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SIMULATION MODELING FOR SUSTAINABLE CONSTRUCTION: A CASE STUDY TO HIGHLIGHT THE SOCIAL ASPECT

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ABSTRACT

To cut costs and drive innovation in product development, many projects have turned to remote worksites for construction component pre-fabrication. Fabricating pipe spools in shops eliminates delays due to weather and allows for better resource planning. This paper aims to optimize labor resource usage in a pipe spool manufacturing plant that fabricates three different types of spools. It utilizes historical data to implement a discrete-event simulation model. The proposed simulation model effectively reduced idle time and evenly distributed the workload. As a result, the overall fabrication time for all three spools was reduced, leading to a 22% decrease in active shop usage. This allowed subsequent jobs to commence earlier, giving the team more flexibility in meeting deadlines and addressing labor constraints. This research provides insights into how resource allocation plans can be created to maximize sustainability results, both socially (through improving working conditions and reducing workloads) and economically.

1 INTRODUCTION

According to an article published by Globe Newswire in early 2021, pipe spool fabrication is one of the components of the piping system whose global market was computed as $1,314 million in 2019 and forecasted to reach $1,641 million by the year 2027 (both piping system and piping spools combined). The study conducted by Research and Markets as published in the aforementioned online article states that exploration and drilling activities globally have promoted the increase of pipe spooling and piping systems. Pipe spools have widespread use in various industries such as chemical, oil and gas, and power plants (Globe Newswire 2021).

Pipe spools play a crucial role in industrial construction projects (Labban et al. 2013), and are manufactured in fabrication shops through a series of processes like cutting, fitting, welding, and quality inspection based on engineering designs. Once they pass multiple tests, the final products are either assembled into large modules or transported directly to the construction site for installation (Mosayebi et al. 2012). These modular construction units are designed to be easily movable and assembled on-site (Mohamed et al. 2007). The fabrication process of pipe spools is critical to the effective completion of industrial projects (Ji and AbouRizk 2016) and frequently requires accelerated, highly disciplined, and organized installation procedures to meet project deadlines (Safarzadeh et al. 2018). However, manufacturing pipe spools is a complicated and uncertain operation, with unique results and a wide range of variables affecting its activities (Labban et al. 2013). The assembly of pipe spools includes numerous uncertainty factors and constraints, making it challenging to manage operations and scheduling (Mohamed et al. 2007). Additionally, pipe-spool fabrication poses challenges in studying and improving its production system because of its high product mix and uniqueness (Wang et al. 2009). Therefore, stakeholders prioritize learning in-depth information about the performance of fabrication shops to ensure prompt on-site pipe installations (Labban et al. 2013).

The concept of sustainable development was first introduced in 1987 by the United Nations General Assembly in their report "Our Common Future." According to the report, sustainable development means meeting present needs while ensuring that future generations can meet their own needs (UN 1987). Later, sustainable construction was defined as creating and operating a healthy built environment through resource efficiency and ecological design (Kibert 1994). Maximizing resource utilization and minimizing harm to the environment, economy, and society are the practical aspects of sustainability (Ghazal and Hammad 2022). However, evaluating the contribution of specific activities to sustainability poses significant challenges. Moon (2016) identified five key challenges in this regard. These include the broad scope of sustainability in terms of time and geography, the complexity of the studied questions, the dynamic and non-deterministic interactions between critical components of the system, the need to investigate the impact of various scenarios or plans, and the requirement to address different levels of granularity concurrently.

