	0700	KB36	Traveler#: TRV-A00002X36-008 Rev 1 Operation #: 10 Drawing # : SV3-KB36-PCS-PLW-04 Rev 1 Drawing Item #: 1 WEC Reference Drawing # APP-PCS-PLW-112 Rev 2 WEC ITEM # 11 Non-conforming condition: It was noticed that Item # 11 (Ball Valve handle) on the above mentioned WEC reference DWG for spool SV3-PCS-PLW-112-1, was found to have interference with the frames center wall shown in the attached pictures. Expected Condition: To be able to position the spool for fit up approximately another ¾" West without any interference from the modules frame.	Repair	Valve is built to specification of PV40-Z0D-404. The handwheel and upper mechanism for PCS-PL-V047B shall be rotated 90 deg clockwise looking down. This is for SV3.
2I	0702	KB36	Traveler#: TRV-A00002A36-006 Rev 0 Operation #: 10 Drawing # : VS2-KB36-PCS-PLW-02-01X Rev 1 & VS2KB36-PCS-PLW-02 Rev 0 Drawing Item #:10 (PCS-PLW-10U-1R) WEC Reference Drawing # APP-KB36-V0-001 Rev 6 & APP-PCS-PLW-10U Rev 2 WEC ITEM # 15 Non-conforming condition: It was noticed that on spool VS2-PCS-PLW-10U-1R when referenced to the dimensions on the WEC REF DWG listed above that dimension #s 137 & 81 (5-3/8" & 3-3/16") are reversed Expected Condition: To be built within tolerance as shown on the ISO drawings.	Re-work	WEC welds 9 (9R) and 15 (15R) shall be removed tee shall be rotated to bring the rise and run into conformance. This will cause the valve stem orientation to not be vertical. Therefore, WEC weld 12 (12R) shall be removed and the valve shall be re-orientated to vertical. WEC welds 9 (9R), 15 (15R), and 12 (12R) shall be re-welded using an appropriate WPS and visually inspected in accordance with ASME B31.1 acceptance criteria. This is for VS2.

Code	NCR #	Module	Description	Proposal	Disposition Details
2I	0756	KB36	Traveler#: TRV-A00002A36-006 Rev 0 Operation #: 25 Drawing # :VS2-KB36-PCS-PLW-04 Rev 1 Drawing Item #: 2 (PCS-PLW-10W-1) WEC Reference Drawing # APP-PCS-PLW-112 Rev 2 WEC Item # : 9 & PCS-MP-01B /N2 1IN RFFE CL150 Non-conforming condition: It was noticed that the riser section that conects to pump APP-PCS-MP-01B is out of level by approximately 3 deg over the riser length and its throwing the alignment of the flange to the pump face flange connection (see attached picture) Expected Condition: To be built correctly and align the flange "Item 9" to the pump "PCS-MP-01B /N2 1IN RFFE CL150" shown on the above WEC reference drawing.	Re-work	Flange misalignment is approximately 1/2". In order to align the flanges, Wec weld 33 shall be removed, the joint re-prepared and inspected as per ASME B31.1 and re-welded using an appropriate WPS. Spool is constructed and inspected to ASME B31.1. This is for VS2.
2I	0769	KB36	Traveler#: TRV-A00002X36-009 Rev 1 Operation #: 120 Drawing # : SV3-KB36-PCS-PLW-05 Rev 1 Drawing Item #: 1 WEC Reference Drawing # APP-PCS-PLW-10K Rev 1 WEC Reference Drawing Item # 1 &4 Non-conforming condition: It was noticed that spool SV3-PCS-PLW-10k-1 was found to be sloping out of tolerance after the weld that connects Item # 1 to Item # 4 on the WEC drawing referenced above. Expected Slope: To be Level Actual Slope: - 0.7 Degrees from level after the weld location mentioned above	Re-work	In its current state, spool will cause the termination point of SV3-DWS-PLW-510-1 to be low by over 1". In order to bring the line into conformance. WEC weld 1 shall be removed, and refit so that the upper floor portion of the pipe is level. The weld shall then be re-welded using an appropriate WPS. The weld is NFPA, but shall be treated as ASME B31.1 for the purposes of this re-work. As such, the weld shall be visually inspected in accordance with ASME B31.1. This is for SV3.

Code	NCR #	Module	Description	Proposal	Disposition Details
2I	0786	KB36	Traveler#: TRV-A00002X36-007 Rev 0 Operation #: 150 Drawing # : SV3-KB36-PCS-PLW-03 Rev 2 Drawing Item #: 6 WEC Reference Drawing # APP-PCS-PLW-10H Rev 1 WEC Reference Drawing Item # 2 &9 Non-conforming condition: It was noticed that the rise of pipe prior to the 6" Bend radius on Item # 2 from on the above mentioned WEC Reference Drawing was found to be sloping out of tolerance Expected condition: To be square and Level Actual Condition: Sloping South by approximately 3°	Repair	In order to bring the pipe and all down stream supports into design intent, WEC socket weld 10 shall be removed, pipe section <6> shall be rotated so that it is vertical, then re-welded at WEC weld 10. The completed weld shall be visually inspected in accordance with ASME B31.1. This pipe is constructed to ASME B31.1. This is for SV3. This is in accordance with N&D APP-KB36-GNR-850126.
2I	0791	KB36	Traveler#: A00002X36- 007 Operation #: 475 Drawing # : N/A Drawing Item #: N/A WEC Reference Drawing # APP-PCS-PLW-10F Rev 2 , APP-PCS-PLW-10V Rev 2 & APP-PCS-PLW-10E Rev 2 WEC Item # : Elbow 6 on dwg 10V & pipe length 2 on dwg 10E Non-conforming conditions: 1.spool SV3-PCS-PLW-10F touches SV3-PCS-PLW-10V at elbow 6. 2.spool SV3-PCS-PLW-10E touches the frame along pipe length 2, near weld 6. Expected Condition: To not touch the other pipe.	Repair	Condition 1: condition is caused from support PCS-PH-12R0221 being low by 5/16". If pipe is raised by raising support PCS-PH-12R0221, a gap of 5/16" between the two pipes is achievable. To raise the support, the existing plate shall be removed and replaced with a plate that is 5/16" thicker. This is an ASME Section III, NF support. All welding and inspection shall be in accordance with ASME Section III, NF, CL 3. Condition 2: As per N&D APP-KB36-GNR-850116, Condition shall be use-as-is. This is for SV3.

Code	NCR #	Module	Description	Proposal	Disposition Details
2I	0849	KB36	TRV-A00002A36-009 DWG# VS2-KB36-DWS-PLW-01 R.1 Pipe Spool# VS2-DWS-PLW-510-1 CB&I supplied spool VS2-DWS-PLW-510-1 has a section of pipe after a weld that is not level as required, it is 1 1/2 deg. out (low). At Weld #5 connecting IT#1 (pipe) to IT#11 (ball valve) as per WECTEC dwg# APP-DWS-PLW-510 R.3 the pipe is 1 1/2 deg. out of level, pointing down, which is not acceptable as per note #1 on DWG#. VS2-KB36-DWS-PLW-01 R.1	Re-work	Deviation of 1.5° at Wec weld 5 will cause termination point of VS2-DWS-PLW-510-1 to be low by over 3 1/16". In order to correct the deviation, WEC weld 5 shall be cut, the joint re-prepared and re-welded. Rework shall be in accordance with ASME B31.1. All inspection shall be in accordance with ASME B31.1. This is for VS2.
2I	0860	Q305	TRV-A00002Y05-004 Op. #25 DWG# SV4-Q305-CVS-PLW-100-00 -Spool 100 overall length is going to be short 1 ¼”. E&DCR APP-CVS-GEF-850037 states the valve is a 1 ¼” shorter than originally design and to “use as is” however both spools have been cut and prepped for previous valve length. WECTEC DWG# APP-CVS-PLW-100 R.0	Repair	To propose “Repair” due to the reduced length of CVS-V045 and spools CVS-PLW-100-1A and CVS-PLW-100-1B being supplied with no excess piping material and prepped for previous length of valve CVS-V045. Valve CVS-V045 as-built location will move 5/8” North of the design location, Spool CVS-PLW-100-1B will be cut and prepped 1” shorter than received and fabrication will add a spool piece 2 ¼” long with added butt weld.
2I	0984	KB36	TRV-A00002Y36-006 R.0 Spool: SV3-PCS-PLW-10T-1 REF DWG: APP-PCS-PLW-10T R.3 Item 1 and Item 4 found to be 2.10˚out of parallel. Note: Item numbers assigned according to APP-PCS-PLW-10T R.3	Re-work	WEC weld 8 shall be removed and section 4 (as per WEC isometric) shall be rotated to bring the spool into conformance. The joint shall be re-welded and inspected in accordance with ASME B31.1. Spool is constructed to ASME B31.1. This is for SV4.

Code	NCR #	Module	Description	Proposal	Disposition Details
2I	1118	Q601	Module: Q601 Unit X01 Traveler: TRV-A00002X01-013 Item # 40 (Westinghouse DWG # APP-RCS-PLW-080 R.0) has not been fabricated correctly. For DWG # APP-RCS-PLW-080 R.0 item 1, pipe is off 9/16'' out of plane when measured at the vertical position. Drawings: SV3-Q601-RCS-PLW-03 R.2,	Repair	In this case the only weld by the partner is W1121 (ISI) which is between Item 43 (valve V011A; Commodity Code: PV01-Z0D-103) & Item 40 (pipe spool; Commodity Code: RCS-PLW-080-1A). The pipe spool as supplied by Wectec is out of vertical plane by 9/16" (see attached photos). To correct the deviation and allow for the fit-up of spool RCS-PLW-080 to RCS-PLW-013, WEC weld 4 shall be removed (see attached) and the spool dimensions shall be corrected. Joint shall be re-prepared in accordance with ASME Section III, NB and PO requirements and re-welded. The finished weld shall be subject to ISI requirements and all other ASME Section III, NB and PO inspection requirements. This is for SV3.
5A	0922	Q223	N&D No.: APP-Q223-GNR-850120 Rev. 0 N&D Title: [Partner to WEC] Damaged Topworx Sensor on Valve SV4-PXS-PL-V013B (S/N BP117) TRV-A00002Y23-010 OP# 385 DWG# SV4-Q223-PXS-PLW-02 r.3 WEC DWG# APP-Q223-VO-001 r.9 Valve PV03-Z0D-104 S/N BP117 was found to have a bent sensor during a customer inspection. This issue has been documented in N&D APP-Q223-GNR-850120.	Other	Disposition as per N&D APP-Q223-GNR-850120: Scrap both proximity switches on valve SV4-PXS-PL-V013B and replace with like proximity switches. The proximity switches are identified as item 32 on SV0-PV03-V2-104002 revision 0. Although the valve is ASME Sec. III Class 1, the switches are not within the code boundary. By performing the replacement of the switches, there is no impact to form, function, fit or interchangeability of the valve. This work shall be completed at site by an authorized repair agency. Unit: SV4

Defect Code	NCR #	Module	Description	Proposal	Disposition Details
5B	0003	Q240	During receiving inspection of this spool (VS2-RNS-PLW-421-1), it was found that the 'As-Built' spool did not match the drawing. The drawing requires the spool to run North and bend East at bend #5. However, the 'As-Built' spool runs North and then bends upward in direction. See attached drawing and picture for reference. The NPP-1 Data Report for this spool (VS2-RNS-PLW-421-1) has additional information added to it after the ANI sign off. See Data Report attached.	Other	Disposition sent to CBI to advise. CBI N&D APP-Q240-GNR-850006 Rev. 0. No further action required by the partner. The corrected NPP-1 Data Report is attached for reference and the conforming spool will be re-turned to CB&I-Laurens for rework. Spool sent to CB&I-Laurens on 19-Oct-15. Bill of Lading attached.
5B	0248	Q223	"WECTEC supplied spools have been received by the partner with raised face dimensions which do not match adjacent flange faces. Spool SV3-PXS-PLW-02X-2 has been received with a raised face portion approximately 1.5" in radius less than adjacent flange faces. (TRV-A00002X23-006) Spool SV3-PXS-PLW-02Y-1 has been received with a raised face portion approximately 1.5" in radius greater than the adjacent flange face. (TRV-A00002X23-007)"	Other	The partner proposes a three part disposition: 1 - To accommodate fabrication schedule, the equal spools for SV4 will replace the affected SV3 spools. Therefore spools SV4-PXS-PLW-02X-2 and SV4-PXS-PLW-02Y-1 will be installed in module Q223-SV3. 2 - The partner will remove the non-conforming flanges on each of the affected spools and weld them on the opposite spool, therefore resulting in acceptable SV3-PXS-PLW-02X-2 and SV3-PXS-PLW-02Y-1 spools. 3 - The partner will then install spools SV3-PXS-PLW-02X-2 and SV3-PXS-PLW-02Y-1 in module Q223-SV4.

Defect Code	NCR #	Module	Description	Proposal	Disposition Details
5B	0784	Q601	WECTEC N&D # APP-Q601-GNR-850022 R.0 generated to document defects on Customer-supplied spool VS2-RCS-PLW-012-1. Expected condition: spool to be dimensionally acceptable Asctual condition: spool found to have 3 conditions that are dimensionally unacceptable See attached N&D for conditions. WEC dwg. reference APP-RCS-PLW-012 Rev. 5	Use as is	Disposition as per N&D APP-Q601-GNR-850022: • Item 6: 8"x 6" Concentric reducer (6" Sch/160) - ID Measured 5.353" Required 5.328" +/- .01" (OOT) Disposition: Use-as-is - Taper angle Measure 25° Required Max 10° (OOT) Disposition: Use-as-is • Item 5: Prep of elbow (14" Sch/160) - Bevel angle Measured 22° Required 32.5° +/- 7.5°(OOT) Disposition: Use-as-is - Taper angle Measure 20° Required Max 10°(OOT) Disposition: Use-as-is • Item 3: FFW 3 - ID Measured 11.482" Required 11.499" +/- .01" (OOT) Disposition: Use-as-is - Bevel angle Measured 22° Required 32.5° +/- 7.5°(OOT) Disposition: Use-as-is See N&D for justification. Unit: VS2

Defect Code	NCR #	Module	Description	Proposal	Disposition Details
5B	0797	Q601	NCR Generated per N&D # APP-Q601-GNR-850030 Rev. 0. Per N&D # APP-Q601-GNR-850030 Rev. 0: During CFM/PFM of VS2-RCS-PLW-015 the following were measured: "W1" (attachment weld to APP-RCS-PLW-013): Counterbore taper angle 26° requirement 10° W4 Counterbore taper angle 27° requirement 10° W5 Counterbore taper angle 34° requirement 10° W9 Counterbore taper angle 34° requirement 10° FFW (connection to APP-RCS-PLW-017) Counterbore taper angle 24° requirement 10° Counterbore length .601" requirement 2tm Branch of Tee (connection to APP-RCS-PLW-016) ID 6.980" requirement 6.999" +/-.010" Length of branch required 10.3/4" measured ~3". See attached N&D.	Repair	Disposition as per N&D APP-Q601-GNR-850030: --- "W1" (attachment weld to APP-RCS-PLW-013) --- The "W1" joint has been identified to have a taper angle of 26-degrees. A disposition of Use-As-Is is acceptable. --- W4 --- The W4 joint has been identified to have a taper angle of 27-degrees. A disposition of Use-As-Is is acceptable. --- W5 & W9 --- The W5 and W9 joints have been identified to have a taper angle of 34-degrees. The W5 and W9 joints are ISI per APP-RCS-M6X-004. APP-GW-P0-007 required the prep be in accordance with APP-GW-VFY-001 which specifies a fitting taper angle of 10-degree maximum. Additionally, the maximum permitted counterbore taper angle on a component is 30-degrees per NB-4250 (used as guidance for this disposition). Therefore, since the taper exceeds the 30-degree guidance the joints shall be made to conform to APP-GW-VFY-001. Disposition is Repair. Re-inspection shall occur in accordance with all applicable specifications. --- FFW (connection to APP-RCS-PLW-017) --- The tee run connection to RCS-PLW-017 has been identified to have a taper angle of 24-degrees and the counterbore length has been measured to 0.601". Since there is no violation of minimum wall thickness this dimension is Meets Requirements. --- Branch of Tee (connection to APP-RCS-PLW-016) --- The branch ID has been identified as 6.980". Additionally, the length of branch has been measured to be approximately 3". The branch of this tee is not ISI and is a non-interface joint. This dimension Meets Requirements. See N&D for additional justification. Unit: VS2

Defect Code	NCR #	Module	Description	Proposal	Disposition Details
5B	0800	Q305	This NCR generated to document Wectec N&D # APP-Q305-GNR-850075 R.0. Per N&D: During CFM/PFM dimensional inspection, it was discovered that the dimension between the Tee (Item 2) and the valve CAS-PLV-V037 (one of the Item 5s) on APP-CAS-PLW-83A Rev. 3 was measured to be 11.3/4" for the full run outside of the 12.5/8" given. The 6.15/16" dimension was also only measured to be 6.1/2". See attached N&D.	Use as is	As per WECTEC N&D APP-Q305-GNR-850075 the deviation is still in acceptable range for linear deviation. Therefore the conditions shall be use-as-is. This is for SV3.
5B	0946	KB36	SV3-KB36-DWS-PLW-HYD-01 R3 SV3-KB36-DWS-PLW-01 R3, Item 8 WEC No.DWS-PL-V244 Ref Dwg: APP-KB36-V0-001 R6 3" Butterfly valve 150# Serial No 1-5464-7-F PV11-Z0D-108 The orientation of the valve does not conform with the desired flow direction, as per the drawing. Note: Actuator orientation is correct to the drawing See attached pictures	Repair	Valve was only trial fit at the time of disposition, torqueing has not been completed. If the valve is rotated so that the flow direction is conforming, then the actuator orientation will not meet the ISO. In order to bring the flow direction and actuator orientation into conformance as per ISO - the actuator shall be rotated so that the stem is up and handwheel is pointed east while the flow direction meets that of the pipe (i.e. towards the 3"x2" reducer). This shall be done in accordance with the PV11 valve vendors manual. This is for SV3.