Simulation modeling is a powerful tool for tackling the challenges of complex and uncertain systems, such as the fabrication shop process. By replicating the behaviors and characteristics of real systems on a computer, simulation modeling instills reliability in the process (AbouRizk 2010). Construction simulation refers to the practice of developing and testing computer-based representations of construction systems to comprehend their underlying behavior (Ji and AbouRizk 2016). As construction processes are intricate and ambiguous, it is crucial to have physically accurate inputs from actual operation processes (Ji and AbouRizk 2016). Hence, computer-based modeling and simulation's ability to shape resources, interactions of activities, queuing, factors, and uncertainties makes it an excellent fit for modeling the pipe spool fabrication operation. It helps in planning, scheduling, and controlling the fabrication process for delivering on-time and meeting project deadlines, regardless of the construction operations' complexity or size (Labban et al. 2013). Discrete-event simulation (DES), a standard simulation method based on activity, offers a promising solution for modeling dynamic and interactive construction systems (Lu 2003). Generally, the simulation model starts with an entity that triggers other events until a termination point is reached. DES's structure and algorithm are simple and flexible, making it an adaptable tool for simulating manufacturing procedures.

The goal of this paper is to enhance the efficiency of labor resources in a pipe spool fabrication and manufacturing facility by analyzing historical data with a DES model. The study suggests ways to allocate resources effectively, considering both economic and social sustainability factors, with a focus on workload. As social sustainability has been less explored in pipe spool fabrication, this research adds to the understanding of simulation modeling and optimization for social sustainability (work burden) in manufacturing processes.

2 LITERATURE REVIEW

2.1 Simulation Modeling Concept, Methods, and Benefits

The process of computer modeling and simulation involves utilizing computational models to analyze the behavior of systems and evaluate operational strategies in both descriptive and predictive modes (Abar et al. 2017). Such an approach helps to improve the comprehension of how a system operates and performs. The term model is considered ‘‘an abstract and simplified representation of a given reality, either already existing or just planned. Models are commonly defined to study and explain observed phenomena or to foresee future phenomena’’ (Bandini 2009). A simulation model includes a set of computing algorithms, mathematical expressions, and equations that accurately capture the behavior and performance of the real-world system in various scenarios (Abar et al. 2017). Moon (2016) described simulation as a set of methods that use computer-based models to imitate the characteristics and behaviors of real-world systems. While simulation is a type of modeling, it is unique in that it facilitates the development of a deeper understanding of a system, the comparison of different scenarios before execution, the prediction of system behaviors, support for decision-making processes, and the development of new investigation tools and training methods.

In the literature, there are many simulation methods used in modeling, but three main ones are widely recognized: Agent-Based Modeling and Simulation (ABMS), Discrete-Event Modeling and Simulation (DEMS), and System Dynamics Modeling and Simulation (SDMS). According to Gilbert (2008), ABMS is a computer modeling method that imitates the behavior and interactions of individual agents within a given environment or system. ABMS studies the micro-level actions and behaviors of the agents in a system to understand complex social phenomena. It is used in various disciplines, such as economics, sociology, ecology, and public policy, especially for analyzing complex events that are difficult to observe or involve multiple levels of analysis. DEMS, as stated by Law (2014), is a simulation modeling technique that focuses on modeling and evaluating systems that undergo different status changes. The process requires building a simulation model that represents a system as a sequence of discrete events, such as arrivals, departures, and state changes. This technique helps understand system behavior and identify opportunities to improve complex systems, such as supply chains, contact centers, industrial lines, healthcare systems, and queuing systems. Sterman (2000) describes SDMS as a technique that aids in understanding how complex systems behave over time through feedback loops. It represents a system as a set of connected stocks and flows that define its dynamics, and feedback loops serve to show the links between various stocks and flows in the system. This approach can be utilized to study a wide variety of systems, including social, economic, and environmental systems, and is particularly beneficial for analyzing non-linear systems.

2.2 Application of Simulation Modelling for Sustainability

According to Bockermann et al. (2005), sustainable development can be achieved by meeting certain minimum requirements. Using two simulation models, they were able to measure energy and material consumption, as well as employment implications, to establish the link between economic growth, environmental damage, and social issues. Their findings indicate that by 2020, it is feasible to attain near-sustainability by reducing unemployment to approximately 3%, cutting CO_2 emissions by 15%, and decreasing material flows by 25%, while the economy grows by 41% - 45%. The authors suggest that increasing resource productivity through technological and social innovation, reducing working hours, stabilizing the social security system, and altering consumption and mobility patterns are key strategic components.