Defect Code	NCR #	Module	Description	Proposal	Disposition Details
5B	1101	Q305	As per APP-CVS-GNR-850009: The spool on CB&I-Laurens as-built drawing indicates the piecemark as SV4-CVS-PLW-092-1R1, which is actually SV4-CVS-PLW-092-1R2 (per E&DCR APP-CVS-GEF-207). For the sake of clarity, the spool will be referred to as SV4-CVS-PLW-092-1R2 in this N&D. Customer Furnished Material supplied by CB&I-Laurens did not incorporate APP-CVS-GEF-207 in the As-Built for Spool SV4-CVS-PLW-092-1R2. Attached is the as-built drawing (See attached N&D). * The length of pipe identified as <3> on the as-built drawing is 15-7/8"; APP-CVS-GEF-207 indicates <3> should be 14-3/4". * The length of pipe identified as <4> on the as-built is 6"; APP-CVS-GEF-207 indicates <4> should be 6-1/16". * The length of valve indentified as CVS-PL-V086 on the as-built is 5-29/32"; APP-PV32-V2-131001 indicates valve is 5.91" +/- 0.06". UNIT: SV4-Q305	Use as is	Note: APP-CVS-GNR-850009 was not incorporated into the Y05 module. APP-Q305-GNR-850113 address this and supersedes APP-CVS-GNR-850009. As per N&D APP-Q305-GNR-850113 Background: E&DCR APP-CVS-GEF-207 Rev.0 was not incorporated during the fabrication of the piping on the Q305 module, impacting the overall length of piping line CVS-PL-L522 and location of piping support APP-CVSPH-11R7075. The off module support design location is clashing with the as-built location of valve CVSPL-V086 and will be relocated 0'-0 ¾" in the positive (Z) plant global coordinate system. Note: E&DCR APP-CVS-GEF-207 Rev.0 moved the piping support location 0'-0 ¾" in the negative (Z) plant global coordinate system. The support is a horizontal cantilevered beam attached to the bottom of in-place steel and the latest archived design requires an additional member/plate to move the support; however, no qualification or red line drawings are provided within the aforementioned E&DCR document. CAPAL 100502007 was created to address and incorporate the redesign of the piping support APP-CVS-PHC-11R7075 and the pipe support drawing APP-CVS-PH-11R7075. Disposition: The design authority has reviewed the piping and support deviations and issues the disposition "Use as is". Justification (Piping Analysis): Shift in length of CVS-PL-L522 and location of CVS-PL-V086 and restraint CVS-PH-11R7075 by less than 1.1/8" results in negligible impact to APP-CVS-PLR-090 Rev. 0 analysis. This deviation results in a change in the length of free end piping above restraint CVS-PH-11R7075 by less

Defect Code	NCR #	Module	Description	Proposal	Disposition Details
5B	1102	Q305	As per APP-Q305-GNR-850037: Spool SV4-CVS-PLW-090-1B as shown on the spool data package (reference 132176-C601.03-404-012-00452) has a sockolet installed at item 6 (item F on as-built). The spool had been shipped to the module fabricator before the change was made to the drawing (from sockolet to weldolet), the module fabricator needs instructions to replace the sockolet with a weldolet. See attached N&D APP-Q305-GNR-850037. Unit: SV4-Q305	Repair	Note: Original scope of the following disposition was originally outlined as part of APP-Q305-GNR-850034 with applicability to both X05 and Y05. However, APP-Q305-GNR-850034 was superseded by APP-Q305-GNR-850037 for the SV4 module exclusively. The partner performed work under the direction of APP-Q305-GNR-850034, however the disposition for both of these N&Ds is the same. There is no impact due to using APP-Q305-GNR-850034 in place of APP-Q305-GNR-850037. As per APP-Q305-GNR-850037: "The Disposition is REPAIR. Spool SV4-CVS-PLW-090-1B is not fabricated in accordance with current design. Part number 6 (APP-CVS-PLW-090) fitting has been added to the process pipe as a Sockolet. Due to high stress at this branch location a Weldolet is required. Fabricator shall cut as-built welds #11 and #13, remove existing spool and replace with new spool piece according to the WEC markup attached. Fabricator shall replace existing Sockolet with the required Weldolet fitting. Fabricator shall perform the repair process in accordance with APP-GW-P0-008 and applicable ASME code." This is for SV4.
3A	0058	Q223	Upon Inspection of box beam noted above 2(two) small notches were found, one was located @ 98 3/4" from the stamped end on the top outside edge of plate # A2034-3 adjacent to weld # W 1355 with a depth greater than 1/32" and less than 1/16". The second notch was located 113" from the stamped end on the bottom outside edge of plate # A2034-3 adjacent to weld # W 1355 with a depth greater than 1/32" and less than 1/16".	Re-work	The first notch is located in an area which will be removed by cutting and machining of the beam. Continuing operations will remove this defect. The second notch shall be smoothed and tapered by shop personnel through a traveler addendum. QC shall ensure parent material dimensions are in accordance with the drawing and applicable tolerances.

Defect Code	NCR #	Module	Description	Proposal	Disposition Details
3A	0073	Q233	During visual inspection (Operation No. 40 of Traveler No. A00002G33-014) it was observed that a flange plate had sustained mechanical damage. The location of damage is approximately 2 1/2" from the stamped end of the box beam, adjacent to W3085, on flange part a3026-1. The damage is approximately 3/8" in length and over a 1/32" in depth.	Re-work	Continuation of the fabrication process will remove this defect at the cutting and machining operations. Receiving inspection of the beam after machining will verify that the defect is removed.
3A	0084	Q223	Material appeared to have sustained damage to the end of column that had been machined for welding. Material was dropped during fabrication operations resulting in loss of material on the prepared end. Material loss is larger than 1/8th of an inch. See attached photos.	Re-work	An addendum will be issued to the traveler instructing the shop to smooth the area to prepare for welding and ensure 45 degrees is maintained in the prep. QC will be instructed to re-inspect the adjacent weld. Joint configuration and fit-up is not affected due to the use of a backing bar.

Defect Code	NCR #	Module	Description	Proposal	Disposition Details
3A	0137	Q240	TRV#: TRV-A00002-X40-004 Rev. 0 Drawings: A4107 Rev. 5, 4013 Rev. 0. WecMk#""s: 163 qty 2, 108, 115, 100 During QC operation 30, it was noticed that damage to the Horizontal HSS members 4012 (APP-Q240-SS-203 MK 100) and 4001 (APP-Q240-SS-202 mk 115) occurred in excess of 1/32" base metal reduction. These locations are in the weld zone and out of the weld zone. This is determined by the fit-up of the end plates of column 4013 to be installed onto the horizontal HSS (4012 and 4001) members. Location and extent of depth is as follows: Lower 4012: Location 1 (W2951 other side) Depth 1/32" min. to 1/16" max. Length of 3". Location 2 (W1127 other side) Depth 1/32" min. To 1/16" max. Length of 6 1/4". Location 3 (W2951 arrow side) Depth 1/16" min. To 3/32" max. Length of 8 1/4". Location 4 (W1127 arrow side) Depth 1/16" min. to 3/32" max. Length of 6". Upper 4001: Location 1: (W2950 other side) Depth 1/32" min. to 1/8" max. Length of 10". Location 2: (W1128 other side) Depth 1/31" min. to 5/32" max. Length of 7". Location 3: (W2950 arrow side) Depth 1/8" min. to 5/32"	Repair	Do a base repair procedure to fill each groove. MT each pass of weld before applying another pass. VT & MT inspect the repaired areas.
3A	0197	Q240	Mechanical damage was observed on item m4048-1 of Support Assembly 4119-3. Base metal reduction is measured to be 3/32" between 5.5"-6.5" from the transition between W3066 and W3072 on item m4075-1.	Re-work	Item #4048-1 on assembly 4119-3 will be removed by grinding and replaced with 4048-3 which is cut from 4008-8 HT#B410075 Lot#1.

Defect Code	NCR #	Module	Description	Proposal	Disposition Details
3A	0244	Q223	While grinding an adjacent weld on a pipe support, a 1 ¼" by ¼" gouge was made in a truss located on the bottom of box beam 2286 parallel to W3044. The depth of the gouge is 1/8", which is out of tolerance. Please see attached drawing for the location of the gouge. Unit SV3	Re-work	An addendum will be issued to TRV-A00002X23-008 to fill the gouge. The original WPS and drawing to do the weld will be used on the addendum. Unit SV3
3A	0947	Q305	Module: Q305: Unit – B05. Q223 Item: CVS-PL-V091 APP-PV01-Z04-104 for unit B05 Drawings: VS3-Q305-CVS-PLW-090-00 R. 2, Station: VS3 Expected condition: Valve components on valves not to be damaged. Actual condition: Valve components on valves: CVS-PL-V091 APP-PV01-Z04-104 for unit B05 have been damaged (bent) out of straightness.	Other	The partner proposes that in order to address this non-conforming condition, an authorized repair agency shall conduct necessary repair action to bring the as-built condition of the valve to design intent condition. It appears to the partner that these parts are easily replaceable allowing the repair process to be conducted at site by the valve vendor. Module: Q305 Unit: VS3
3A	0949	Q223	Module: Q223: Unit – B23 Item:Q223-PXS-PL-V124B APP-PV03-Z04-195, Q223-PXS-PL-V112B APP-PV03-Z04-195 for unit B23 Drawings: VS3-Q223-PXS-PLW-01 R.4 Station: VS3 Expected condition: Valve components on valves not to be damaged. Actual condition: Valve components on valves:Q223-PXS-PL-V124B APP-PV03-Z04-195, Q223-PXS-PL-V112B APP-PV03-Z04-195 for unit B23 have been damaged (bent) out of straightness.	Other	The bent sensors on valves PV03-Z0D-195 (S/N BN446) and PV03-Z0D-195 (S/N BN441) have been captured on customer N&D's APP-PV03-GNR-850007 and APP-Q223-GNR-850057, respectively. These sensors will be replaced at site by an authorized repair agency at site. See attached N&Ds for reference.

Defect Code	NCR #	Module	Description	Proposal	Disposition Details
3C	0103	Q240	Item 4013 (WEC MK#108), on dwg. A4102 R.1 found to be fit and welded 90 degrees skewed to it""'s required orientation. WEC Dwg. APP-Q240-SS-203 R.2 Traveler TRV-A00002X40-001 R.1	Re-work	This is for SV3 Grind remove assembly 4013 from the module. Clean / repair assembly as required. Re-fit 4013 back into the module. Check to ensure the correct orientation. Weld complete.
3C	0196	Q233	TRV-A00002X33-003 OP#: 125 Parts: 3107 & 3108 Welds: W849 & W851 Drawing: A3113 - Rev 2 During final dimension inspection OP# 125 on X33 it was found that the grating support (W849 and W851) is dimensionally out of tolerance. As shown in the attached drawing it is located at 6'-0 ¾" but the drawing calls for it to be at 6'-1 ¾". WEC Drawing: APP-Q233-SS-301/302 WEC Parts: 1606 & 1605	Re-work	Fabrication will be directed to remove the grating support. The area will be visually inspected. The grating support will be welded in the correct position and inspected. An addendum to the traveler will be issued.

Defect Code	NCR #	Module	Description	Proposal	Disposition Details
3C	0229	Q233	Traveler: TRV-A00002-A33-002 R.1 Operation: 150 & 150.1 Items: SA3000 from A3105 R.3, SA3031 & SA3012 from A3108 R.4 A3114 R.1 Wk item #s: 405 & 610 Wec ref. dwg: APP-Q233-SS-202 DI-Q233-VS2/VS3/SV3/SV4 Wec ref. dwg: APP-Q233-SS-205 DI-Q233-VS2/VS3/SV3/SV4 Wec ref. dwg: APP-Q233-SS-207/209/210 DI-Q233-VS2/VS3/SV3/SV4 Station: VS2 Dimensional results from operation 150 and operation 150.1 in A33-002 have resulted in measurements out of drawing tolerances. See attached drawings Dimensional results from operation 150 in A33-002: Drawing A3105 R.3 Item: SA3000 Nominal measurement 1'-5 5/8". Actual measurement: 1' 5 3/16" Drawing A3108 R.4 Item: SA3031 Nominal measurement 1'-11 3/4". Actual measurement: 1' 11 5/16" Item: SA3012 Nominal measurement 1'-5 1/4". Actual measurement: 1' 4 15/16" Dimensional results from operation 150.1 in A33-002 Drawing A3114 R.1 Nominal measurement 12""-10 5/8". Actual measurement: 12""-10.9497"	Repair	APP-Q233-GNR-850013 was presented by the customer with a repair disposition for this issue. 1). Drawing: A3105, Item SA3000 The excessive 7/16" gap shall be built up by adding a 1/2" plate under the 3231 plate on SA3000 with an all-round 3/8" fillet weld. The plate shall be 9"x1'-7", A572 GR 50 and have slotted holes templated from 3231. 2). Drawing: A3108, Item SA3031 The excessive 7/16" gap shall be built up by adding a 1/2" plate under the 3228 plate on SA3031 with an all-round 3/8" fillet weld. The plate shall be 1'-5"x1'-5", A572 GR 50 and have holes templated from 3228. 3). Drawing: A3108, Item SA3012 The excessive 5/16" gap shall be built up by adding a 3/8" plate under the 3298 plate on SA3012 with an all-round 1/4" fillet weld. The plate shall be 8 3/4"x1'-5 1/2", A572 GR 50 and have slotted holes templated from 3298. 4). Drawing: A3114 The site constructor shall move the beam seat as necessary to align the center locations with the base plates. No action by the partner re-quired. A33 Drawings and as-builts affected shall be redlined to include new part numbers, welds numbers and updated BOMs. Unit: VS2

Defect Code	NCR #	Module	Description	Proposal	Disposition Details
3C	0272	Q233	TRV A00002X33-006 Rev.0 Op# 25 Item# 17E DWG# SV3-Q233-PXS-PLW-01XX Rev.1 WEC Reference DWG# APP-Q233-VO-001 Rev.6 SV3 During Op.25 which required fabrication to prepare support item 17E. The cut length specified on the drawing is 2’-5 3/8” but it was cut to 25 3/8” which makes it 4” shorter than the required length.	Other	The partner proposes a two part disposition. 1 - To accommodate fabrication schedule, the damaged support piece on SV3-Q233 will be replaced with the equal piece from SV4-Q233. Therefore, SV4-PXS-PH-11R0361-6 will be installed in module SV3-Q233 and the incorrectly cut SV3-PXS-PH-11R0361-6 will be scrapped. 2 - The partner requires a new support piece for SV4-Q233 be shipped to replace SV4-PXS-PH-11R0361-6 being transferred to SV3-Q233. Customer to advise. Unit: SV3
3C	0331	Q233	TRV-A00002X33-006 R.0 Op. 1095 Item – 16C (8.05, 8.06) DWG: SV3-Q233-PXS-PLW-01 R.1, SV3-Q233-PXS-PLW-01XX R.1 WEC DWG: APP-Q233-V0-001 R.6 During execution of operation 1095 (preparation for welding), item 16C was cut too short. The existing condition will not allow for the part to be fit into the module within tolerance. Please see attached photos. Unit SV3	Repair	An addendum shall be issued to TRV-A00002X33-006 to instruct the shop to perform a repair weld on the HSS component of item 16C (SV3-PXS-PH-11R0031-6). The CJP repair weld shall be completed and controlled with weld number "W16CR" as per the attached markup of drawing SV3-Q233-PXS-PLW-01XX Rev. 2. The parts shall be prepared with a nominal 80 degree combined bevel. The weld shall be completed without backing bar and inspected using 100% VT, 100% MT and 100% RT. The existing HSS seam is outside the scope of these inspections. This NCR is applicable to module Q233-SV3.

Defect Code	NCR #	Module	Description	Proposal	Disposition Details
3C	0341	Q240	TRV-A00002A40-005 Rev. 0, Op. 725 Drawing: VS2-Q240-RNS-PLW-01-10X Rev. 1 WECTEC Drawing: APP-Q240-V0-001 & 002 Rev. 5 During trial fit of item 29, the partner fabrication cut the pipe support (item 29A) 3 7/8" too short, causing the item to be out of dimensional tolerance. Cut was made on the end joining to item 29B. See attached photo.	Repair	N/A
3C	0360	Q240	TRV-A00002A40-005 R.0, Op. 537.3 VS2-Q240-RNS-PLW-03-02X R.1 The fit and tack weld (W2) on the additional shim plate for Item 5A was visually inspected in accordance with QCP 310.2 R.18 acceptance criteria, and was found to be unacceptable at time of inspection due to excesive grinding on the shim plate of the existing support. East side of additional shim plate: 1/8" to 5/32" reduction of existing existing shim plate, 1/4" to 3/8" deep. West side of additional shim plate: 3/32" to 1/8" reduction of existing shim plate, 1/8" deep.	Repair	Rev. 1 Disposition: The excessively ground area will be repaired by completing the welds, increasing the vertical leg length and performing MT on every pass. Vertical leg length shall be increased to 1/4" plus the gap dimension. This is for VS2. Rev 2 Addition: Work has been completed using the Rev 1 disposition and control notice CN-173 Rev 0. N&D APP-Q240-GNR-850079 Rev. 0 specifies that VT, in addition to MT, shall be conducted on each pass of the weld. This requirement is the partner's quality program requirement in addition to the N&D. The welds shall be ground back to the original non-conforming conditions, VT and MT/PT of the ground zone, then welded with the following conditions: 1. Every weld pass shall be visually inspected. 2. Every weld pass shall have MT or PT done. 3. Final geometry of the weld shall have vertical leg length at 1/4"+ gap height. This is for VS2.

Defect Code	NCR #	Module	Description	Proposal	Disposition Details
3C	0368	Q240	Traveler: TRV-A00002-A40-005 R.0 Operation: 919 (A39 R.0) Drawings: VS2-Q240-RNS-PLW-01-05X R. 2, VS2-Q240-RNS-PLW-01-16X R. 1, VS2-Q240-RNS-PLW-02-02X R. 6. Items: Supports 19A, 19B, 49, 3C and 3A. Station: VS2 NCR Attachment: IR-A40-036 total of 2 pages. Verify piping dimensions operation 919 in TRV-A00002-A40-005 R.0 has resulted in non-conforming (2.) Supports to pipe clearances (gaps). For the following items: Cumulative and Non-Cumulative Gaps (Ref. Dwg). Spool 1: Support Items: Cumulative gap: 19A to 19B = 0.142”. Non-cumulative gap: 49 = 0.132”. Spool 2: Support Items: Cumulative gap: 3C to 3A = 0.054”.	Repair	Item 49 is a temporary support and will be removed at site. This dimension will not affect the fit, form or function of the unit. The partner requests a use as is for this support. Item 19A and 19B corresponds to VS2-Q240-RNS-PH-11R0047 item 2 and 3 respectively. Item 3C and 3A correspond to VS2-Q240-RNS-PH-11R0127 item 4 and 2 respectively. The partner will repair these supports. This is for VS2

Defect Code	NCR #	Module	Description	Proposal	Disposition Details
3C	0371	Q240	During Inspection of operations 195 & 355 in traveler TRV-A00002A40-007 Rev 0, multiple end preps were found out of tolerance. The attached detailed report reflects all ends preps that are non-conforming. OP #, DRAWING # & WELD # OP 355, VS2-Q240-RNS-PLW-HYD-02 Rev 3, W1 & W2 OP 195, VS2-Q240-RNS-PLW-HYD-01 Rev 3, W5 DRAWING #, Item # VS2-Q240-RNS-PLW -01 Rev 6, Item # 6 VS2-Q240-RNS-PLW -02 Rev 3, Item # 1 WEC DWG # APP-Q240-V0-001 & 002 Rev 5 APP-Q240-SS-205 & 213 Rev 3	Repair	For the non-conforming joint preparation at W5 on spool 1 (W2 of VS2-RNS-PLW-018-1), a repair of the minimum wall condition shall be completed. The repair shall be done by removing up to 1/2" of material from the end of the pipe, then re-machining joint into conformance. The 1/2" shall maintain the tolerance allowance for this FW joint. See IR-A40-035 for pipe position relative to datum. As per APP-Q240-GNR-850082, all other conditions shall be use as is.

Defect Code	NCR #	Module	Description	Proposal	Disposition Details
3C	0386	Q223	Travelers: TRV-A00002A23-006 R. 0 TRV-A00002A23-008 R. Operations: 1695.1 and 1390.1. Drawings: DWG'S: VS2-Q223-PXS-PLW-01 R. 3, VS2-Q223-PXS-PLW-01X R. 3, VS2-Q223-PXS-PLW-01XX R. 2, VS2-Q223-PXS-PLW-03 R. 1, VS2-Q223-PXS-PLW-03X R. 1. Items:13A, 13B, 16E, 14D, 17C, 17D, 15B, 15C, 11A, 11C, 11B. Station: VS2. Condition 1./ Pipe to support clearance (gap check) is rejected on supports; 13A, 13B, 16E, 14D, 17C, 17D, 15B, 15C, 11A, 11C. Condition 1./ Spool 1 items: 13A, 13B. Nominal: 0.125" to 0.15625". Actual: 0.083". O.O.T.: -0.042". 16E, 16E. Nominal: 0.03125" to 0.125". Actual: 0.000". O.O.T.: -0.03125" 14D, 14D. Nominal: 0.03125" to 0.125". Actual: 0.008". O.O.T.: -0.02325". 17C, 17D. Nominal: 0.03125" to 0.125". Actual: 0.143". O.O.T.: 0.018" 15B, 15C. Nominal: 0.03125" to 0.125". Actual: 0.193". O.O.T.: 0.068" Condition 1./ Spool 3 items: 11A, 11C. Nominal: 0.03125" to 0.125". Actual: 0.021". O.O.T.: -0.01025" Condition 2./ : Alignment of the pipe centerline to the centerline of the shim is rejected on 11A and 11B.	Repair	The following affected items shall be repaired: 16E of PXS-PH-11R0130 17C, 17D of PXS-PH-11R0278 15B. 15C of PXS-PH-11R0132 For the gaps of the following items, the partner requests a use-as-is disposition: 13A, 13B - of PXS-PH-11R0128 14D - of PXS-PH-11R0129 11A, 11C - of PXS-PH-11R0140 The partner requests a use as is disposition of the misalignment of the shim as per condition 2. The location of the shim plate does not affect the function of the support. This is for VS2.