Duran-Encalada and Paucar-Caceres (2012) created a model using system dynamics to explain how business sustainability policies are developed and executed at Petroleos Mexicanos (Pemex). The model analyzed the roles of internal and external stakeholders in defining sustainability and driving initiatives. The study found that leadership, stakeholder motivation, and external factors were the three main variables that could be used to improve an organization's sustainability efforts. Increasing stakeholder motivation and proactive leadership actions were found to have a significant positive impact on the path to sustainability, while external economic considerations had a lesser influence.

Romero and Ruiz (2014) proposed an analytical framework for redesigning industrial regions into eco-industrial parks based on sustainable strategies. Their model incorporated a knowledge database for identifying cooperative tactics like material exchange networks and used game theory to assess supportive interactions and make strategic decisions. While Nikolaou et al. (2015) contributed to the literature by developing a dynamic model that examined the relationships between climate change risks, financial performance, and business operations. Their focus was to determine the impact of operational, legal, regulatory, and reputational risks. The proposed approach was based on Stella software, system thinking, system dynamics, and business climate change management.

2.3 Social Aspect of Sustainability

Social sustainability, as described by Rajak and Vinodh (2015), is concerned with the way communities, societies, and individuals live, focusing on equity and basic needs. This includes working conditions, human rights, fair wages, cultural diversity, and stakeholder participation. Their research involved an extensive literature review and consultation with industry experts to develop criteria and corresponding attributes for evaluating social sustainability performance. The resulting conceptual model comprised four dimensions: internal human resources, external population, stakeholder participation, and macro-social performance (Vinodh 2011). Within each dimension, specific criteria were identified to measure social sustainability. For example, job opportunities, which involve promoting a challenging work environment for a diverse workforce, gender equity (Norris et al. 2012), and the ability to hire local skills (Ziout et al. 2013), was identified as crucial criterion under the first dimension. Another important criterion under the internal human resources dimension was health and safety practices, with attributes such as working conditions and their impact on long-term health (Ziout et al. 2013), ensuring a safe, clean, and injury-free workplace (Dillard et al. 2009), workplace illumination, and noise levels (Chen et al. 2012).

Crews currently prioritize safety management by identifying and eliminating physical hazards involving chemicals, site conditions (like exposed trenches, high places, and tight spaces), and equipment (such as electrocution and operational accidents). These dangers are considered high-risk due to past accidents (Zhang et al. 2015; Saurin 2016; Golovina et al. 2016). However, human factors are often overlooked in safety assessments (Fard Fini et al. 2018). Human-related risks in the workplace can stem from worker behavior or environmental conditions. Long-term self-caused behaviors, driven by both personal and external factors outside of work, can include noncompliance with rules or forgetfulness and can be difficult to detect in advance (Garrett and Teizer 2009; Li et al. 2015). Conversely, work-related stress and burdens can be foreseen and managed by management to avoid risky behaviors (Alyanchi et al. 2012). Therefore, reducing the workload by hiring more workers can improve work conditions, decrease stress, and ultimately enhance safety-related actions.

2.4 Application of Simulation Modelling in Pipe Spools Fabrication

Liu et al. (2017) stated that as part of the industrial modular construction process, pipe spools are created in fabrication shops using raw pipes and fittings like elbows, tees, and flanges. These spools are then transported to the module yard for assembly or directly to the installation site. Each module contains unique components based on its location and function within the plant, such as structural steel frames, pipes, cables, equipment, or a combination of these. Before the assembly process begins, all components must be in the correct positions. Although modules may have similar sizes and dimensions, their internal designs and components differ (Mohamed et al. 2007). Therefore, timely delivery of raw materials, product variability, material availability, workforce performance and availability, shop loading and capacity, and offsite prefabricated elements are critical to the success of industrial modular construction projects (Liu et al. 2017).

Figure 1 illustrates the typical process of pipe spool fabrication, which begins with the owner's requirements and design specifications. Engineering personnel create shop drawings based on these details (material type, pipe size, schedule, etc) and release them to the next level, ensuring quality control at every step to eliminate errors. The required materials, including elbows, tees, flanges, and olets, are gathered and cut to the desired length with beveled edges for fitting examination. The aligning team checks for the proper alignment and applies temporary tack welds before the spool is processed for either roll welding or position welding. Then, the spool is processed through either roll welding or position welding, with the latter being more time-consuming and labor-intensive. Quality control tests and inspections, such as visual inspection, non-destructive examination (NDE), post-weld heat treatment (PWHT), and hydro testing, are conducted. Once the spool passes all tests, it may undergo sandblasting or painting before leaving the shop floor. The final product is either sent to the module yard for assembly or shipped directly to the construction site.

Numerous studies have explored the use of simulation modeling in pipe spool fabrication. For example, Wang et al. (2009) offered a simulation-based approach that incorporated lean production principles and flow production into shop fabrication. This study aimed to minimize waste by implementing lean principles, such as underproduction and overproduction. Ji and Abourizk (2016) developed a Bayesian inference-based simulation method for estimating the fraction of nonconforming welds. The proposed methodology models the pipe welding inspection process as the 'Bernoulli process' and employs historical inspection data as input. The simulation outcomes demonstrate good reliability and accuracy compared to the actual project's weld repair rates. Safarzadeh et al. (2018) recommended a new linear programming model for scheduling spool fabrication activities based on the flexible job-shop scheduling problem (FJSP). The author proposed a heuristic algorithm grounded on priority dispatching rules to solve the suggested linear programming model. Labban et al. (2013) introduced a discrete event simulation model specifically designed to manage pipe-spool fabrication operations at Consolidated Contractors Group (CCC). The model has two advantages: 1) predicting and analyzing fabrication resource requirements, and 2) managing operations and predicting resource and time requirements during project execution. It enables engineers to test various construction scenarios, evaluate resource utilization and identify bottlenecks, and anticipate time and cost constraints without having to go to the site.

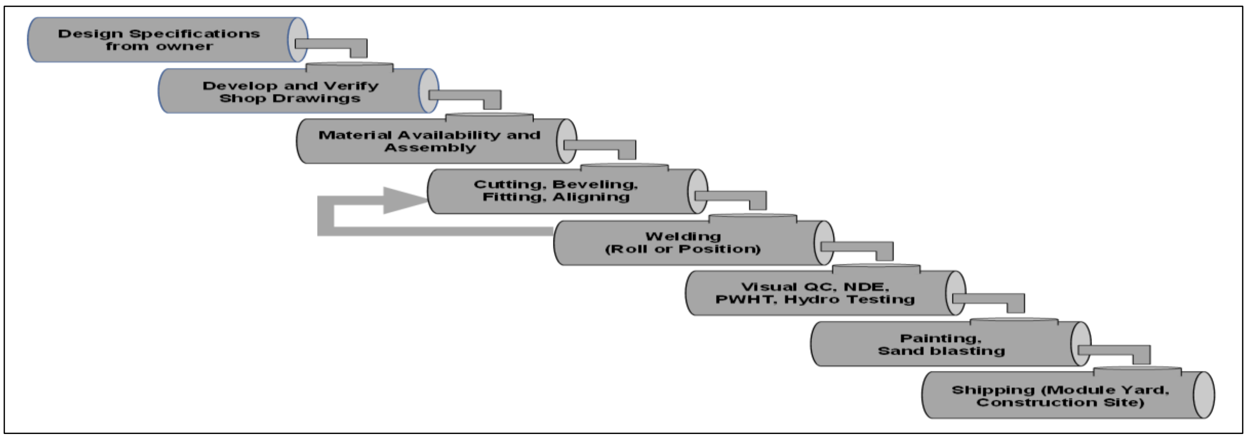

Figure 1: Steps involved in a typical industrial pipe spool fabrication process.