Defect Code	NCR #	Module	Description	Proposal	Disposition Details
3C	0421	Q223	Traveler: TRV-A00002A23-013 Operation: 106.2 Drawing: VS2-Q223-PXS-PLW-03X R. 1 and VS2-Q223-PXS-PLW-03XXX R. 0 Channel numbers 2064-2 and 2063-2 could not be installed due to interference with previously installed valves below. Channel 2064-2 has interference with valve S/N 0019089846 and channel 2063-2 has interference with valve S/N 0021294100. Elevation of the valves was checked to the module datum point and was verified to be in the correct position. There is approximately 1" of interference/overlap between the respective channels and valves.	Repair	The partner proposes a "Repair" disposition. Propose to notch out both channels to fit over the valve bodies near the inlet. Unit: VS2
3C	0453	Q223	TRV-A00002A23-006 Rev. 0 Op. 1695.16 Drawing: VS2-Q223-PXS-PLW-01XX Rev. 2 WECTEC Drawing: APP-Q223-V0-001 Rev. 2 Dimensional inspection of gap dimensions between item 15B/15C was performed and found to be unacceptable at the time of inspection. See attached Inspection Report IR-A23-023 for details.	Repair	As per N&D APP-Q223-GNR-850064 for NCR A00002-000-0386, the partner is instructed to repair this gap. An addendum will be issued detailing the repair.
3C	0478	Q305	ITEM 2A LISTED ON BOM DWG SV3-Q305-PLW-83A-00 REV 1 AS 5"LG HAS BEEN CUT TO 4-1/2" LG THE DIMENSION SHOWN AS 6-1/4" ON DWG SV3-Q305-CAS-PLW-83A-01 REV 2 CANNOT BE MAINTAINED AND IS RESULTING IN A DIMENSIONAL VIOLATION EXCEEDING THE ALLOWABLE TOLERANCE. WEC DWG APP-CAS-PLW-83A REV 3. WEC# CAS-PH-11R2162-1/2	Re-work	An addendum will be written to add a shim to item 2A thus returning the dimensional violation to within tolerance. This is for SV3.

Defect Code	NCR #	Module	Description	Proposal	Disposition Details
3C	0577	Q305	TRV-A00002A05-003 Operation 435 DWG: VS2-Q305-CVS-PLW-092-00 R.3, VS2-Q305-CVS-PLW-092-01 R.1 WEC DWG: APP-CVS-PH-11R21661 R.2 Items: 2D, 2A, 2B WEC Items: 2, 3, 4 weld: W4 Pipe support item 2 was found to be out of tolerance after welding. Required Height: 5 - 1/4" Actual Height: 7 - 3/16"	Repair	An addendum will be created to grind remove W4 from item 2, MT after grinding, cut to required length and reweld W4. This is for VS2.
3C	0703	KB36	ModuleKB36-Frame Assembly-Miscellaneous Attachments. TRV: A00002Y36-002, R.0 Op. 115-Verify fit up and visually inspect tack welds. Sleeve pocket item numbers 1265-27 and 1265-31 have been placed at the incorrect offset in relation to the outer face of HSS item #1137. Drawings show 3 ½" from outer vertical face of HSS to center of sleeve pocket. Sleeve pockets mentioned were set back 4". 1/8" tolerance is permissible according to reference drawings. Dwg.: A1106, R.3	Re-work	Handrail sleeves shall be removed from current position and re-welded in the correct position. Care shall be taken to not violate base metal when removing existing welds. This is for SV4.

Defect Code	NCR #	Module	Description	Proposal	Disposition Details
3C	0870	Q240	TRV-A00002Y40-008 R.0 Op. 150/160 DWG: SV4-Q240-RNS-PLW-01-13X R.0 WEC DWG: APP-RNS-PH-11R01141 R.1 Support Number: RNS-PH-11R0114 Items: 36A, 36B WEC Items 4, 6 Fit-up of W75 was completed by fabrication and signed off as acceptable by QC. The existing condition is non-conforming. SV4-Q240-RNS-PLW-01-13X R.0 - Section B (Looking North): Required Dimension: 19" Actual Dimension: 19 3/4" The existing condition offsets the spool centerline 3/4" from the shim plate centerline.	Repair	In order to bring the support RNS-PH-11R0114 into design intent, items 36A and 36B will have tack weld W75 removed and item 36B will be cut to the correct length. Weld removal and inspection shall be per ASME Section III. Support is constructed to ASME Section III. This is for SV4.

Defect Code	NCR #	Module	Description	Proposal	Disposition Details
3C	0954	Q223	TRV-A00002B23-006 R.0 – Op. 1990 DWG: VS3-Q223-PXS-PLW-01 R.4, VS3-Q223-PXS-PLW-01X R.2, VS3-Q223-PXS-PLW-01XX R.1, VS3-Q223-PXS-PLW-01XXX R.1, VS3-Q223-PXS-PLW-01XXXX R.2. WEC REF: APP-Q223-V0-001 R.9 During inspection of support-to-pipe clearance (Cumulative Gaps), three (3) separate items were found to be non-conforming. Expected Condition: Cumulative gap measurement tolerance: greater than or equal to 0.03125" & less than or equal to 0.125" Existing Condition: Item 15 – APP-PXS-PH-11R0130 Shim/spool centerline: Acceptable Shim cumulative gap measurement: Item 15D to 15D = 0.15” Rejected Item 15B to 15C = 0.085” Acceptable Item 16 – APP-PXS-PH-11R0278 Shim/spool centerline: Acceptable Shim cumulative gap measurement: 16E to 16E = 0.03125” Acceptable 16D to 16C = 0.132” Rejected	Repair	N&D APP-Q223-GNR-850125 allows for a “use-as-is” on Item 14 (VS3-PXS-PLW-11R0278) and Item 16 (VS3-PXS-PLW-11R0129). However, the cumulative gap from Item 15D to Item 15D on VS3-PXS-PLW-11R0130 is unacceptable and requires a repair to bring the cumulative gap into drawing tolerance. An addendum will be issued to complete the repair. Unit: VS3

Defect Code	NCR #	Module	Description	Proposal	Disposition Details
3C	0997	KB36	TRV-A00002X36-016 Op. 455 Drawing: SV3-KB36-DWS-PLW-01 Rev. 3 WEC DRAWING: APP-DWS-PLW-510 Rev 3; APP-DWS-PLW-513 Rev 2 The handle on the DWS-PLW-513 valve (DWS-PL-V247) is interfering with the actuator body on DWS-PL-V244, limiting functionality of the valve handle. See attached picture. UNIT SV3-KB36.	Repair	As per N&D APP-KB36-GNR-850156, The handwheel of valve DWS-PL-V247 shall be modified to resolve the clash. The grips of the handwheel shall be ground smooth, free of burrs, shavings and sharp edges so as to provide the necessary room to operate the valve. The handwheel shall be re-painted in accordance with WI-025 following grinding. This is for SV3.
3C	1029	KB36	TRV-A00002Y36-010 OP# 65 Dwg# SV4-KB36-PCS-PLW-05 R.0 Wectec Dwg# APP-KB36-VO-001 R.6 Spool# SV4-PCS-PLW-10K-1 On spool SV4-PCS-PLW-10K-1 on the other side of the valve where the stainless spool starts the spool is out of level dropping 1.6 degrees.	Re-work	WEC weld 2 shall be completely removed and both sides of the joint shall be re-machined. Weld shall then be re-performed and inspected in accordance with ASME B31.1. This is an ASME B31.1 pipe. This is for SV4.

Defect Code	NCR #	Module	Description	Proposal	Disposition Details
3C	1036	KB36	TRV-A00002Y36-007 R.0 Op. 100 DWG: SV4-KB36-PCS-PLW-02 R.1, SV4-KB36-PCS-PLW-02-02X R.0 WEC REF: APP-KB36-V0-003 R.3, APP-KB36-V0-001 R.6 Items: 7A, 18B, 18C W29 Required Condition: Pipe spool Item 7A (PCS-PLW-111-1R2) is required to be in contact with pipe support item 18B, to facilitate fit-up of item 18C. Existing Condition: Pipe spool Item 7A (PCS-PLW-111-1R2) is not in contact with Item 18B, a ¾" gap exists between the two items. Item 7A is 5/8" out from the nominal requirement of the terminal end to datum point dimension (4' – 5 7/16"). See attached.	Repair	Condition is due to the heat exchanger position being north by 5/8". Heat exchanger mounting holes are drilled and tapped. All other piping into the heat exchanger is completed. Disposition shall be to replace the existing piece, (PCS-PH-12R0320 Item 6) with qualified material that is 3/4" longer to compensate the gap. Total length of the new member shall be 9 7/8". Existing welds between Item 4 and item 6 shall be removed and re-performed using the new HSS. Material shall be qualified in accordance with ASME B31.1. This is for SV4.

Defect Code	NCR #	Module	Description	Proposal	Disposition Details
3C	1080	KB36	Traveler: TRV-A00002Y36-007 R.0 OP: 110 Drawing: SV4-KB36-PCS-PLW-02-05X R.1 During fit-up of support 23, it was noted that the Pipe location, item 9, is 1" south of specified position of the drawing and therefore the reference dimension of 10 1/8 can not be achieved. Unit: SV4	Repair	In accordance with APP-KB36-GNR-850179: "Disposition: The design authority has reviewed the non-conforming condition and approves a "Repair" disposition. The non-conforming condition is limited to the pipe centerline dimension at pipe support PCS-PH-12R0302 (Ref. 1) as described in this non-conformance. See attached markup of Ref. 1 for details of repair. Justification: Changes in pipe layout remain within field fabrication tolerances per APP-GW-P0-008 (ref. 3). Shift in location of pipe termination point shown in APP-PCS-PLW-10M (Ref. 11) results in negligible impact to piping analysis APP-PCS-PLR-100 (Ref. 10). Deviation of the termination point of piping detailed in Ref. 11 shall not exceed 1" or another N&D shall be processed. There is no impact to the piping analysis. A length decrease of up to 1/2" for item 2 of Ref. 1 is acceptable per the qualification provided in the pipe support analysis (Ref. 8). This analysis considers support loading at the OD of the pipe, which is conservative given the reduction in length of item 2. Therefore there is no impact to the pipe support analysis (Ref. 8). The non-conforming dimension, detailed on the drawing markup attached, is not within the mechanical module design tolerance per the mechanical module general notes; 24" </= Dimension; Tolerance +/- 3/8" (Ref. 4 & 5). The non-conforming condition (up to 1" pipe and hanger centerline OOT) is acceptable from a module design perspective. Out of tolerance condition does not result in any deviation in the support/module attachment location. This offset results in negligible changes to reaction forces at support attachment location on the module structural frame. Module frame qualification for KB36 (see Ref. 6) remains valid. The repair proposed in block (8) is acceptable. Welds between items 1 &

Defect Code	NCR #	Module	Description	Proposal	Disposition Details
3C	1082	KB36	TRV-A00002Y36-010, item 10C welded to 10B Drawing: SV4-KB36-CVS-PLW-01-04X R.0 The shop fitted item 10C at the wrong elevation. Drawing shows a reference dimension of 19 1/8" to the bottom of item 10C, the shop fitted the item to the center which puts it out of tolerance by 2".	Re-work	Condition is violation of the 1' 7 1/8" measurement on APP-CVS-PH-12R04051. The support weld W227 shall be completely removed, the area visually inspected and undergo MT or PT. The support shall be re-fit, welded, and inspected in accordance with ASME B31.1. This is for SV4.
3C	1085	Q305	Module: Q305 Unit Y05 Traveler: TRV-A00002Y05-003 R.0 Operation: 665 When doing dimensionally inspection for the alignment of the support to pipe, Support # 5 was found to be out of the tolerance. There is 1 5/8'' gap between the item 5B to Pipe on the right side of support when looking west; SV4-Q305-CVS-PLW-096-03 R.0 The minimum required gap on the right side of support #5 is 1 3/4'' Affect Item: Item # 5B, SV4-Q305-CVS-PLW-096-03 R.0	Re-work	Support item 5B shall be removed from current position and re-welded in the correct position.
3C	1094	KB36	Module: KB36 Unit Y36 Traveler: TRV-A00002Y36-010 R.0 Operation: 345 When doing fit up and dimensional inspection for W226, found the dimensions of support center relative to the datum are out of tolerance; 21' – 4 5/8'' for center of support (8A) to datum, the drawing is required 21'-3 5/8''. The maximum allowed tolerance is 5/16''. Affect Items: #8A, 8B, W225, W226. Drawings: SV4-KB36-CVS-PLW-01-03X R.0	Re-work	W225 shall be completely removed, the area VT'd and MT'd or PT'd, and the part re-fit to the proper location. New weld shall be visually inspected in accordance with ASME B31.1. This is for SV4.

Defect Code	NCR #	Module	Description	Proposal	Disposition Details
3C	1127	Q601	TRV-A00002X01-013 Dwg: SV3-Q601-RCS-PLW-03-03X Item: Wectec pipe support RCS-PH-11Y0811 Description: Item 46D (Lisega bracket) has been welded to Item 46A (Lisega supplied HSS & plate) at elevation 2'-10". The as-built valve center line is at 2'-10 ½". There is a ½" mismatch between bracket & valve. Customer to advise. Per Drawing SV3-Q601-RCS-PLW-03-03X the horizontal distance to the Lisega bracket (46D) is indicated to be 3'-9 3/8" + ¾" (= 3'-10 1/8") while on the Wectec drawing (APP-RCS-PH-11Y08111) the distance is 3'-3 5/8" + 5" + ¾" (= 3'-9 3/8"). Therefore, the dimension is ¾" greater than the Wectec dimension. 46A & 46B have been welded to the 3'-9 3/8" beam.	Repair	As per APP-Q601-GNR-850102: "Disposition: The design authority has reviewed the non-conforming condition and approves the "Repair" disposition for issue 1, and a "Meets Requirements" disposition for issue 2. In addition, the design authority has reviewed the non-conforming strut pin to pin dimension described in the justification below and approves a "Use As Is" disposition. Justification: Issue 1: The ½" deviation from the as designed location of the bracket is within the 2" design tolerance considered in the pipe support design analysis (Ref. 3). The load distribution to the intermediate plate (item 6) between the Lisega bracket (item 1) and HSS (item 6) will change nominally due to the offset bracket. Sufficient margin exists to account for nominal changes in load distribution to item 6 and the weld of item 6 to item 8 per the deviation described in this N&D. Therefore this repair disposition is acceptable. In addition, the strut pin to pin dimension shown on Ref. 5 of 2'-0.8/7" will now be 2'-1.3/8". This is within the allowable adjustment range of the type 2-395039S Lisega strut of 25.15/16" (see page 186 of Ref. 7; 25.3/8"< 25.15/16") and within construction tolerance for the as-built location. Therefore this deviation can be accepted "use as is." APP-RCS-PH-11R08121 (Ref. 5) has been listed as an impacted document. Issue 2: The 3'-9.3/8" dimension from the Q601 frame member to the centerline of the Lisega weld on bracket (item 1) is consistent with dimensions shown on the pipe support drawing (Ref. 2). Therefore there is no deviation with

Defect Code	NCR #	Module	Description	Proposal	Disposition Details
3C	1144	Q601	TRV-A00002X01-013 op. 1435 Drawing: Sv3-q601-rcs-plw-03-02x For X01: Inspection for pipe to support gap clearance. The allowed gap is 1/32" (.0325) to 1/8" (.125). Actual measurement is .020 at weld W1170 and .005 at weld W1172. This gives an accumulative measurement of .025 which is outside allowed tolerance.	Repair	As per N&D APP-Q601-GNR-850108: "Disposition: According to the gap evaluation (per APP-GW-PHC-003), the maximum pipe expansion due to thermal and pressure effects is 0.0276" which is greater than the 0.0250" that is currently available. For this reason, the design authority has reviewed the non-conforming condition and does not approve the "Use As-Is" disposition suggested in block 8. Instead, an engineering disposition of "Repair" is required. The stainless steel transition plates located at welds W1170 and W1172 may be trimmed to a minimum thickness of 3/16" in order to achieve the gap as specified on the pipe support drawing. A markup of the Westinghouse pipe support drawing is provided. Justification: The purpose of the stainless steel transition plates on RCS-PH-11R0059 is to ensure no contact between carbon steel and hot stainless steel pipe. "Hot" is defined as 650 °F, and the pipe for this support is 4" NPD at 660°F. As the pipe is 10°F above the maximum temperature specified in the design spec, a reduction in plate thickness below the ¼" minimum specified on the drawing is acceptable. A new minimum thickness of 3/16" is acceptable in order to achieve the gap specified on the pipe support drawing. To justify the minimum thickness, a re-evaluation of the transition plate welds and transition plate pull-out is required. The reduction in plate thickness requires the ¼" fillet weld to be considered as having the same capacity as a 3/16" leg size fillet weld. An updated evaluation is provided in this report.

Defect Code	NCR #	Module	Description	Proposal	Disposition Details
3G	0438	Q233	TRV-A00002-A33-011, op 15 Dwg: A3113 Rev 4, Item 3124 Wec Dwg: APP-Q233-SS-301/302, Mark # 1621 Hand rail, item no. 3146, does not fit into the sleeves, item no 3124. handrail measures 17-7/8" center to center Spacing between sleeves measure 18-3/16" center to center.	Re-work	Handrail, item no. 3146 shall be reworked to fit into its corresponding location on frame A33. Instructions to remove the kickplate weld and grow the centre to centre dimension of the handrail posts will be given in an addendum to TRV-A00002A33-011. This will require removal of paint in the weld area and touch up after the weld is reworked.
3G	0821	Q223	Traveler: TRV-A00002B23-007 Rev. 0 Operation: 120 Drawing: SV3-Q223-PXS-PLW-02 Rev. 4 Westinghouse Drawing: APP-PXS-PLW-02Y Rev. 1 The valve handle on valve item 6, on the Westinghouse drawing, was installed in the wrong direction. The partner fabrication was not notified of this and installed the spool (SV3-PXS-PLW-02Y-2B) as per the partner's drawing orientation. Due to this, the spool has now been installed and welded in the wrong direction. Pup piece item 3 (18-3/4") and 4 (16-1/2") on the Westinghouse drawing are currently inversed on each side of the valve, moving the location of the valve 2-1/4" South. Reference the attached drawings.	Repair	The partner proposes to leave the spool as it was welded in. According to NCR A00002-000-0594 (N&D APP-Q223-GNR-850110) the actuator of the valve received by the partner in reverse orientation was to be rotated, leaving the valve in reverse orientation. The valve was installed in the module in the correct orientation causing item 3 (18-3/4") and weld 6 to be on the North side of valve PXS-PL-V013B and item 4 (16-1/2") and weld 7 to be on the South side of valve PXS-PL-V013B (Reference drawing: APP-PXS-PLW-02Y). The interface prep of the spool is in the correct location, however, valve PXS-PL-V013B has been shifted 2-1/4" to the South. The valve does not interfere with the frame or any other major components in this location. To accommodate the valve in the current location, the cutouts of two grating panels, MkK#1925 and MK#1927, will be changed. Note that the grating panels are commercial grade. See attachments and photos. Unit: VS3

Appendix D

Sampled NCR: Impact Estimate

84 NCRs were sampled out of the 693 geometric-related non-conformance. Each NCR was reviewed for their cost impact (new materials and extra man-hours) and time impact (additional labour).