3 RESEARCH GAP

Although previous research has examined emissions and productivity in construction, with a focus on scheduling and spool fabrication, there is a gap in understanding the ideal balance of time, resources, and utilization in spool fabrication facilities, particularly when it comes to incorporating social sustainability. The social dimension of sustainability has been overlooked in the context of pipe spool fabrication. According to Moon's (2016) study on simulation applications across industries, the 'Environmental' dimension has been covered the most (42%), followed by 'Economic' (31%) and 'Social' (27%). Therefore, it is necessary to conduct research that addresses this gap and explores how to optimize resources in spool fabrication facilities while considering workers' conditions and workload as a crucial aspect of social sustainability. This approach offers a new perspective and a comprehensive understanding of spool fabrication operations and their impact on both the environment and society.

4 RESEARCH METHODOLOGY

In this study, simulation modeling is proposed and applied to a pipe spool fabrication process in a real workshop setting. The research methodology flowchart in Figure 2 outlines four phases. The first phase involves a thorough literature review of simulation modeling concepts, methods, and benefits, as well as its application for sustainability, the social aspect of sustainability, and the application of simulation in pipe-spool fabrication. This phase was crucial in determining the current status of simulation modeling and identifying areas for improvement. The second phase includes a case study of a pipe spool fabrication process. The authors narrowed their findings to a research paper by Liu et al. (2017), which provided all the necessary data to build a simulation model. The model was then used to mimic a case study of three pipe spools fabricated in a workshop for an oil sands expansion project in Fort McMurray, Alberta, Canada.

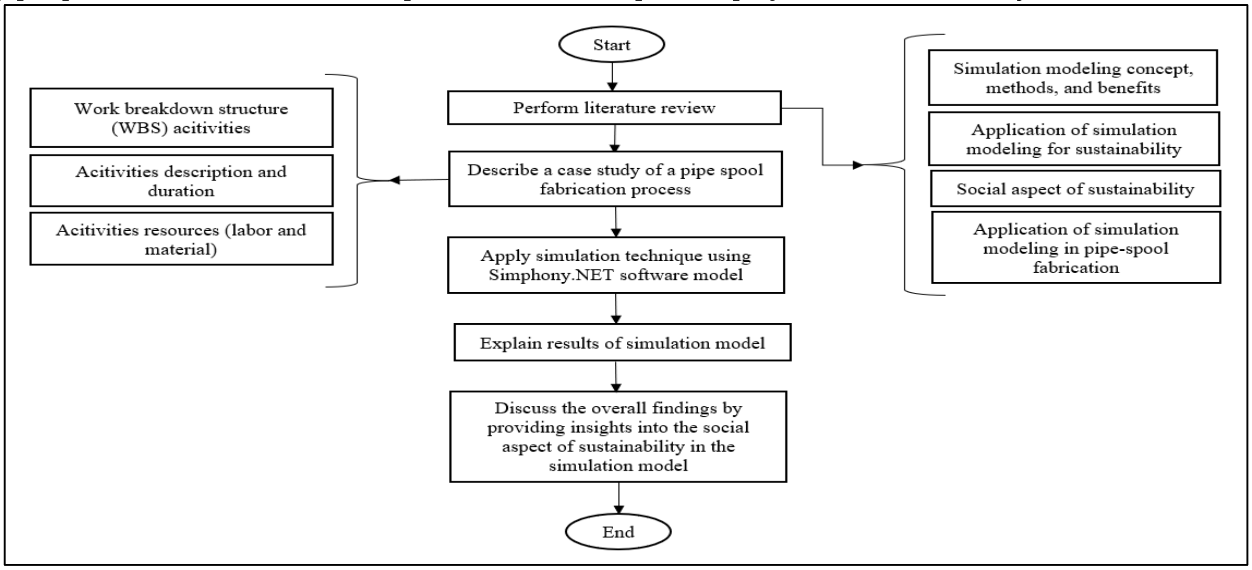

Figure 2: Research methodology flowchart.

In the third phase of the study, the simulation model was executed for 100 runs to derive conclusions on the recommended optimization effort. To achieve this, simulation software such as Simphony.NET was used, allowing for a dynamic approach in varying conditions and parameters to investigate outcomes in significantly less time than manual calculations or fabrication shop floor modifications. This approach also aids in understanding behaviors over a long period and identifying surface problems that can be observed more closely, making the entire pipe spool fabrication process cost-effective to study.

In the fourth phase, the discussion section focuses on the social pillar of sustainable construction and how simulation modeling tools can improve issues within it. The section highlights the emerging benefits of simulation modeling beyond traditional applications, such as estimating time, cost, labor hours, equipment hours, required material, and reducing carbon emissions. It also provides insights into how resource allocation strategies can optimize not only the environmental and economic dimensions of sustainability but also the social dimension. This paper aims to fill the current gap in the literature by identifying open issues and future directions associated with the application of simulation modeling in the social dimension of sustainability. The authors focus solely on human-related risk factors, specifically, conditions imposed on workers such as workload and work burden, although other factors exist within social sustainability, such as work-life balance, fair employment practices, continuous learning, and skill development.

5 CASE STUDY

In our case study, a process similar to the one shown in Figure 1 is being followed. The objective of the case study is to examine the feasibility of simultaneously constructing three pipe spools in the yard and assess the resource requirements, including materials and manpower. The study specifically focuses on fitting and welding operations, considering constraints related to the availability of fitters and welders. Mathematical considerations were made to incorporate resource availability within specified timelines, represented as deadline constraints. Material constraints were also considered, accounting for irregularities and material handling. Similarly, network constraints were considered to address the flow of Work

Breakdown Structure (WBS) IDs. The detailed computation and elaboration for these constraints are beyond the scope of this paper. Table 1 provides an overview of the WBS activities, their descriptions, and durations in minutes.

Table 1: WBS activities and their durations for the three pipe spools (Liu et al. 2017).

WBS ID	Activity Name	Dur (mins)	WBS ID	Activity Name	Dur (mins)
A1	Fit 2″ elbow & 2″ flange	30	C3	Fit 6″ elbow & 6″ pipe	15
B1	Weld 2″ elbow & 2″ flange (sub1_1)	30	D3	Weld 6″ elbow & 6″ pipe (sub3_2)	14
C1	Fit the sub1_1 with 2″ pipe	11	E3	Fit sub3_1 & sub3_2	18
D1	Weld the subassembly with 2″ pipe (Sub1_2)	30	F3	Weld sub3_1 & sub3_2 (sub3_3)	12
E1	Fit sub1_2 with olet	13	G3	Fit 6″ pipe & tee	31
F1	Weld sub1_2 with olet (sub1_3)	17	H3	Weld 6″ pipe & tee (sub3_4)	56
G1	Fit two 6″ pipes together	36	I3	Fit sub3_4 & reducer	37
H1	Weld two 6″ pipes together (sub1_4)	44	J3	Weld sub3_4 & reducer (sub3_5)	46
I1	Fit sub1_3 & sub1_ 4	24	K3	Fit sub3_5 & 3″ pipe	19
J1	Weld sub1_3 & sub1_4	57	L3	Weld sub3_5 & 3″ pipe (sub3_6)	15
A2	Fit 6″ elbow with 6″ pipe	41	M3	Fit sub3_6 & 3″ Flange	11
B2	Weld 6″ elbow with 6″ pipe (sub2_1)	68	N3	Weld sub3_6 & 3″ Flange (sub3_7)	130
C2	Fit sub2_1 with 6″ pipe	39	O3	Fit sub3_3 & 6″ pipe	27
D2	Weld sub2_1 with 6″ pipe	69	P3	Weld sub3_3 & 6″ pipe (sub3_8)	52
A3	Fit 6″ hydro pipe & 6″ elbow	12	Q3	Fit sub3_7 & sub3_8	29
B3	Weld 6″ hydro pipe & 6″ elbow (sub3_1)	42	R3	Weld sub3_7 & sub3_8	80
	Total Duration (in minutes)				1155