Defect Code	NCR #	Impact				
		Material ($)	NCR (Manhour)	Labour (Manhour)	Schedule (Manhour)	Cost ($)
2C	211	-	6	0	6	390
	597	-	6	0	6	390
	1132	-	6	10	16	1,040
2D	75	-	6	0	6	390
	105	-	6	0	6	390
	161	-	6	0	6	390
	163	-	6	2	8	520
	396	-	6	4	10	650
	441	-	6	0	6	390
	593	-	6	2	8	520
	594	-	6	0	6	390
	624	-	6	4	10	650
	662	-	6	4	10	650
	829	-	6	8	14	910
	1040	-	6	2	8	520
2I	393	-	6	5	11	715
	400	-	6	4	10	650
	434	600	6	12	18	1,770
	449	-	6	11	17	1,105
	497	600	6	12	18	1,770
	500	600	6	12	18	1,770
	546	-	6	22	28	1,820
	627	-	6	11	17	1,105
	630	-	6	11	17	1,105
	689	-	6	44	50	3,250
	690	-	6	22	28	1,820
	697	-	6	11	17	1,105
	698	-	6	11	17	1,105
	699	-	6	22	28	1,820
	700	-	6	4	10	650
	702	-	6	11	17	1,105
	756	-	6	11	17	1,105
	769	-	6	11	17	1,105
	786	-	6	11	17	1,105
	791	-	6	11	17	1,105
	849	-	6	11	17	1,105
	860	600	6	12	18	1,770
	984	-	6	16	22	1,430
	1118	-	6	11	17	1,105

Defect Code	NCR #	Impact				
		Material ($)	NCR (Manhour)	Labour (Manhour)	Schedule (Manhour)	Cost ($)
5A	922	-	6	0	6	390
5B	3	-	6	0	6	390
	248	-	6	44	50	3,250
	784	-	6	0	6	390
	797	-	6	8	14	910
	800	-	6	0	6	390
	946	-	6	4	10	650
	1101	-	6	0	6	390
	1102	-	6	11	17	1,105
3A	58	-	6	2	8	520
	73	-	6	0	6	390
	84	-	6	2	8	520
	137	-	6	11	17	1,105
	197	300	6	16	22	1,730
	244	-	6	4	10	650
	947	-	6	0	6	390
	949	-	6	0	6	390
3C	103	-	6	16	22	1,430
	196	-	6	3	9	585
	229	500	6	0	6	890
	272	-	6	0	6	390
	331	-	6	11	17	1,105
	341	-	6	11	17	1,105
	360	-	6	11	17	1,105
	368	-	6	16	22	1,430
	371	-	6	8	14	910
	386	-	6	16	22	1,430
	421	-	6	2	8	520
	453	-	6	16	22	1,430
	478	-	6	7	13	845
	577	-	6	10	16	1,040
	703	-	6	4	10	650
	870	-	6	2	8	520
	954	-	6	16	22	1,430
	997	-	6	4	10	650
	1029	-	6	11	17	1,105
	1036	600	6	12	18	1,770
	1080	-	6	19	25	1,625
	1082	-	6	11	17	1,105
	1085	-	6	16	22	1,430
	1094	-	6	11	17	1,105
	1127	-	6	4	10	650
	1144	-	6	16	22	1,430
3G	438	-	6	1	7	455
	821	200	6	0	6	590

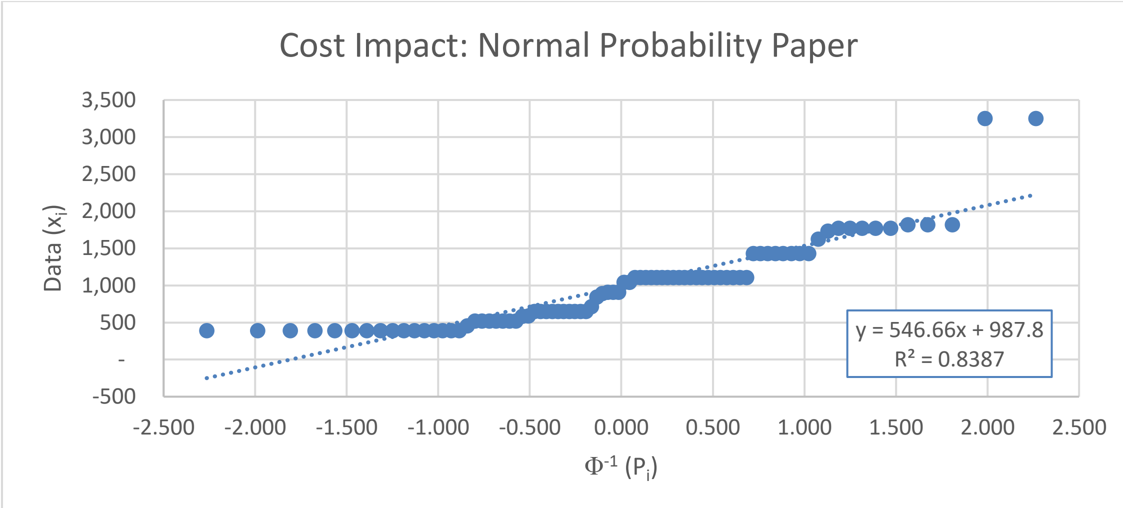
Appendix E
Sampled NCR: Impact Probability Distributions

The cost and time impact of 84 sampled geometric-related non-conformance are fitted with three common probability distributions, which are as follows:

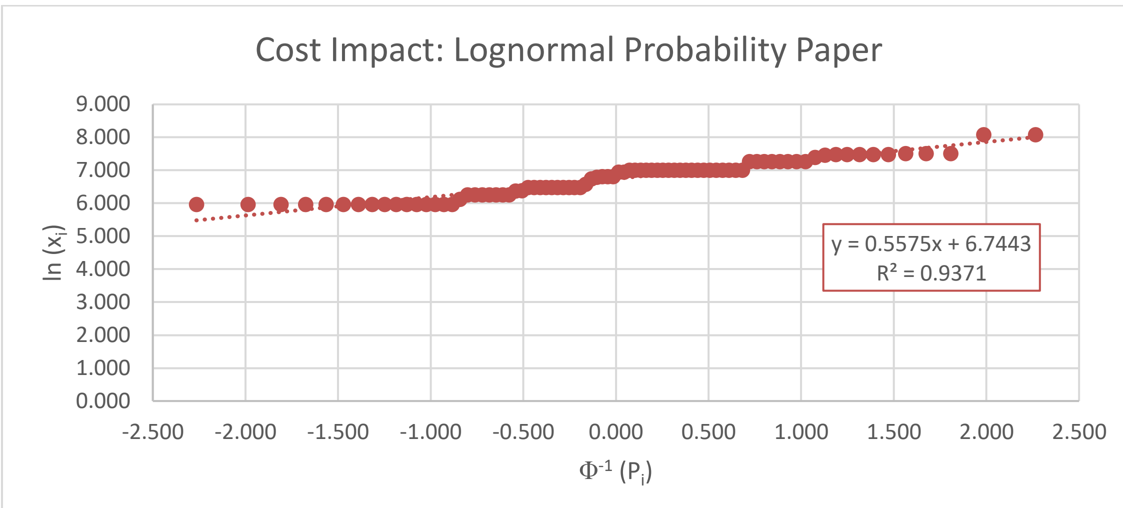
1. Normal distribution
2. Lognormal distribution
3. Weibull distribution

NCR Number	Cost ($)	Ascending Order	Rank Prob P_i	$\Phi^{-1}(P_i)$	$\ln(x_i)$	Weibull Inverse
1	390	390	0.012	-2.265	5.966	-4.437
2	390	390	0.024	-1.986	5.966	-3.738
3	1,040	390	0.035	-1.808	5.966	-3.326
4	390	390	0.047	-1.674	5.966	-3.032
5	390	390	0.059	-1.565	5.966	-2.803
6	390	390	0.071	-1.471	5.966	-2.615
7	520	390	0.082	-1.389	5.966	-2.454
8	650	390	0.094	-1.316	5.966	-2.314
9	390	390	0.106	-1.249	5.966	-2.190
10	520	390	0.118	-1.187	5.966	-2.078
11	390	390	0.129	-1.129	5.966	-1.976
12	650	390	0.141	-1.075	5.966	-1.883
13	650	390	0.153	-1.024	5.966	-1.796
14	910	390	0.165	-0.975	5.966	-1.715
15	520	390	0.176	-0.929	5.966	-1.639
16	715	390	0.188	-0.884	5.966	-1.568
17	650	455	0.200	-0.842	6.120	-1.500
18	1,770	520	0.212	-0.800	6.254	-1.436
19	1,105	520	0.224	-0.760	6.254	-1.374
20	1,770	520	0.235	-0.722	6.254	-1.316
21	1,770	520	0.247	-0.684	6.254	-1.260
22	1,820	520	0.259	-0.647	6.254	-1.206
23	1,105	520	0.271	-0.611	6.254	-1.154
24	1,105	520	0.282	-0.576	6.254	-1.103
25	3,250	585	0.294	-0.541	6.372	-1.055
26	1,820	590	0.306	-0.508	6.380	-1.008
27	1,105	650	0.318	-0.474	6.477	-0.962
28	1,105	650	0.329	-0.442	6.477	-0.917
29	1,820	650	0.341	-0.409	6.477	-0.874
30	650	650	0.353	-0.377	6.477	-0.832
31	1,105	650	0.365	-0.346	6.477	-0.790
32	1,105	650	0.376	-0.315	6.477	-0.750
33	1,105	650	0.388	-0.284	6.477	-0.710
34	1,105	650	0.400	-0.253	6.477	-0.672
35	1,105	650	0.412	-0.223	6.477	-0.634
36	1,105	650	0.424	-0.193	6.477	-0.596
37	1,770	715	0.435	-0.163	6.572	-0.560
38	1,430	845	0.447	-0.133	6.739	-0.523
39	1,105	890	0.459	-0.103	6.791	-0.488
40	390	910	0.471	-0.074	6.813	-0.453
41	390	910	0.482	-0.044	6.813	-0.418
42	3,250	910	0.494	-0.015	6.813	-0.384
43	390	1,040	0.506	0.015	6.947	-0.350
44	910	1,040	0.518	0.044	6.947	-0.316

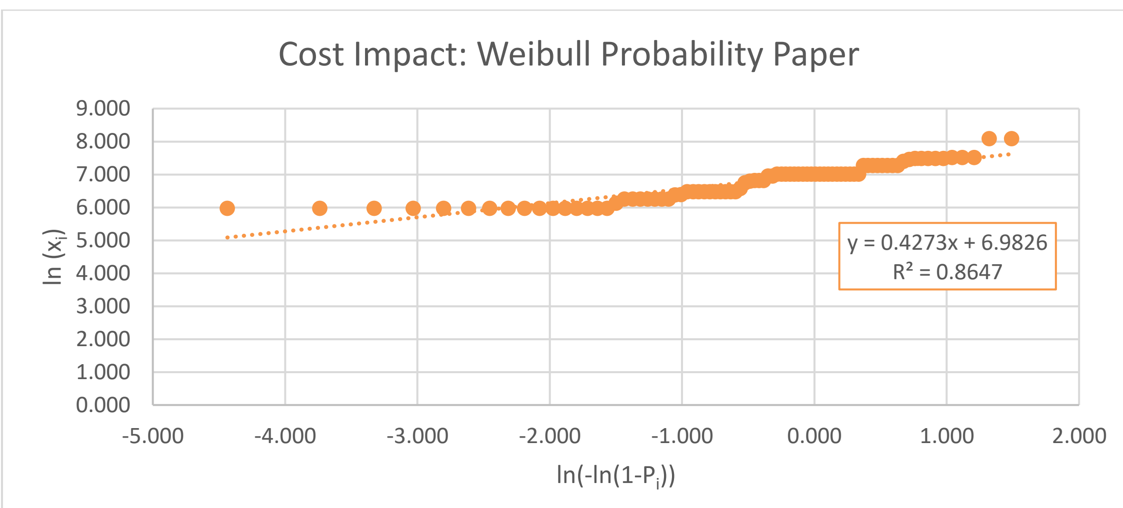
NCR Number	Cost ($)	Ascending Order	Rank Prob P_i	$\phi^{-1}(P_i)$	ln (x_i)	Weibull Inverse
45	390	1,105	0.529	0.074	7.008	-0.283
46	650	1,105	0.541	0.103	7.008	-0.250
47	390	1,105	0.553	0.133	7.008	-0.217
48	1,105	1,105	0.565	0.163	7.008	-0.184
49	520	1,105	0.576	0.193	7.008	-0.152
50	390	1,105	0.588	0.223	7.008	-0.120
51	520	1,105	0.600	0.253	7.008	-0.087
52	1,105	1,105	0.612	0.284	7.008	-0.055
53	1,730	1,105	0.624	0.315	7.008	-0.023
54	650	1,105	0.635	0.346	7.008	0.009
55	390	1,105	0.647	0.377	7.008	0.041
56	390	1,105	0.659	0.409	7.008	0.073
57	1,430	1,105	0.671	0.442	7.008	0.105
58	585	1,105	0.682	0.474	7.008	0.137
59	890	1,105	0.694	0.508	7.008	0.169
60	390	1,105	0.706	0.541	7.008	0.202
61	1,105	1,105	0.718	0.576	7.008	0.235
62	1,105	1,105	0.729	0.611	7.008	0.268
63	1,105	1,105	0.741	0.647	7.008	0.301
64	1,430	1,105	0.753	0.684	7.008	0.335
65	910	1,430	0.765	0.722	7.265	0.369
66	1,430	1,430	0.776	0.760	7.265	0.404
67	520	1,430	0.788	0.800	7.265	0.440
68	1,430	1,430	0.800	0.842	7.265	0.476
69	845	1,430	0.812	0.884	7.265	0.513
70	1,040	1,430	0.824	0.929	7.265	0.551
71	650	1,430	0.835	0.975	7.265	0.590
72	520	1,430	0.847	1.024	7.265	0.630
73	1,430	1,625	0.859	1.075	7.393	0.672
74	650	1,730	0.871	1.129	7.456	0.715
75	1,105	1,770	0.882	1.187	7.479	0.761
76	1,770	1,770	0.894	1.249	7.479	0.809
77	1,625	1,770	0.906	1.316	7.479	0.860
78	1,105	1,770	0.918	1.389	7.479	0.915
79	1,430	1,770	0.929	1.471	7.479	0.975
80	1,105	1,820	0.941	1.565	7.507	1.041
81	650	1,820	0.953	1.674	7.507	1.117
82	1,430	1,820	0.965	1.808	7.507	1.207
83	455	3,250	0.976	1.986	8.086	1.322
84	590	3,250	0.988	2.265	8.086	1.491



Cost Impact: Normal Probability Paper
Data (x_i)
3,500
3,000
2,500
2,000
1,500
1,000
500
-
-500
-2.500
-2.000
-1.500
-1.000
-0.500
0.000
0.500
1.000
1.500
2.000
2.500
Φ^{-1} (P_i)
y = 546.66x + 987.8
R^2 = 0.8387



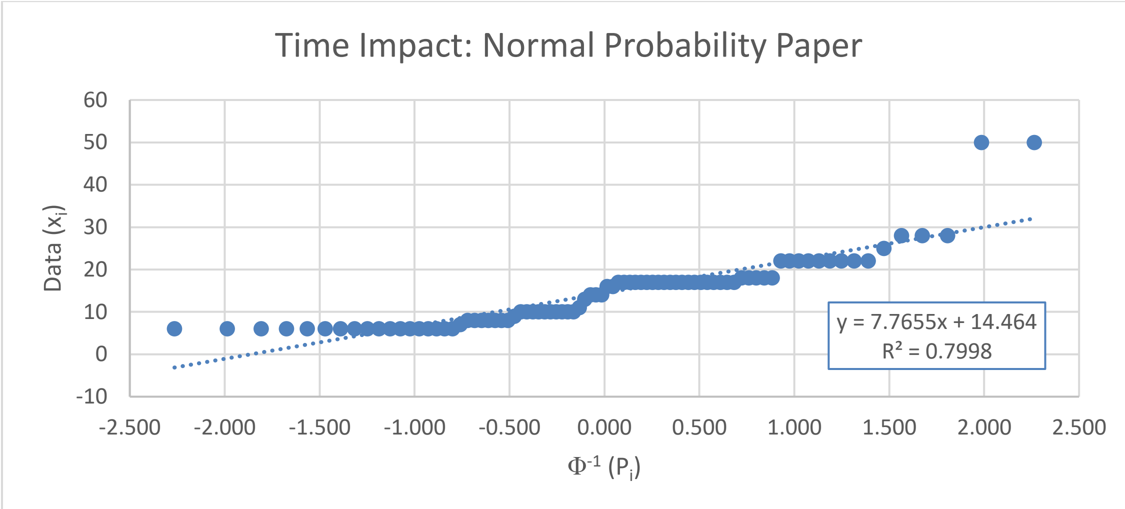
Cost Impact: Lognormal Probability Paper
ln (x_i)
9.000
8.000
7.000
6.000
5.000
4.000
3.000
2.000
1.000
0.000
-2.500
-2.000
-1.500
-1.000
-0.500
0.000
0.500
1.000
1.500
2.000
2.500
Φ^{-1} (P_i)
y = 0.5575x + 6.7443
R^2 = 0.9371



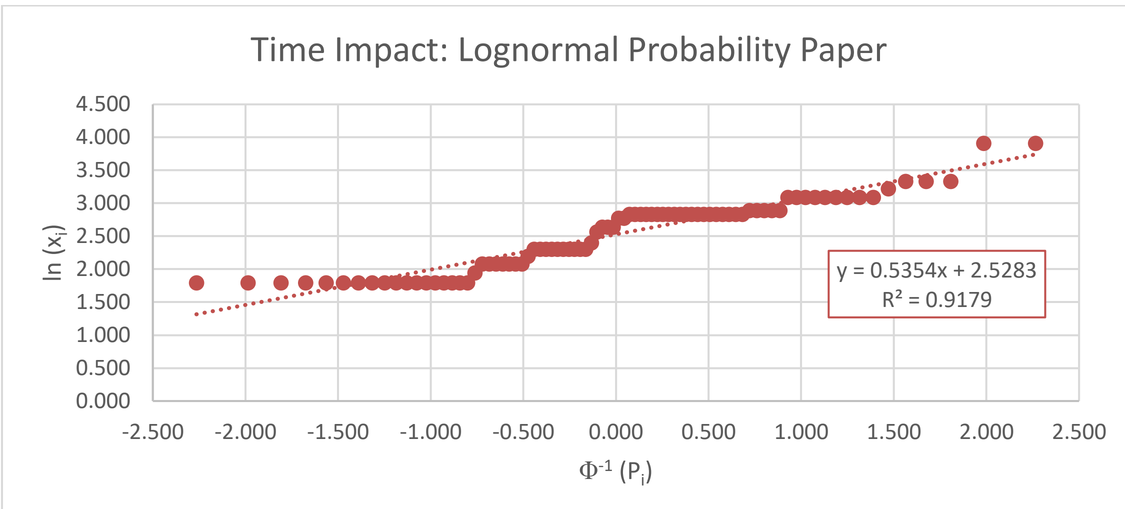
Cost Impact: Weibull Probability Paper
ln (x_i)
9.000
8.000
7.000
6.000
5.000
4.000
3.000
2.000
1.000
0.000
-5.000
-4.000
-3.000
-2.000
-1.000
0.000
1.000
2.000
ln(-ln(1-P_i))
y = 0.4273x + 6.9826
R^2 = 0.8647

NCR Number	Time (Manhour)	Ascending Order	Rank Prob P_i	$\phi^{-1}(P_i)$	ln (x_i)	Weibull Inverse
1	6	6	0.012	-2.265	1.792	-4.437
2	6	6	0.024	-1.986	1.792	-3.738
3	16	6	0.035	-1.808	1.792	-3.326
4	6	6	0.047	-1.674	1.792	-3.032
5	6	6	0.059	-1.565	1.792	-2.803
6	6	6	0.071	-1.471	1.792	-2.615
7	8	6	0.082	-1.389	1.792	-2.454
8	10	6	0.094	-1.316	1.792	-2.314
9	6	6	0.106	-1.249	1.792	-2.190
10	8	6	0.118	-1.187	1.792	-2.078
11	6	6	0.129	-1.129	1.792	-1.976
12	10	6	0.141	-1.075	1.792	-1.883
13	10	6	0.153	-1.024	1.792	-1.796
14	14	6	0.165	-0.975	1.792	-1.715
15	8	6	0.176	-0.929	1.792	-1.639
16	11	6	0.188	-0.884	1.792	-1.568
17	10	6	0.200	-0.842	1.792	-1.500
18	18	6	0.212	-0.800	1.792	-1.436
19	17	7	0.224	-0.760	1.946	-1.374
20	18	8	0.235	-0.722	2.079	-1.316
21	18	8	0.247	-0.684	2.079	-1.260
22	28	8	0.259	-0.647	2.079	-1.206
23	17	8	0.271	-0.611	2.079	-1.154
24	17	8	0.282	-0.576	2.079	-1.103
25	50	8	0.294	-0.541	2.079	-1.055
26	28	8	0.306	-0.508	2.079	-1.008
27	17	9	0.318	-0.474	2.197	-0.962
28	17	10	0.329	-0.442	2.303	-0.917
29	28	10	0.341	-0.409	2.303	-0.874
30	10	10	0.353	-0.377	2.303	-0.832
31	17	10	0.365	-0.346	2.303	-0.790
32	17	10	0.376	-0.315	2.303	-0.750
33	17	10	0.388	-0.284	2.303	-0.710
34	17	10	0.400	-0.253	2.303	-0.672
35	17	10	0.412	-0.223	2.303	-0.634
36	17	10	0.424	-0.193	2.303	-0.596
37	18	10	0.435	-0.163	2.303	-0.560
38	22	11	0.447	-0.133	2.398	-0.523
39	17	13	0.459	-0.103	2.565	-0.488
40	6	14	0.471	-0.074	2.639	-0.453
41	6	14	0.482	-0.044	2.639	-0.418
42	50	14	0.494	-0.015	2.639	-0.384
43	6	16	0.506	0.015	2.773	-0.350
44	14	16	0.518	0.044	2.773	-0.316

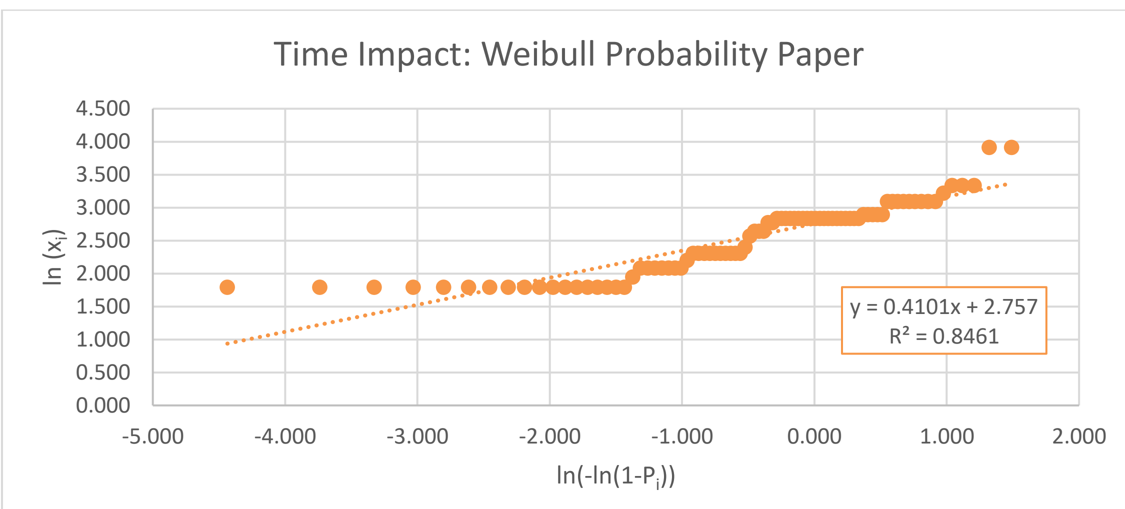
NCR Number	Time (Manhour)	Ascending Order	Rank Prob P_i	$\phi^{-1}(P_i)$	ln (x_i)	Weibull Inverse
45	6	17	0.529	0.074	2.833	-0.283
46	10	17	0.541	0.103	2.833	-0.250
47	6	17	0.553	0.133	2.833	-0.217
48	17	17	0.565	0.163	2.833	-0.184
49	8	17	0.576	0.193	2.833	-0.152
50	6	17	0.588	0.223	2.833	-0.120
51	8	17	0.600	0.253	2.833	-0.087
52	17	17	0.612	0.284	2.833	-0.055
53	22	17	0.624	0.315	2.833	-0.023
54	10	17	0.635	0.346	2.833	0.009
55	6	17	0.647	0.377	2.833	0.041
56	6	17	0.659	0.409	2.833	0.073
57	22	17	0.671	0.442	2.833	0.105
58	9	17	0.682	0.474	2.833	0.137
59	6	17	0.694	0.508	2.833	0.169
60	6	17	0.706	0.541	2.833	0.202
61	17	17	0.718	0.576	2.833	0.235
62	17	17	0.729	0.611	2.833	0.268
63	17	17	0.741	0.647	2.833	0.301
64	22	17	0.753	0.684	2.833	0.335
65	14	18	0.765	0.722	2.890	0.369
66	22	18	0.776	0.760	2.890	0.404
67	8	18	0.788	0.800	2.890	0.440
68	22	18	0.800	0.842	2.890	0.476
69	13	18	0.812	0.884	2.890	0.513
70	16	22	0.824	0.929	3.091	0.551
71	10	22	0.835	0.975	3.091	0.590
72	8	22	0.847	1.024	3.091	0.630
73	22	22	0.859	1.075	3.091	0.672
74	10	22	0.871	1.129	3.091	0.715
75	17	22	0.882	1.187	3.091	0.761
76	18	22	0.894	1.249	3.091	0.809
77	25	22	0.906	1.316	3.091	0.860
78	17	22	0.918	1.389	3.091	0.915
79	22	25	0.929	1.471	3.219	0.975
80	17	28	0.941	1.565	3.332	1.041
81	10	28	0.953	1.674	3.332	1.117
82	22	28	0.965	1.808	3.332	1.207
83	7	50	0.976	1.986	3.912	1.322
84	6	50	0.988	2.265	3.912	1.491



Time Impact: Normal Probability Paper
60
50
40
30
20
10
0
-10
Data (x_i)
-2.500
-2.000
-1.500
-1.000
-0.500
0.000
0.500
1.000
1.500
2.000
2.500
Φ^-1 (P_i)
y = 7.7655x + 14.464
R² = 0.7998



Time Impact: Lognormal Probability Paper
4.500
4.000
3.500
3.000
2.500
2.000
1.500
1.000
0.500
0.000
ln (x_i)
-2.500
-2.000
-1.500
-1.000
-0.500
0.000
0.500
1.000
1.500
2.000
2.500
Φ^-1 (P_i)
y = 0.5354x + 2.5283
R² = 0.9179



Time Impact: Weibull Probability Paper
4.500
4.000
3.500
3.000
2.500
2.000
1.500
1.000
0.500
0.000
ln (x_i)
-5.000
-4.000
-3.000
-2.000
-1.000
0.000
1.000
2.000
ln(-ln(1-P_i))
y = 0.4101x + 2.757
R² = 0.8461

Appendix F
FlexSim Simulation Modelling

When starting a new model, the first decision is specifying the model's units of measure. FlexSim is unit-less, meaning simulations are conducted using general time units and distance units. Therefore it is up to the modeller to specify the units appropriate for the system being modelled. It was determined that metres and minutes are appropriate to serve as the spatial and temporal metrics.

FlexSim relies relies on two resources to model discrete-event simulation, which are the fixed resources and the task executers (mobile resources). In order to break down the activities which process the flow items and the operators that carry out these tasks, a swimlane process flow diagram is able to visually distinguish responsibilities for sub-processes. The complete fabrication workflow as illustrated earlier in Figure 3-4 is modified, where Figure 3-29 exhibits the information required to determine what fixed resources are needed, who is accountable for them, and the logic and events with which items are transferred to the next activity. The research industry partner's prefabrication facilities in Edmonton, Alberta and Cambridge, Ontario were consulted independently to confirm the accuracy of the materials presented in Figure 3-29. It is important to note that not all pipe spool fabrications follow the same process since each project is unique; however, this workflow exemplifies as the majority of typical projects in the industry, therefore it is adequate in representing the sequencing of activities and events.

F.1 Modelling Multi-Process Activities and Feedback Loop

A couple observations can be made from Figure 3-29 in relation to simulation modelling in FlexSim. Firstly, there are some activities carried out by the same operator successively, such as “layout” and “tack spool” by the fitters. These can be represented as a multiprocessor in the model, as shown in Figure F - 1.

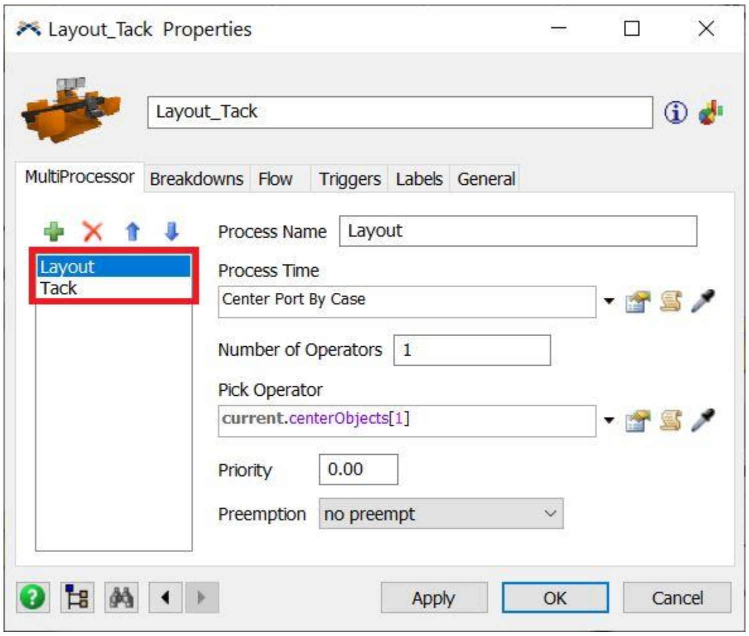


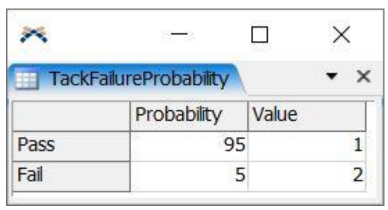
Figure F - 1. MultiProcessor – Layout and Tack

When a flow item enters this multiprocessor, it will automatically go through “Layout” process first as highlighted in red in the left panel, and after processing is finished, the flow item will go through “Tack” and wait for instruction after processing is finished. The reason these two activities are not modelled as one single process is because they have varying processing times, therefore it would be difficult to conduct analysis of the model afterwards.

The second observation from Figure 3-29 is the feedback loop of flow items at different stages of quality control. For example, after tack is completed, the fitters conduct checks on the overall geometry of the pipe spool; if tack is compliant, the spool goes to the welder for full penetration weld, however, if tack is noncompliant, then the fitter needs to remove the tack, and layout the components again for tacking. A number of mechanisms must be applied in FlexSim in order to model the exact representation of the physical processes as described above:

1. A label for the item currently in the multiprocessor is generated at the “On Process Finish” trigger, to determine if the item is tack compliant or not.
2. The probability for the value associated with the label generation is linked to a Global Table.
3. The multiprocessor output port opens/closes based on the value generated for the label, to determine which activity the item needs to be sent next (weld or remove tack).
4. The multiprocessor input port opens/closes based on the value generated for the label, to restrict subsequent flow items from entering the multiprocessor while a flow item is processing or travelling within the feedback loop.

The purpose of generating a label is to simulate the decision after quality control. Label value generation relies on parameters specified in a Global Table, Figure F - 2 shows what a typical table would look like.


TackFailureProbability

	Probability	Value
Pass	95	1
Fail	5	2

Figure F - 2. Global Table – Tack Failure Probability

If a Global Table is linked to label generation within a trigger of a fixed resource, the way the table is set up is that the first column specifies the probability, and its summation must equal to 100. As shown in Figure F - 2, the probability of passing and failing quality control is 95% and 5% respectively. The second column specifies what value is being assigned to the particular label. In this case the label value of 1 has a 95% probability of being generated.

When a flow item finishes processing in the multiprocessor (i.e. after tack process is complete), the “On Process Finish” trigger is prompted, and the action is to “Set Label”. Figure F - 3 displays the parameters associated with setting up a label.

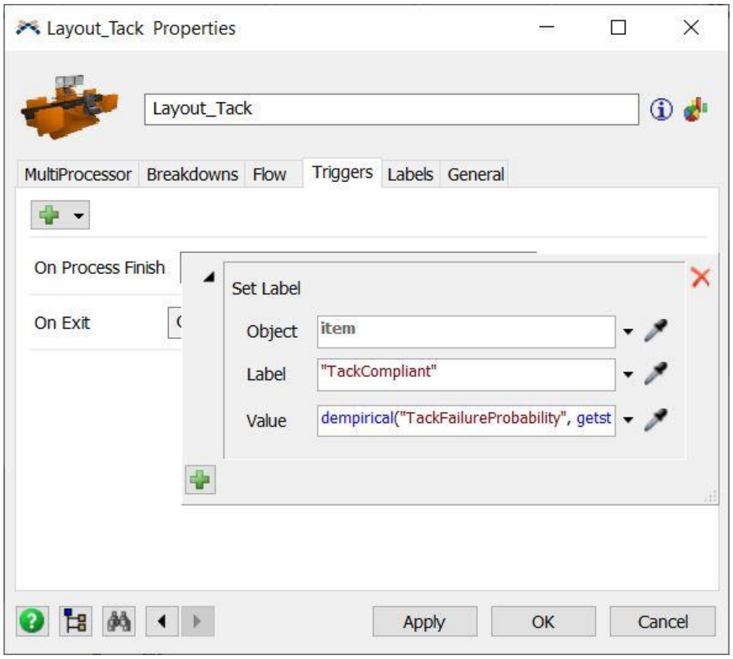


Figure F - 3. MultiProcessor – "On Process Finish" Trigger to Set Label

The Object field specifies what is being assigned a label, and in this case "item" refers to the flow item that is currently in the multiprocessor, and "TackCompliant" is the name of the specific label attached to the item. The Value field can be modified by a couple of options, by either following a statistical distribution or linking to a Global Table directly. In this case, the discrete empirical distribution "dempirical" is used, and it references the "TackFailureProbability" Global Table, as shown previously in Figure F - 2, to return the explicit value listed in the table based on its associated probability. The FlexScript code of this trigger is as follows:

```
Object current = ownerobject(c);
Object item = param(1);
int opnum = param(2);
{ // ************* PickOption Start ************* //
/***popup:SetLabel*/
/**Set Label*/
Object involved = /** \nObject: *//***tag:object*//**/item/**/;
string labelname = /** \nLabel: *//***tag:label*//**/"TackCompliant"/**/;
Variant value = /** \nValue:
*//***tag:value*//**/dempirical("TackFailureProbability",
getstream(current))/**/;
involved.labels.assert(labelname).value = value;
} // ******* PickOption End ******* //
```

The “getstream” command of the code returns a unique random stream associated with the current object, which is the multiprocessor. If the object does not yet own a stream attribute, or if its stream attribute is 0, FlexSim will assert the attribute and assign it a unique stream number. The algorithm uses a prime modulus multiplicative linear congruential generator (PMMLCG) as a “random number generator” to create a stream, which is actually a list of pseudo-random numbers. The algorithm is based on the following formula:

$$Z_i = (aZ_{i-1}) \bmod m^*$$

where a is assigned the value of 630,360,016 and $m*$ is assigned the value of $2^{31} - 1$ (Marse and Roberts 1983). Each stream will generate a uniquely different set of numbers because each stream is initiated with a unique seed value.

After the “On Process Finish” trigger is completed and the flow item is ready to exit the multiprocessor, the “On Exit” trigger is activated, and it takes advantage of the label value assigned previously to control its action to “Close and Open Ports”. Figure F - 4 displays the parameters associated with port control.

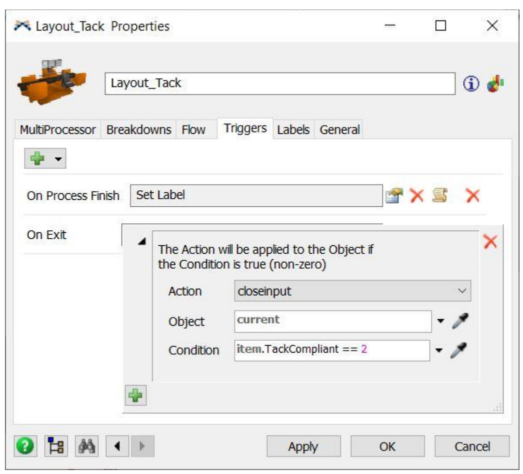


Figure F - 4. MultiProcessor – “On Exit” Trigger to Close and Open Ports

The Action dropdown menu specifies what response will be triggered, and in this case “closeinput” forces the “current” Object, which is the multiprocessor, to close all of its input ports to prevent upstream flow items from entering. This trigger is activated only when its condition is met, which is when a value of 2 is assigned to the TackCompliant label. Recall previously in Figure F - 2 that this value is associated with failing quality control. There are two reasons for forcing the input port of the multiprocessor to close. First of all, in the physical system, the same fitter who had previously performed the layout and tacking of pipe spool components would also be responsible for removing the tack, and typically each station is manned by one fitter at a time; the fitter does not work on the next spool until the current spool has been passed down to the welder. Secondly, if the first flow item exits the “Layout_Tack” multiprocessor and enters the “Remove_Tack” processor, and there is an available flow item upstream ready to enter the multiprocessor, it will require the fitter to transport and process the flow item in the multiprocessor. After processing, if the second flow item is assigned a value of 2 to its TackCompliant label, then the feedback loop becomes stuck. The second flow item in the “Layout_Tack” multiprocessor cannot enter the “Remove_Tack” processor since the first flow item is already there, and the first flow item in the “Remove_Tack” processor cannot enter back into the “Layout_Tack” multiprocessor since the second flow item is also there. Therefore the restriction of fixed resource input ports using the “On Exit” trigger is an effective mechanism to control the feedback loop. Note there are multiple approaches to achieve the same result, the means described above is the one implemented in simulation modelling of this research.

When the multiprocessor is done processing, the flow item has two possible destinations downstream: (1) “Remove_Weld” processor or (2) “Weld” processor. Figure F - 5 depicts the hierarchy of output ports.

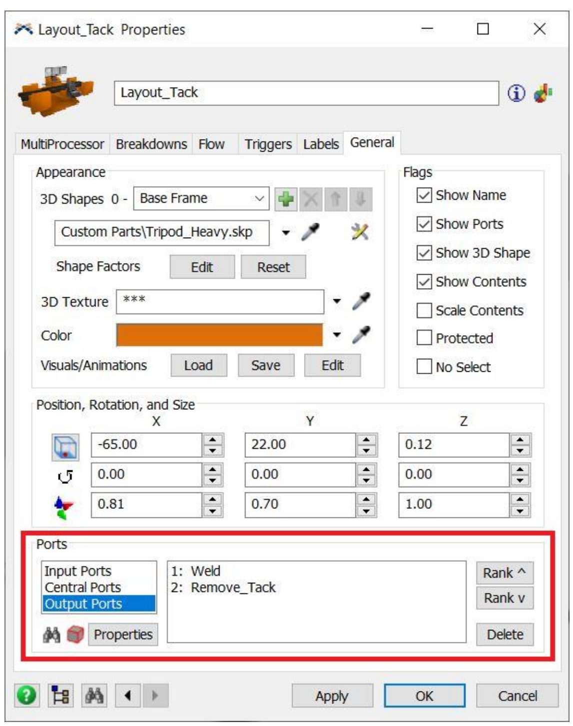


Figure F - 5. MultiProcessor – Output Ports

Rank 1 means Output Port 1 of the multiprocessor is linked to the "Weld" processor, and similarly rank 2 means Output Port 2 of the multiprocessor is linked to the "Remove_Tack" processor. The distinction between the output ports is important since it affects where the flow item will exit.

Finally, after generating a label and assigning a value to the label, as well as establishing the connection between the output ports and the downstream objects, rules dictating which output port the flow item will exit need to be enacted. Figure F - 6 displays the conditional procedure for controlling exit.