The duration of each pipe spool's Work Breakdown Structure (WBS) activities - ranging from A1 to J1 for Spool 1, A2 to D2 for Spool 2, and A3 to R3 for Spool 3 - were obtained by solving the mathematical models associated with the constraints mentioned above. The resource requirements, including both labor and materials, for delivering each WBS of the three pipe spools are presented in Table 2.

Table 2: Resources (labor and materials) needed for each activity (Liu et al. 2017).

WBS ID	Resources Needed	WBS ID	Resources Needed
A1	2 Fitters, 2" Elbow-1, 2" Flange-1	B1	1 Welder
C1	2 Fitters, 2" Pipe-1m	D1	1 Welder
E1	2 Fitters, Olet-1	F1	1 Welder
G1	2 Fitters, 6" Pipe-12.1 m	H1	1 Welder
I1	2 Fitters	J1	1 Welder
A2	2 Fitters, 6" Elbow-2, 6" Pipe-0.6m	B2	1 Welder
C2	2 Fitters, 6" Pipe-5.8m	D2	1 Welder
A3	2 Fitters, 6" Elbow-1, 6" Hydro Pipe-1	B3	1 Welder
C3	2 Fitters, 6" Elbow-1, 6" Pipe-0.6m	D3	1 Welder
E3	2 Fitters	F3	1 Welder
G3	2 Fitters, 6" Pipe-2.7m, Tee-1	H3	1 Welder
I3	2 Fitters, 6" x 3" Reducer-1	J3	1 Welder
K3	2 Fitters, 3" Pipe-1.3m	L3	1 Welder

M3	2 Fitters, 3" Flange-1	N3	1 Welder
O3	2 Fitters, 6" Pipe-0.6m	P3	1 Welder
Q3	2 Fitters	R3	1 Welder

Liu et al. (2017) presented an activity on node (AON) network diagram that established the logical relationships associated with each spool from start to finish. The AON diagram closely reflected the actual sequencing and execution of work in the fabrication shop. The authors of this paper accepted the data presented at its true value to mimic the fabrication shop floor process into a Simphony.NET simulation software model.

6 SIMULATION MODEL AND RESULTS

A simulation model was created by the authors to analyze the production of three pipe spools simultaneously. Each spool was modeled individually to optimize the allocation of resources, primarily labor, by experimenting with various scenarios (Figure 3). The goal was to identify the optimal number of fitters and welders to maximize plant utilization and reduce the workload of labor. Furthermore, the study aimed to evaluate the impact of resource variations on the time required for spool fabrication. This knowledge would aid the shop manager in efficiently managing operations based on the owner's delivery needs.

The Simphony model was used to incorporate the available resources, such as labor and materials listed in Table 2, as depicted in Figure 3. Initially, 2 fitters and 1 welder were employed for the fabrication process of three pipe spools. The AON logic was applied to model the process, starting from "CreateSpoolx" and ending at "FinishSpoolx" (x=1,2,3). Each activity had unique attributes, such as duration, required labor, and specific materials. Spool 3 was given priority by the owner's specifications, and was therefore ranked higher than Spools 1 and 2 in the model. After each operation, data was collected and analyzed. During the case study, a delay occurred in acquiring a 6" Pipe and a 6" x 3" reducer, leading to a suspension of the entire process for 265 minutes (4.42 hours) between 335 and 600 minutes. This delay was accurately depicted in Figure 5.