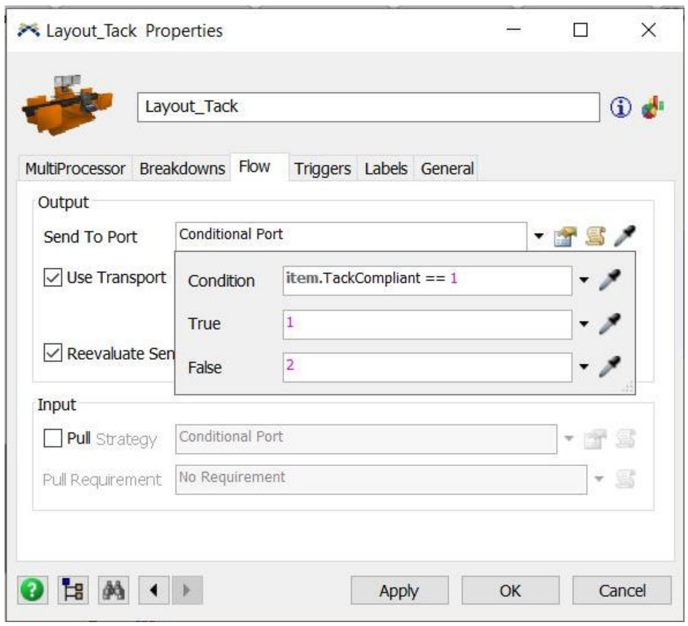


Figure F - 6. MultiProcessor – Send To Port

In FlexSim, the "Send To Port" function is a picklist that returns the output port number connected to the object that the flow item should be moved to. The default is "First Available", where all outputs are opened and the flow item is moved to the first downstream object that is able to receive it. However, in this case, since the destination matters depending on the quality control decision, "Conditional Port" is used. It specifies that if the TackCompliant label of the flow item currently in the multiprocessor has a value of 1 (passes quality control), then it will exit through Output Port 1 (linked to the "Weld" processor). For all other cases, i.e. TackCompliant label has a value of 2 (fails quality control), then the flow item will exit through Output Port 2 (linked to the "Remove_Tack" processor).

Thus completes the modelling of successive multi-process activities in the pipe spool fabrication workflow using FlexSim's MultiProcessor fixed resource, where layout and tacking are completed by the same fitter at the same station, and each process is able to modify its own processing times. The generation of label at "On Process Finish" trigger and the assignment of its value based on the "TackFailureProbability" Global Table are an integral part of controlling the feedback loop between the "Layout_Tack" multiprocessor and the "Remove_Tack" processor. Both "On Exit" trigger and "Send To Port" function capitalise on the label to regulate the opening and closing of the multiprocessor's input ports and output ports, ensuring the system in the model is exercising the exact same procedure as the physical fabrication workflow.

F.2 Modelling Task Executers Functions and Behaviours

The logic of feedback loop between the multiprocessor (layout and tacking) and the processor (removing tack) is established, and now the act of processing flow items and the movement of the transport systems need to be modelled. Two types of task executer are used in the feedback loop, which are the Operator and the Crane. In order for the task executers to execute a given task, they must be connected to the fixed resource that is calling out to them. Figure F - 7 depicts the central ports ranking of the "Layout_Tack" multiprocessor.

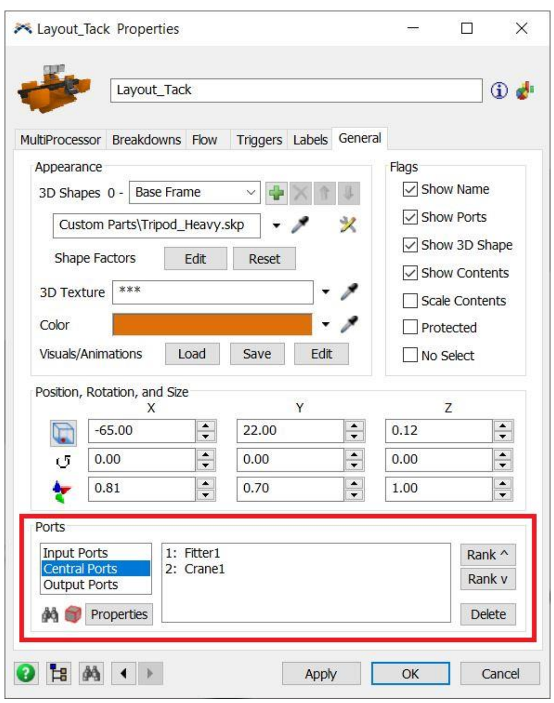


Figure F - 7. MultiProcessor – Central Ports

Rank 1 means Central Port 1 of the multiprocessor is linked to the operator named “Fitter1”, and similarly rank 2 means Central Port 2 of the multiprocessor is linked to the crane named “Crane1”. Analogous to the hierarchy of the output ports, the distinction between the central ports is important since it affects which task executer is performing a given task required by the fixed resource. In the case of the feedback loop, “Fitter1” is responsible for the processing of flow items as they go through both the “Layout” process and the “Tack” process in the multiprocessor. Figure F - 8 shows the “Pick Operator” function of the “Layout” process linking to Central Port 1, which is “Fitter1”. On the other hand, “Crane1” is responsible for the transport of flow items as they move from station to station during the fabrication workflow. Typically pipe spools are hooked up and secured by several straps, then carried by overhead crane across the work bay to the next location, whether it be for welding or final shipment spool laydown. Figure F - 9 shows the “Use Transport” function of the multiprocessor linking to Central Port 2, which is “Crane1”.

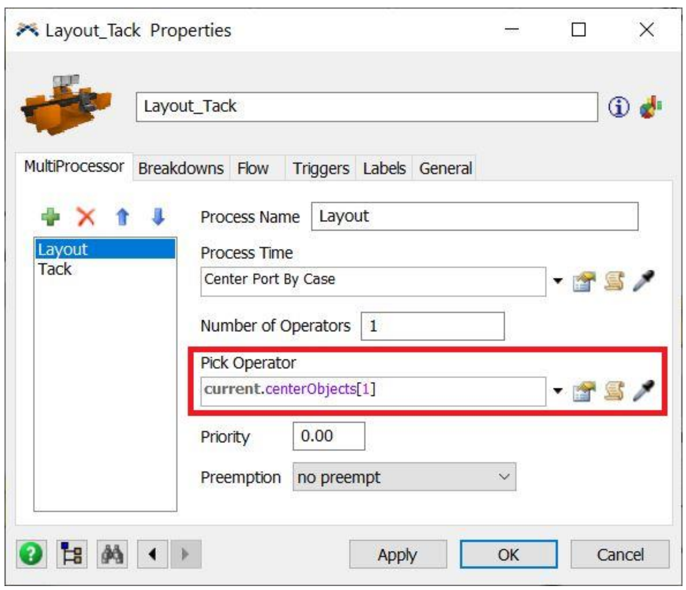


Figure F - 8. MultiProcessor – Pick Operator

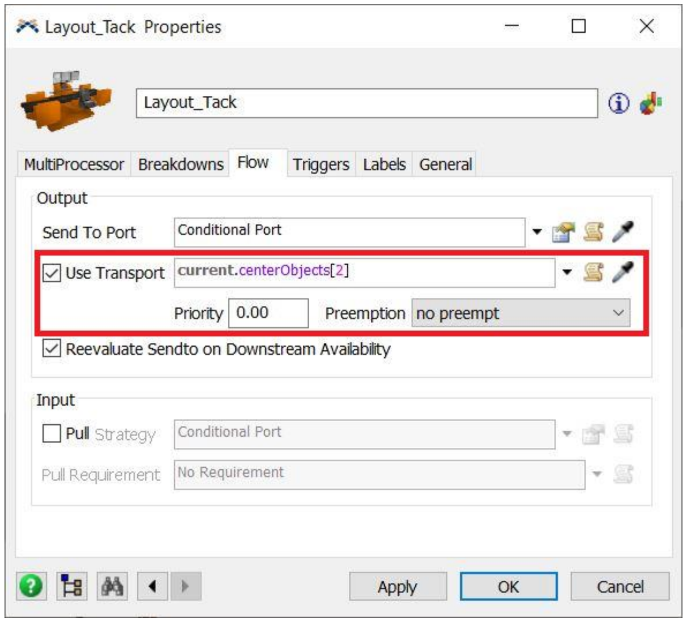


Figure F - 9. MultiProcessor – Use Transport

If the "Pick Operator" function does not specify a particular task executer to process the flow items, the flow items will still be processed by the fixed resource itself under the specified processing times. Likewise, if the "Use Transport" function is not used or it does not specify a particular task executer to transport the flow items to the downstream fixed resource, then the flow items will automatically teleport to the next station according to the "Send To Port" control. It is important to note that the code associated with specifying the central port only identifies with the port, not the task executer itself. For example, if the ranking of the multiprocessor central port is reversed, i.e. Central Port 1 is "Crane1" and Central Port 2 is "Fitter1", then the "Use Transport" function in Figure F - 9 would call out "Fitter1" to transport flow items instead of the intended task executer, which should be "Crane1" (Central Port 1).

In the model, the task executers would theoretically work nonstop whenever they are given a task to perform by the fixed resources, until the simulation run ends. However, this is not true in the physical process of pipe spool fabrication. A typical craft worker in prefabrication would have an eight-hour work day, with three breaks in total: (1) a 15-minute break two hours into the shift, (2) a 30-minute break four hours into the shift, and (3) another 15-minute break six hours into the shift. In FlexSim, Time Tables are used to specify deterministic resource availability, such as shift schedules and break times, or any planned downtimes that occur on a known and recurring basis. Figure F - 10 exhibits a Time Table for the operators, which lists the members that will adhere to this command.

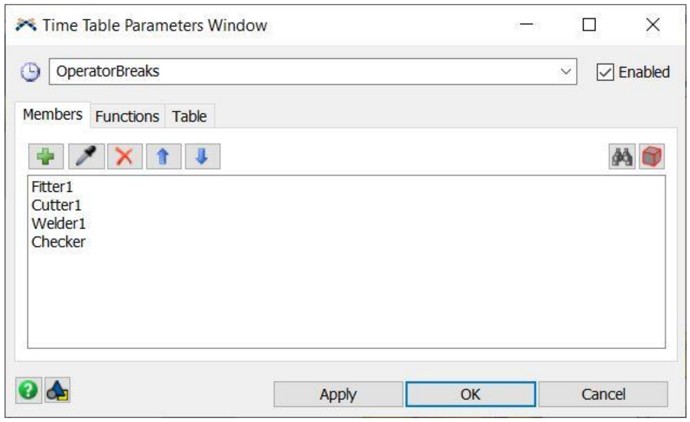


Figure F - 10. Time Table – Members

In this case, only the operators in the model are selected since the scheduled breaks only affect them, however, any object can be subjected to a downtime or multiple types of downtimes. For example, a fixed resource undergoing routine inspections for its components would need to use a Time Table to schedule the timings and their durations. Next, Figure F - 11 shows the functions that control members of the table.

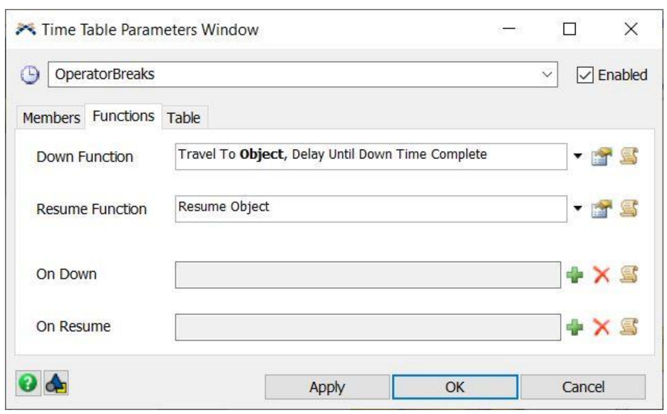


Figure F - 11. Time Table – Functions

Functions are used to control what happens when a resources goes down and then resumes. By default, FlexSim stops the object wherever it is and whatever it is doing, and it remains at that location for the prescribed duration. While this may be true, a more realistic model would be to have the operators take their break in a specified location (e.g. lunch room). In this case, the Down Function "Travel To Object, Delay Until Down Time Complete" prompts the operators to travel to a network node that acts as a proxy for lunch room, and remain there until the schedule down time is complete. The default Resume Function "Resume Object" simply allow the operators to become available again to receive call outs from any resources that have their central ports connected to them. Lastly, Figure F - 12 displays the exact timing and duration of the scheduled downtime.

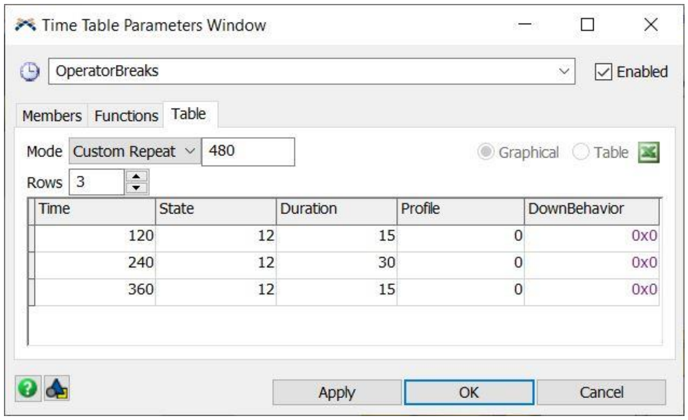


Figure F - 12. Time Table – Table

The Time column sets when the resources would become unavailable, and the Duration column specifies for how long the resources would be unavailable. Recall that when the model was first created, the unit of measure for time is in minutes, therefore the data input in the Time Table must be in minutes as well. In the table, at 120 minutes (two hours) into the simulation run, a 15-minute downtime takes place, and similar events take place for the next two scheduled breaks. The Mode of this table is set to "Custom Repeat", meaning the downtime pattern that is entered in this table will repeat every eight hours (480 minutes) of simulation time as indicated. By doing so, the downtimes for each shift do not have to be explicitly included in the time list, and the pattern would repeat as long as the simulation runs. Furthermore, the State column has the value of 12 for all the rows, which is associated with the state "Scheduled Down"; whenever an operator is on break, their state would change from "Idle" or "Processing" or whatever its state is at the time, to "Scheduled Down".

Although the operators now have their breaks, the crane as a task executer still acts independently, and therefore would be able to transport the flow items between fixed resources. In reality, the crane is controlled by the operators, therefore should not be performing its task when the operators are away. There are many approaches to implement this behaviour, and the easiest solution is to create another Time Table that includes "Crane1" as its member, and match the exact same scheduled downtime and duration as the operators. The only difference would be instead of travelling to the lunch room with the operators, the hoist of the crane would simply stop wherever it is and whatever it is doing.

Thus completes the modelling of task executers, which include the operators that perform the action of processing flow items in the fixed resources, as well as the crane that transports flow items from one fixed resource to the next; these behaviours are carried out as long as the task executer is connected to the fixed resource through the central port, and the functions correctly specify which port to call out. Their breaks throughout the shift are also taken into account in the model, where the use of Time Table is able to effectively schedule downtimes as well as their duration. As explained previously regarding travel systems, A* navigator is used to model the movements of the task executers.

F.3 Modelling Spatial Environment and Flow Items

FlexSim allows importing layouts and modifying object graphics for specific applications. For example, hospital floor plans and dialysis equipment would be used for healthcare, and warehousing might require a rack layout and ASRS systems. Building models on a layout makes setting sizes, locations, and distances much easier; this is especially important when considering the transport of items between objects by task executers since distance affects system performance. The research team visited the partner's fabrication facilities in order to gain a better understanding of the physical work environment, pipe spool fabrication procedure, and machineries used. Figure F - 13 illustrates the shop layout at the partner's prefabrication facility located in Cambridge, ON.

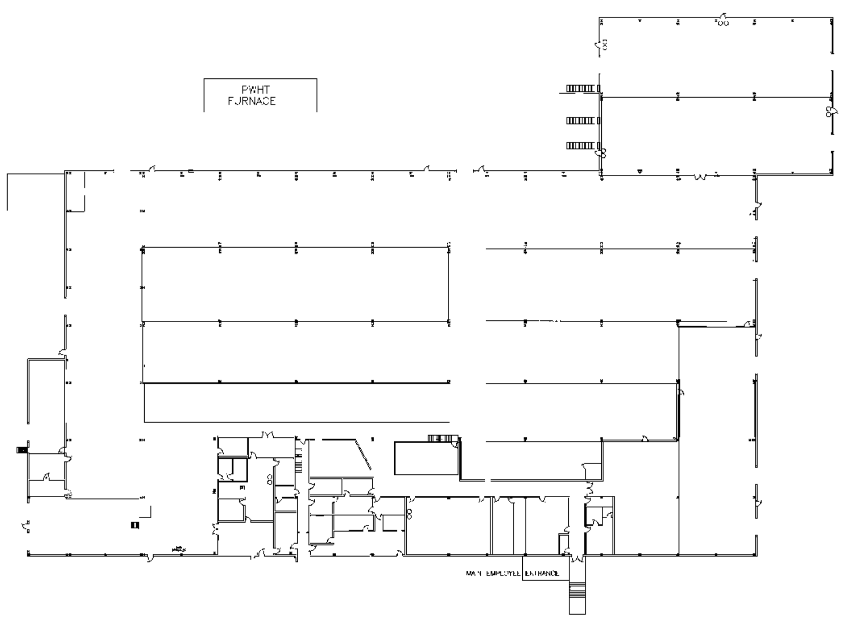


Figure F - 13. The Partner's Shop Layout in Cambridge

There are 18 bay doors around the main fabrication facility, allowing trucks to enter to unload materials and ship spools to site. The shop is partitioned into 12 bays, with each bay equipped to manage specific projects. Specifically, there are five bays intended for small bore pipes sized less than 12” in diameter, three bays intended for large bore pipes sized between 12” and 24”, and four large bore pipes sized over 24”. The layout is imported into the model to scale, and objects are subsequently placed in their appropriate locations, creating a rigorous model that accurately represents the physical process.

Specific objects can also be imported into the model, to create a detailed model that reflects physical equipment used, thus providing a more intuitive visualisation. In FlexSim, any object’s 3D shape can easily be customised. For example, 3D shapes created in AC3d, 3ds Max, SketchUp, etc. can be directly imported into the model, as can objects from the extensive and open-source 3D Warehouse.

FlexSim has several default 3D shapes to represent flow items, such as a box, a cylinder, or a sphere. To visualise the fabrication of pipe spools better, a feeder spool fabricated at the partner’s Cambridge facility for the mock-up of Darlington Nuclear Generation Station in Ontario was used as a reference. The feeder spool has four distinct components: (1) hub end, (2) pipe segment 1, (3) reducer, and (4) pipe segment 2. Figure F - 15 to Figure F - 18 in the follow pages illustrate how they look in 3D from different angles. The complete assembly was originally created in Autodesk Inventor, and it was segmented into the four components mentioned earlier, and subsequently combined to create three new spools, as illustrated in Figure F - 20 to Figure F - 22. The four individual components and three new spools are exported from Inventor into STL, a file format that describe only the surface geometry of a 3D object with unstructured triangulated surface by the unit normal and vertices of the triangles. FlexSim is able to import STL files as custom 3D objects to be used as flow items.

In the model, the “Source” fixed resource can only generate one type of flow item, therefore four sources are needed to model the receipt of the four components needed for the pipe spools. Each source specifies what flow item it is creating and sending to the downstream fixed resource. Figure F - 14 shows an example fixed resource that generates the Hub component.

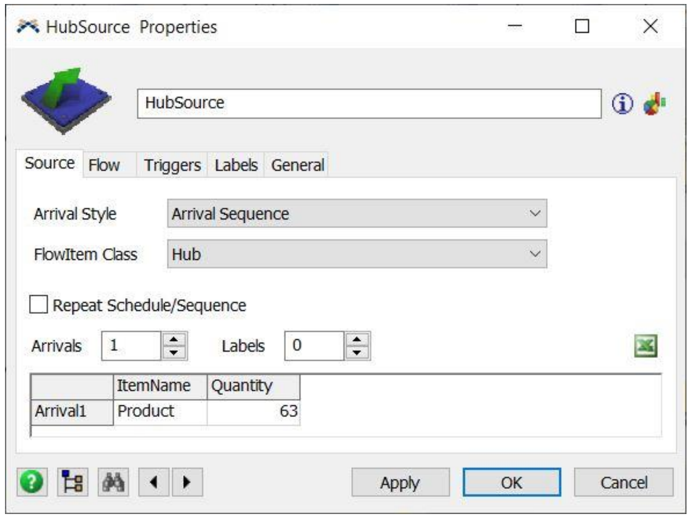


Figure F - 14. Source – Hub

There are three different "Arrival Style" functions to be chosen, the default is "Inter-Arrival Time" based on a statistical distribution. The simulation would theoretically run forever, since the flow items would continue to be generated, unless a specific simulation stop time is established. To keep the coming analysis consistent, a limited number of flow items would ensure the simulation ends when the last flow item has been processed and exits the model. This consistency would also allow the analysis to compare runtime between different scenarios, which are to be described in Section 3. To limit the number of flow items, "Arrival Sequence" option as shown in Figure F - 14 sets the quantity of items generated by the source at each specific arrival wave, and in this case the model assumes all the materials are received at once by the supplier, therefore only one arrival is specified. While typical prefabrication projects in the industry would see components arrive in different batches, the supply chain of these materials are not within the scope of this research, and would not have a significant impact on the research interest of risk mitigation during fabrication.

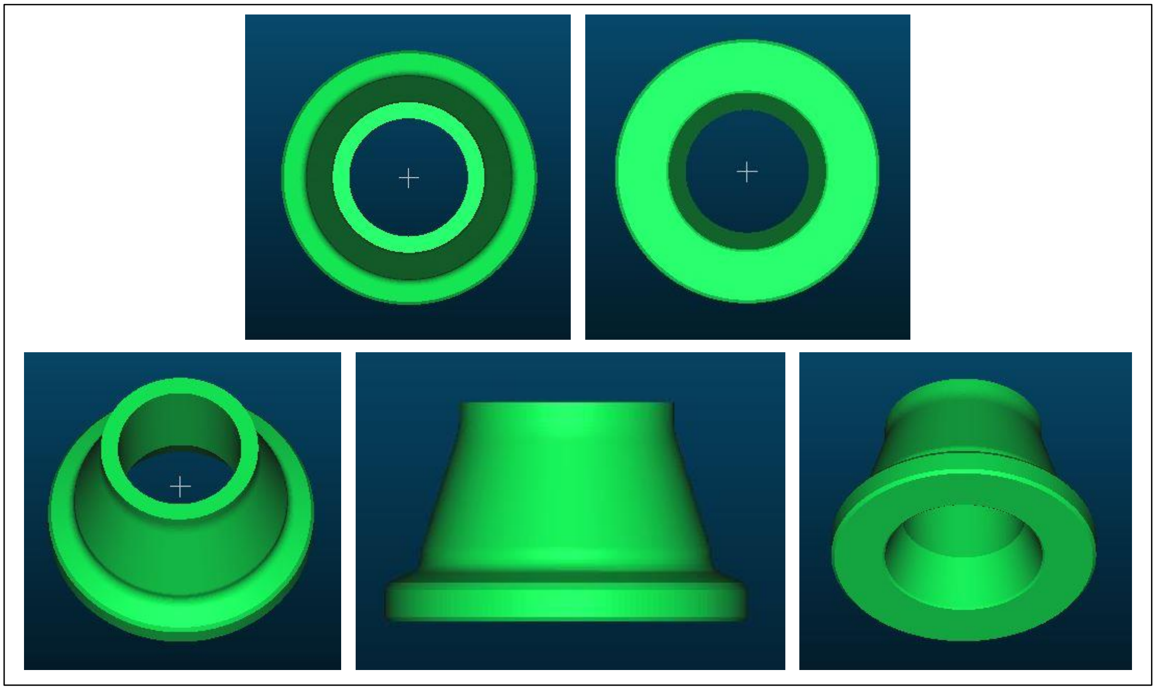


Figure F - 15. Spool Model – Hub

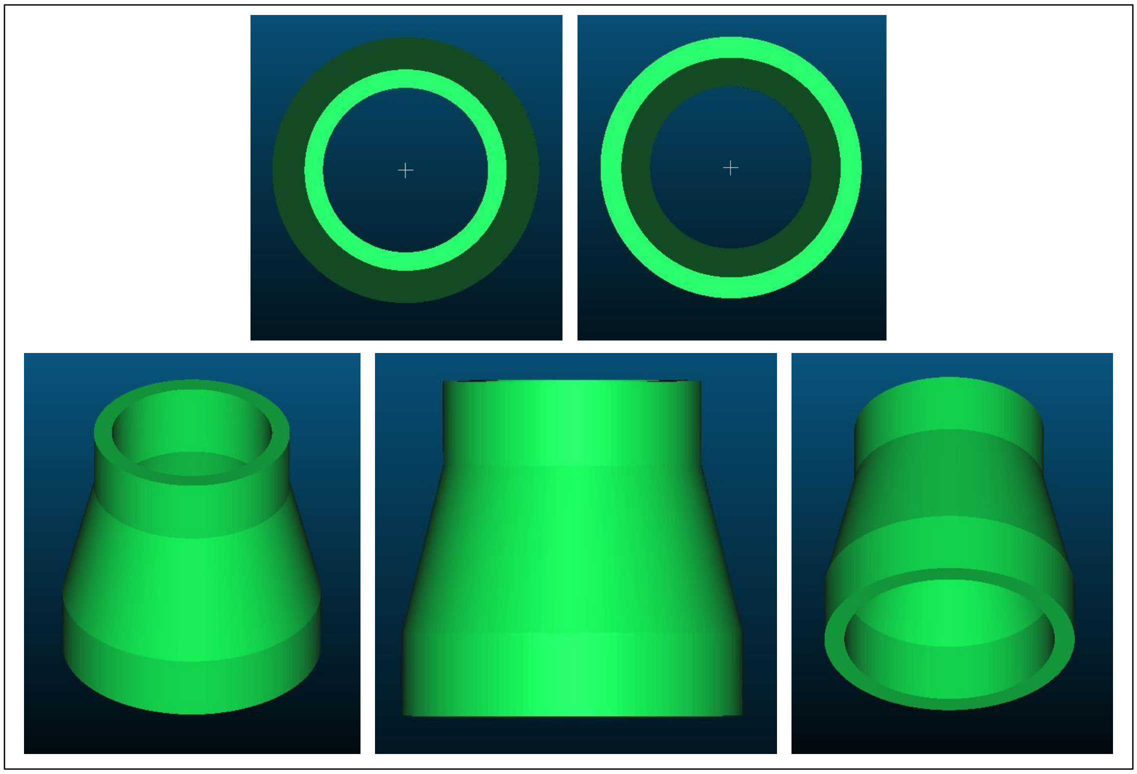


Figure F - 16. Spool Model – Reducer

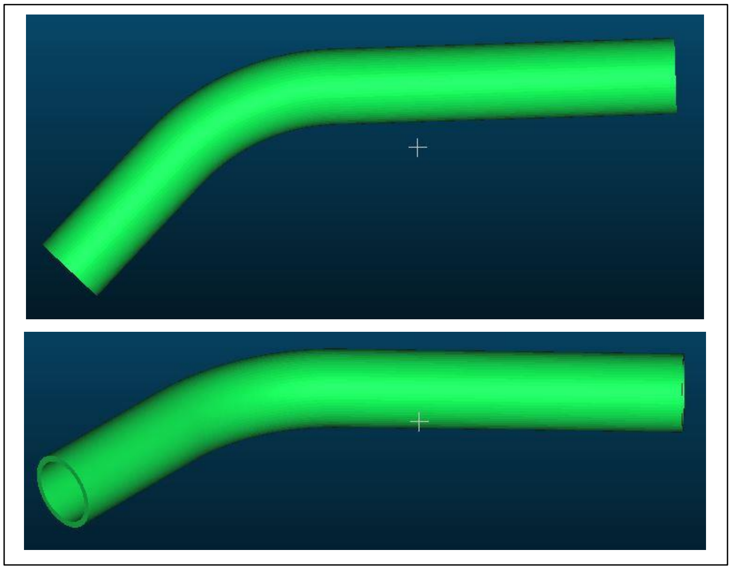


Figure F - 17. Spool Model – Pipe 1

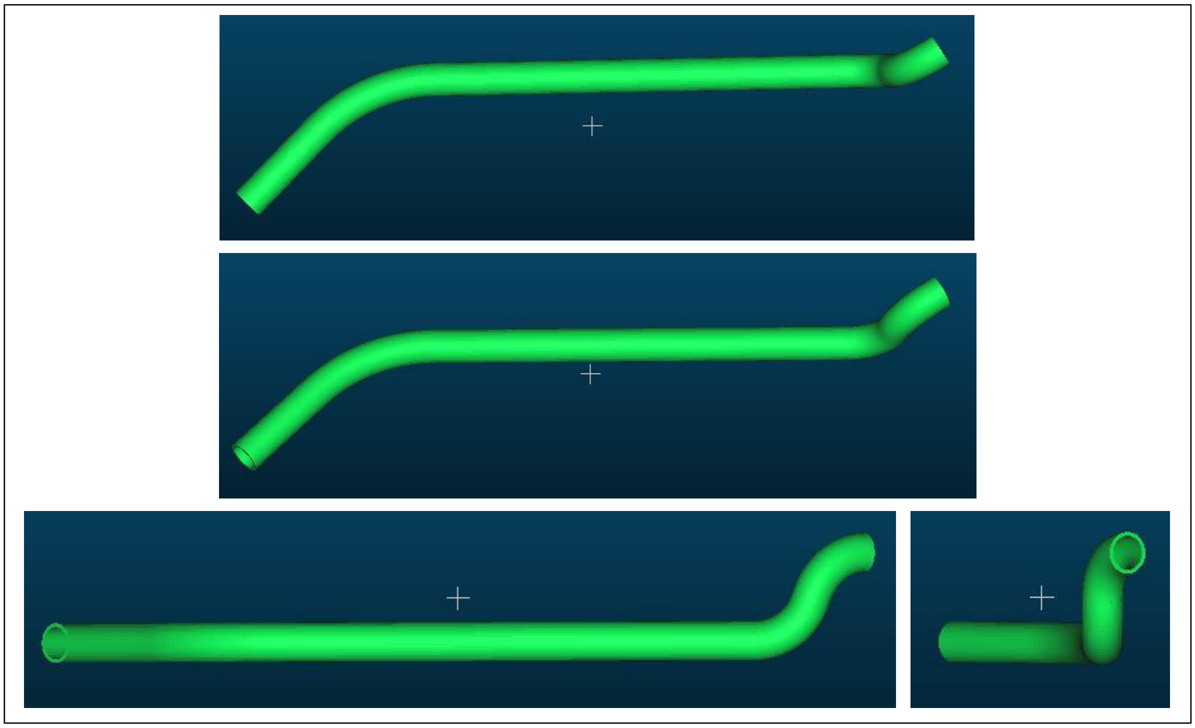


Figure F - 18. Spool Model – Pipe 2

Three spools are created using the four components shown from Figure F - 15 to Figure F - 18. The first spool will have two components, the second spool will join an additional component to the first spool, and lastly the third spool will join the last component to the second spool. Figure F - 19 outlines the creation of the three pipe spools used in this model. While it might be more accurate to generate spools using completely different components, it does not affect system performance since it would take a similar amount of time to simulate their processing in the model.

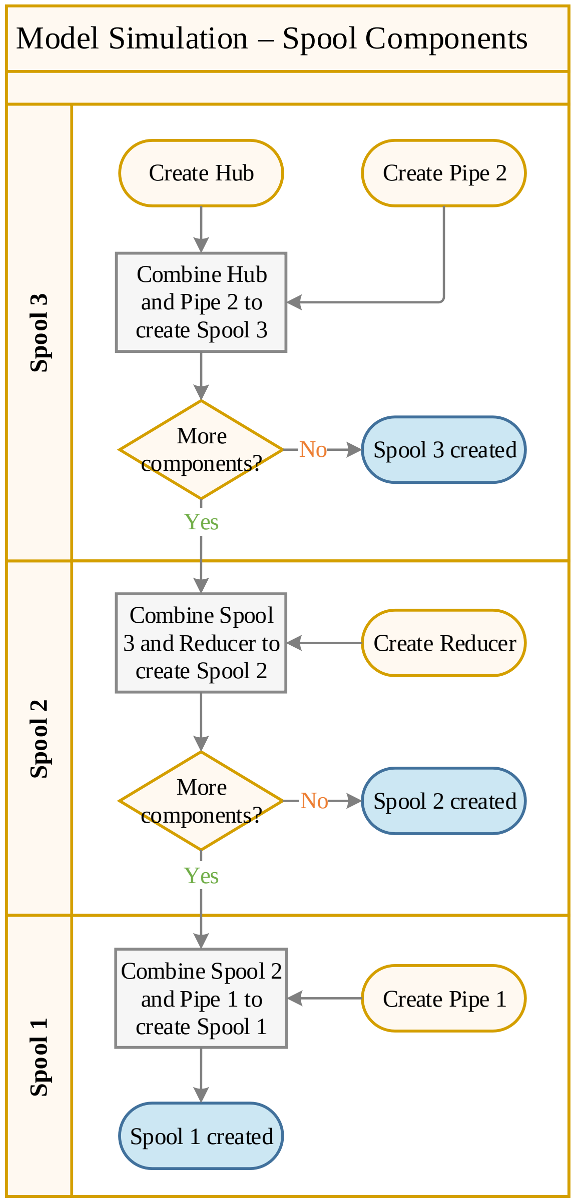


Figure F - 19. Spool Model Creation Flow

The creation of the three pipe spools in the model is relatively consistent and linear, taking advantage of the same components shared between them in different combinations. Figure F - 20 to Figure F - 22 in the following pages illustrate how the spools look in 3D from different angles.

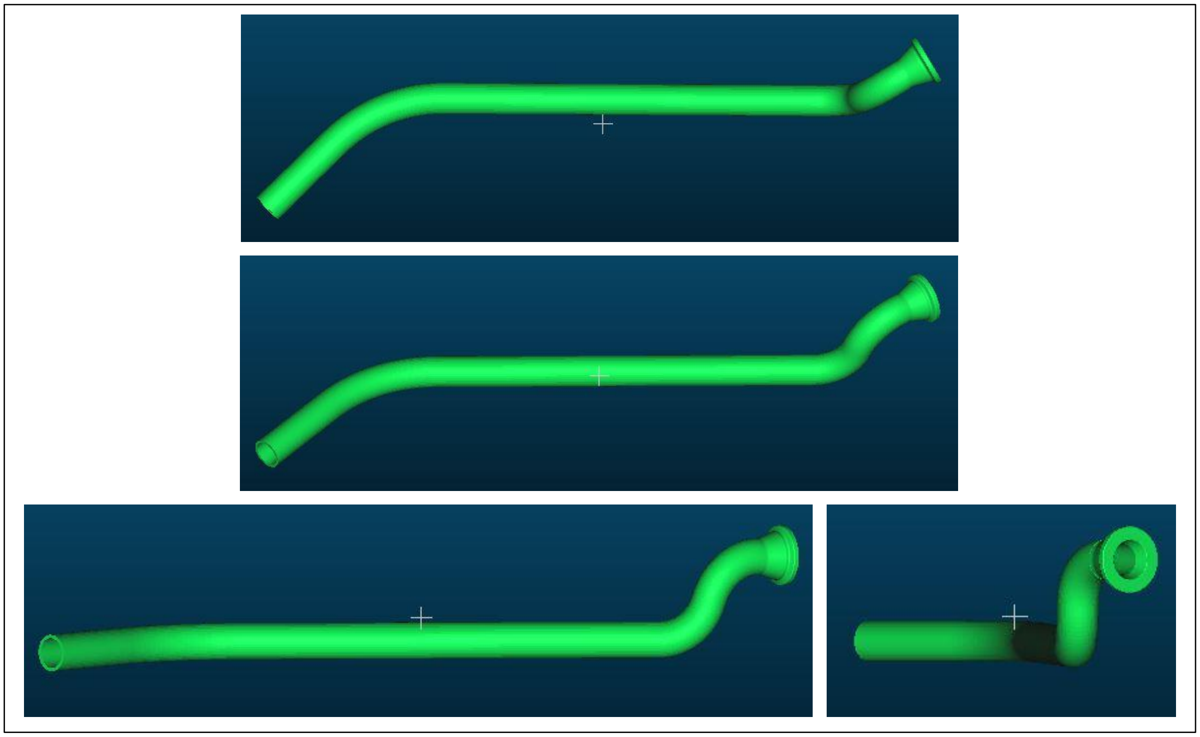


Figure F - 20. Spool Model – Spool 3

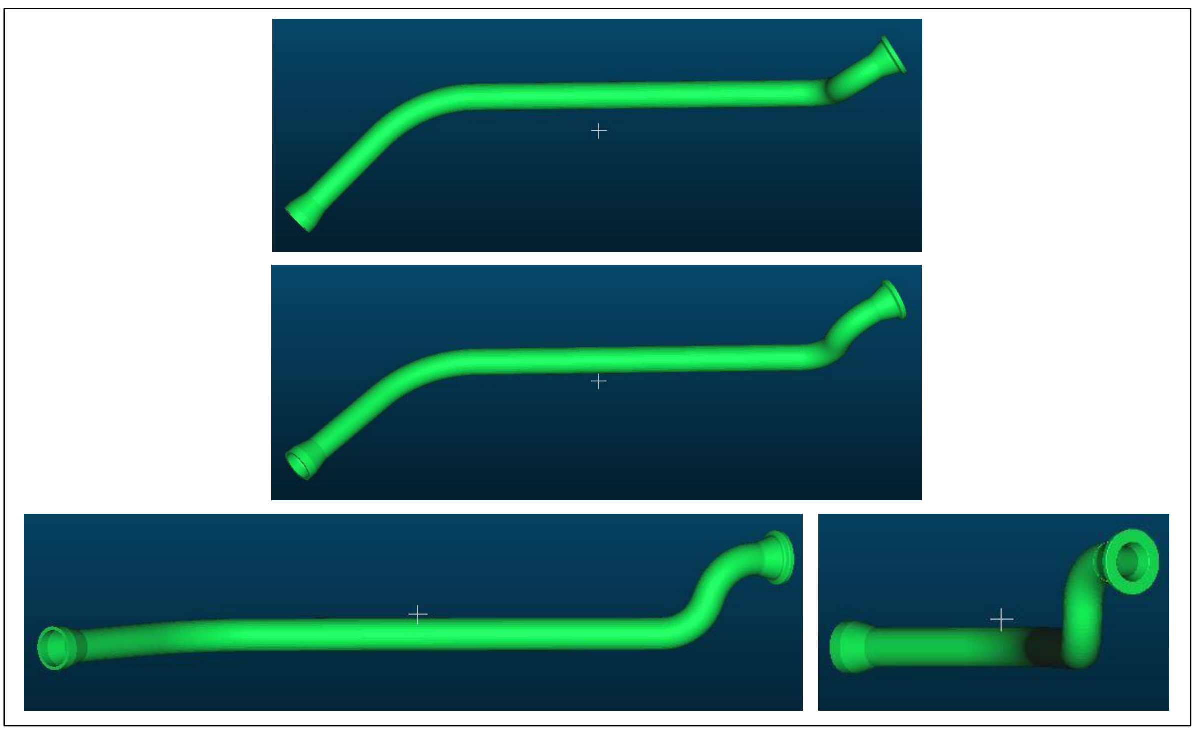


Figure F - 21. Spool Model – Spool 2

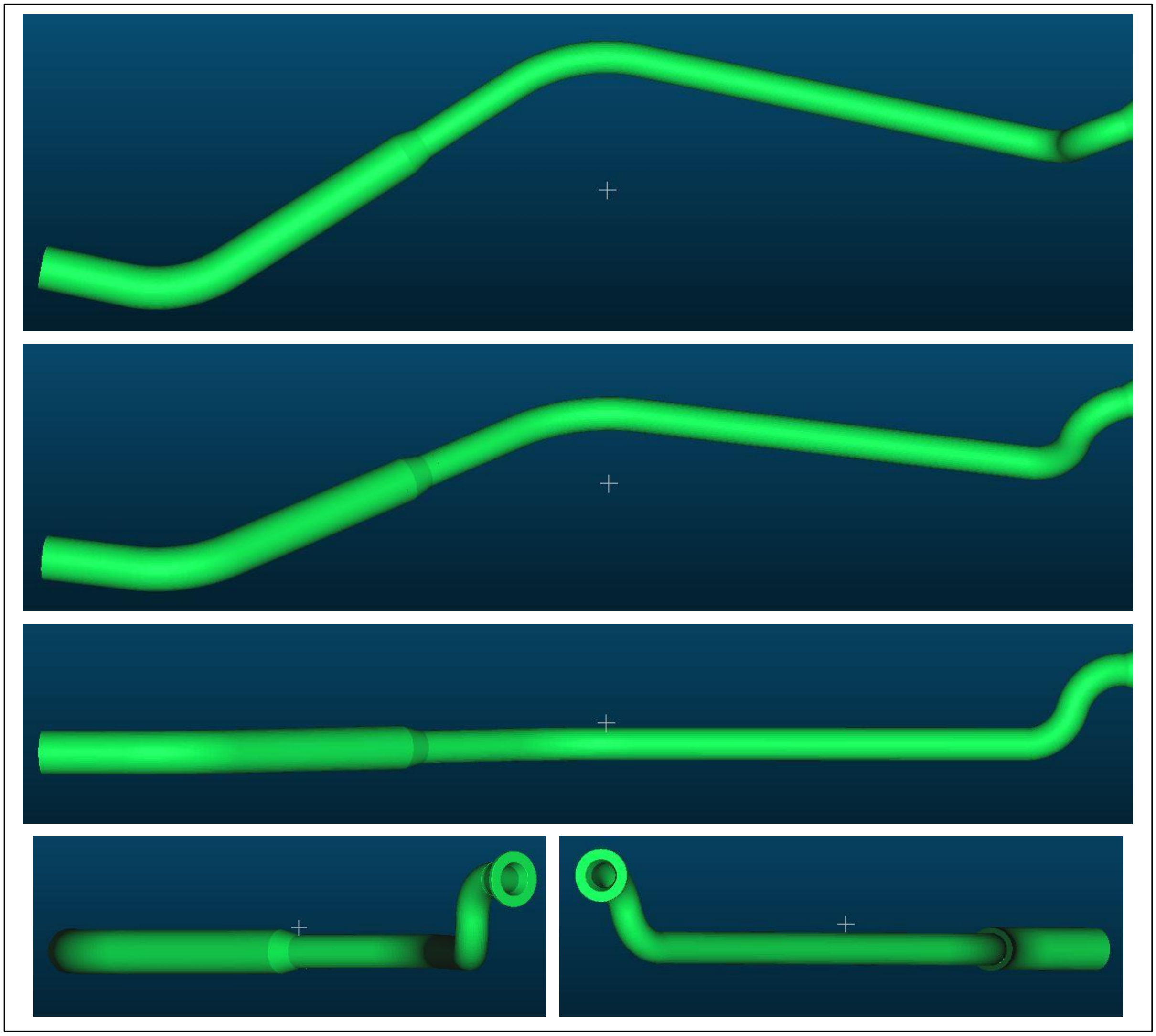


Figure F - 22. Spool Model – Spool 1

The four components need to be imported into FlexSim specifically as flow items, otherwise the “Source” fixed resources would not be able to select and generate them. Similarly, the three pipe spools also need to be imported as flow items, so they can be created during the fabrication process in the model, and be passed through the fixed resources until they eventually exit through the “Sink” fixed resource, symbolising shipment to site. Figure F - 23 shows the viewer within FlexSim that lists all the flow items available in the model, and allows their properties to be modified.

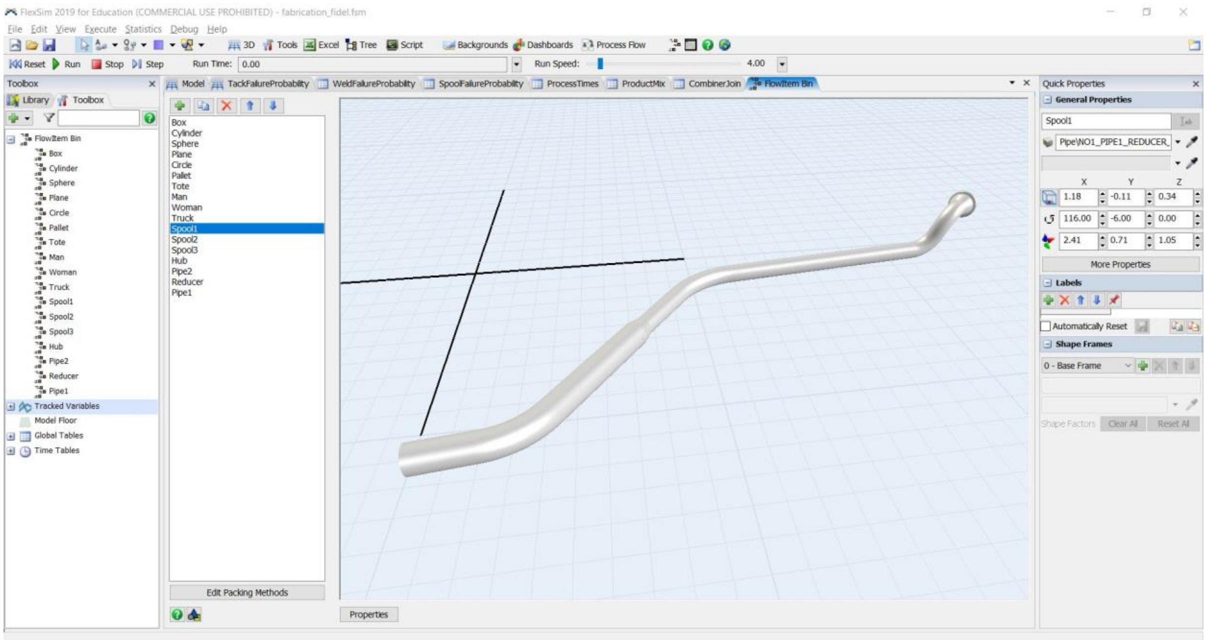
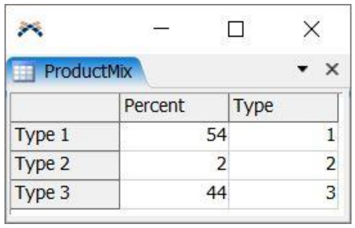


Figure F - 23. Flow Item Bin

Several mechanisms are applied in FlexSim in order to model the visualization of joining components into spools:

1. A label “Type” for Pipe 2 is generated in the “Source” fixed resource at the “On Creation” trigger, to specify what type of spool the component belongs to during fabrication.
2. The probability for the value associated with the label generation is linked to a Global Table.
3. Another label “AddComp” for Pipe 2 is generated again in the “Source” fixed resource at the “On Exit” trigger, to indicate how many additional components the spool type needs.
4. The label “AddComp” is modified in the “Queue” fixed resource after welding.
5. Another label “Join” for the pipe spool in same “Queue” fixed resource is generated at the “On Exit” trigger, to control what components need to be joined to the spool.
6. The “Combiner” fixed resource is used to join the components together to create spools, and its input ports close/open based on the value specified for the “Join” label.
7. The 3D shape for the flow item currently in the “Combiner” fixed resource is specified and changed at the “On Process Finish” trigger.

The purpose of generating a label is to simulate the different types of spools a typical project would encounter. Label value relies on parameters specified in a Global Table, as shown in Figure F - 24.



	Percent	Type
Type 1	54	1
Type 2	2	2
Type 3	44	3

Figure F - 24. Global Table – Product Mix

Similar to the Global Table that defines tack failure probability in Section F.1, the first column specifies the probability, and its summation must equal to 100. Type 1 refers to the spool with all four components, Type 2 has three components, and Type 3 only has two component. Their probability is based on the feeder spool project for the mock-up of Darlington Nuclear Generation Station, where a total of 63 spools were shipped to site. There were 28 spools that required four components (Type 1), one spool that required three components (Type 2), and 23 spools that required two components (Type 3); the rest of the spools only had one component, so the material received from the supplier is transported directly to site without any additional modifying work.

When the flow items are generated in the source, the “On Creation” trigger is prompted, and the action is to “Set Label”. Figure F - 25 displays the parameters associated setting up the label.

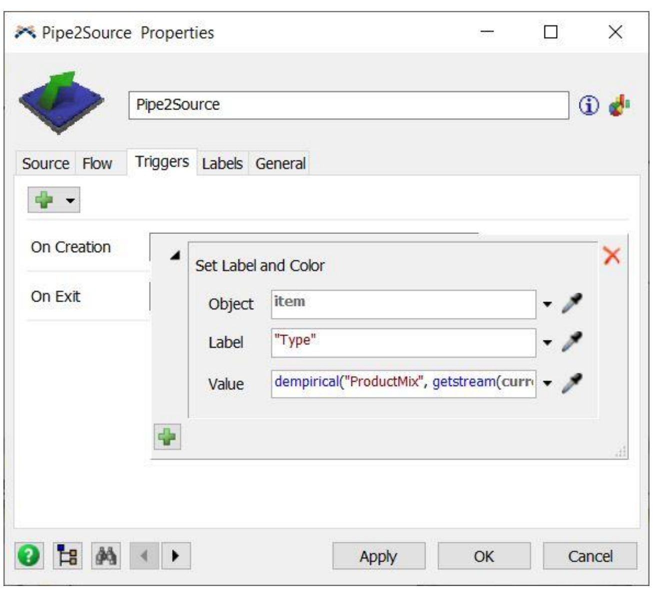


Figure F - 25. Source – “On Creation” Trigger to Set Label

The label is applied to Pipe 2 in the model because it is one of the first two components to be combined into a spool, and the label will be attached to the flow item until it exits. This means that for a flow item prescribed as Type 1, even if its 3D shape is that of Type 3, the label designation will dictate where the flow item travels to in the model and if additional components need to be added to the spool, until the 3D shape matches its label. Pipe 2 also exists in all three types of feeder spool, so the label only needs to be applied at this source once, instead of specifying to the sources for the other three components as well. The Object field specifies that the "item", which is the flow item that is currently in the source, would be attached with a label named "Type". The value of the label depends on the discrete empirical distribution "dempirical", which references the "ProductMix" Global Table, as shown previously in Figure F - 24, to return the explicit value listed in the table based on its associated probability.

A second label named "AddComp" is generated when flow items are exiting the source. It describes how many additional components the flow item needs to be combined with. For example, for a Pipe 2 component that has been assigned a Type 3 label, it needs to have one more component to create its spool. Likewise, a Pipe 2 component that has been assigned a Type 1 label at the source will need to have three more components. The FlexScript code of this trigger is as follows:

```
Object current = ownerobject(c);
Object item = param(1);
int port = param(2);
{ // ************* PickOption Start ************* //
/***popup:SetLabel*/
/**Set Label*/
Object involved = /** \nObject: *//***tag:object*//**/item/**/;
string labelname = /** \nLabel: *//***tag:label*//**/"AddComp"/**/;
Variant value; // = /** \nValue: *//***tag:value*//**//**/;

if (item.Type == 1) {
         value = 3;
} else if (item.Type == 2) {
         value = 2;
} else {
         value = 1;
}

involved.labels.assert(labelname).value = value;
} // ******* PickOption End ******* //
```

Therefore, when Pipe 2 exits its source, it will have two labels attached; "Type" label prescribes what kind of spool the flow item will become in the end, and "AddComp" specifies how many additional components the spool still needs. While "Type" label remains the same throughout the simulation, “AddComp” changes whenever a new component has been combined. After a flow item completes the full weld in the model, it enters a queue waiting to be joined with the next component, and Figure F - 26 displays how and when the “AddComp” label value changes.

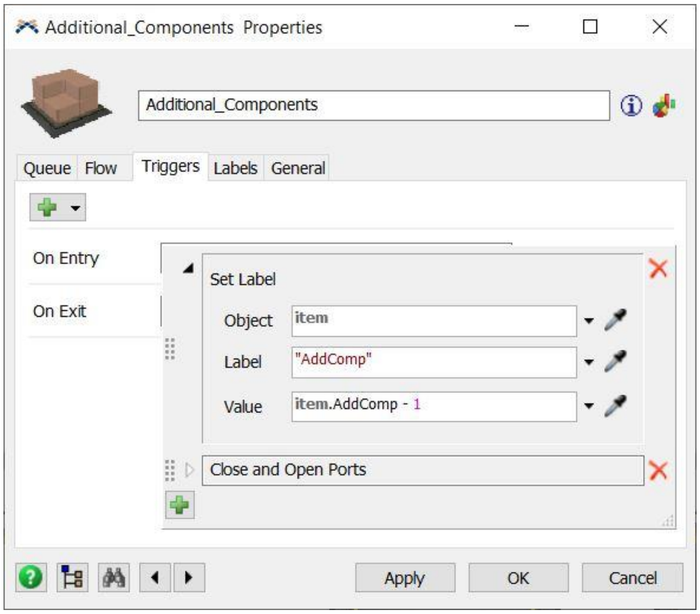


Figure F - 26. Queue – “On Entry” Trigger to Set Label

After welding, the flow item can either pass or fail the quality check; a pass directs the flow item to the laydown area to wait for additional components, and a fail directs it to the laydown area for rework. Therefore the number of remaining components would decrease only if the flow item passes the quality check. Since each weld operation only combines two components at a time, the value of “AddComp” is decreased by one.

A third and final label associated with the spool is generated as it exits the laydown area to be joined with additional components. The FlexScript code of this trigger is as follows:

```
Object current = ownerobject(c);
Object item = param(1);
int port = param(2);
{ // ************* PickOption Start ************* //
/***popup:SetLabel*/
/**Set Label*/
Object involved = /** \nObject: *//***tag:object*//**/item/**/;
string labelname = /** \nLabel: *//***tag:label*//**/"Join"/**/;
Variant value; // = /** \nValue: *//***tag:value*//**//**/;

if (item.Type == 1 && item.AddComp == 2) {
   value = 1;
} else if (item.Type == 2 && item.AddComp == 1) {
   value = 2;
} else if (item.Type == 1 && item.AddComp == 1) {
   value = 3;
}

involved.labels.assert(labelname).value = value;
} // ******* PickOption End ******* //
```

The “Join” label is prescribed a value based on its “Type” and “AddComp” labels. The code above describes the logic of how the value is determined. The value of one, two, and three is meant to represent the three different columns in the “CombinerJoin” Global Table. Figure F - 27 shows the table, and it outlines the conditions for the opening/closing of input ports for the “Combiner” fixed resource.

CombinerJoin

	Join 1	Join 2	Join 3
fromPort2	1	1	0
fromPort3	0	0	1

Figure F - 27. Global Table – Combiner Join Conditions

Input Port 2 of the Combiner is linked to the Reducer component, and Input Port 3 is linked to Pipe 1. If a flow item is Type 1 (four components) and has two remaining components, or if a flow item is Type 2 (three components) and has one remaining component, it means the next component they need is the Reducer. Therefore for “Join” label value of one and two, Combiner Input Port 2 is opened and Input Port 3 is closed. Similarly, if a flow item is Type 1 (four components) and has one remaining component to be joined, then the next component it needs is Pipe 1; therefore for “Join” label value of three, Combiner Input Port 3 is opened. Refer to Figure F - 19 for the creation flow of pipe spools in this model.

By default, the Combiner pulls flow items from its Input Port 1, which is the queue for pipe spools that have already gone through at least one weld and passed the quality control. These spools are then joined with components (Reducer or Pipe 1) from the rest of the input ports (Port 2 or Port 3). This means that the component list of the combiner can only be changed from Input Port 2 and higher. Figure F - 28 shows the "On Entry" trigger used in the Combiner to update the component list using "Join" label and references the "CombinerJoin" Global Table.

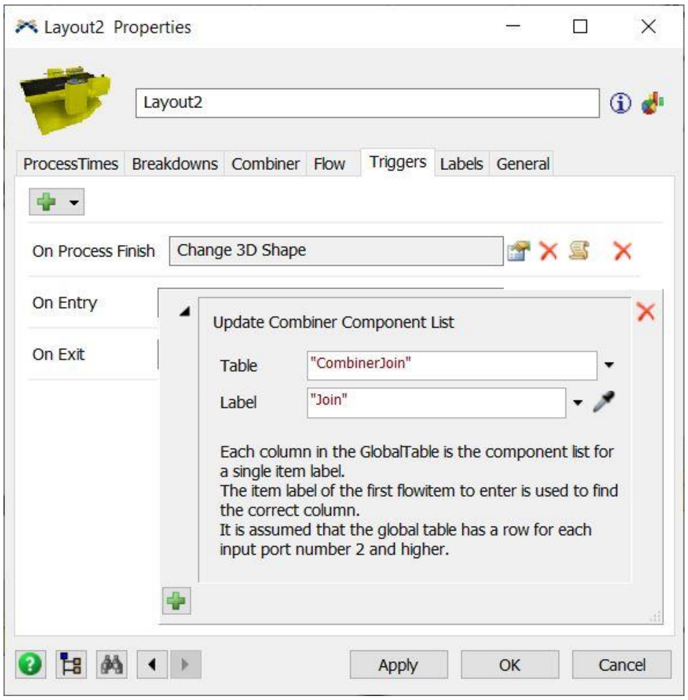


Figure F - 28. Combiner – "On Entry" Trigger to Update Combiner Component List

The Input Ports 2 and 3 of the Combiner open and close based on the "Join" label attached to the flow item from Input Port 1, and this ensures the correct component is transported to this station from upstream fixed resources. By default, the flow items would overlap each other while being processed in the Combiner, and only flow item from Input Port 1 would exit, retaining its 3D shape. For example, if a box and a sphere enter through Input 1 and 2 respectively, after processing, the box would exit the Combiner and continue to the next fixed resource, while the sphere would disappear and effectively be discarded from the model. To reflect changes in the pipe spool geometry after each iteration of layout, the last step is to change the 3D shape of the flow item at the "On Process Finish" trigger. The FlexScript code of this trigger is as follows:

```
Object current = ownerobject(c);
Object item = param(1);
{ // ************* PickOption Start ************* //
/***popup:Change3DShape*/
/**Change 3D Shape*/
Object involved = /** \nObject: *//***tag:object*//**/item/**/;
string shapename; //= /** \nShape:
*//***tag:shapepath*//**/"fs3d\\General\\Box.3ds"/**/;

if (item.Join == 1) {
   shapename = "Pipe\\NO2_REDUCER_PIPE2_HUB.stl";
} else if (item.Join == 2) {
   shapename = "Pipe\\NO2_REDUCER_PIPE2_HUB.stl";
} else if (item.Join == 3) {
   shapename = "Pipe\\NO1_PIPE1_REDUCER_PIPE2_HUB.stl";
} else {
   shapename = "fs3d\\General\\Box.3ds";
}

double theindex = getshapeindex(shapename);

double x;
double y;
double z;

//Grab the current size of the object
if (shapename == "Pipe\\NO2_REDUCER_PIPE2_HUB.stl") {
   x = 1.74;
   y = 0.43;
   z = 0.63;
} else if (shapename == "Pipe\\NO1_PIPE1_REDUCER_PIPE2_HUB.stl") {
   x = 2.43;
   y = 0.71;
   z = 1.05;
} else {
   x = 0.5;
   y = 0.5;
   z = 0.5;
}

sets(shape(involved),shapename);
setobjectshapeindex(involved,theindex);

//Update the object to the original size
applyshapefactors(involved);
setsize(involved, x, y, z);
} // ******* PickOption End ******* //
```

As described earlier, “Join” label value of 1 and 2 effectively transforms the flow item into Spool 2 with three components, while “Join” label value of 3 transforms the flow item into Spool 1 with four components. Since the size of the object remains the same, after each change in 3D shape, a new size needs to be specified.

Thus completes the modelling of the spatial environment of the model, using the shop layout from the partner’s facility in Cambridge as the basis of gauging distance between workstations, creating a rigorous system. Spools containing different number of components are taken into account, simulating typical projects that have a variety of unique products. Equipment pertinent to the fabrication of pipe spool are also imported into the model, in an attempt to create faithful representation of the physical process.

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