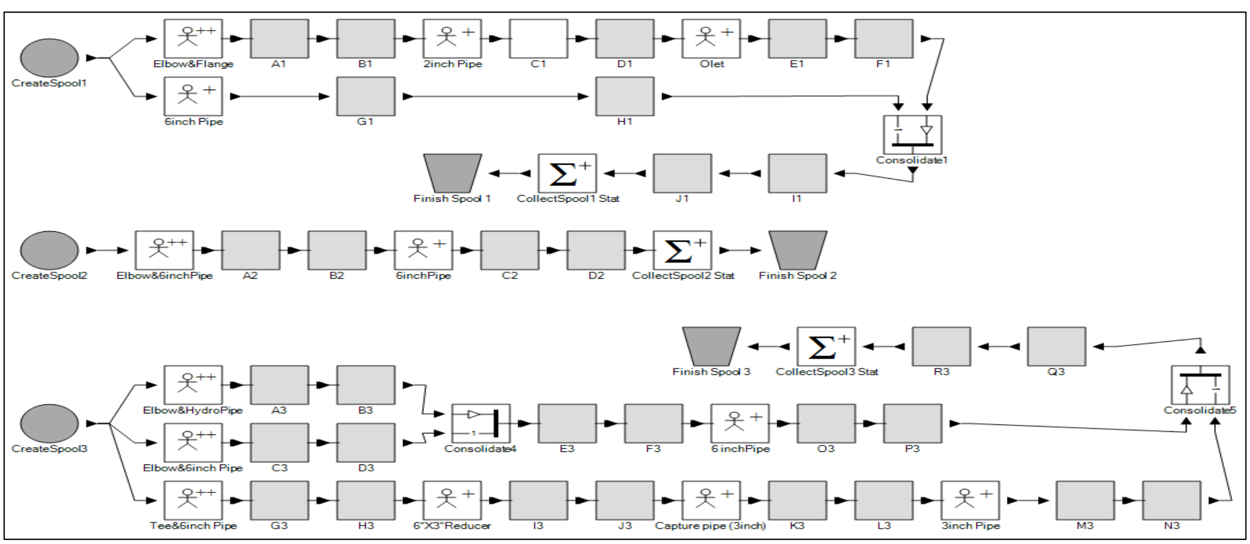

Figure 3: Simulation model showing pipe spool fabrication of three different spools.

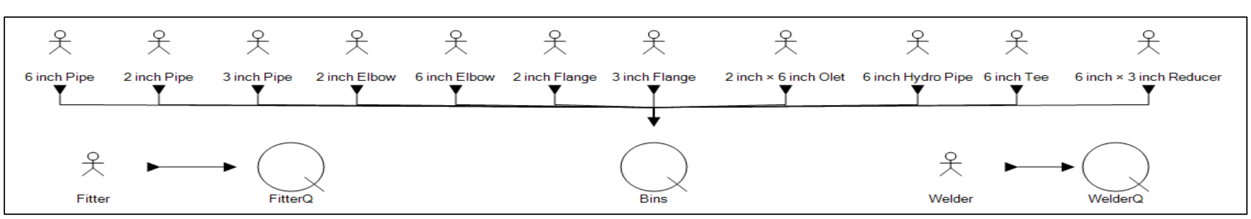

Figure 4: Resource (labor and materials) utilized in the spool fabrication process.

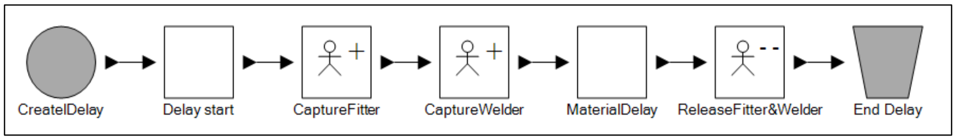

Figure 5: Simulating a temporary freeze of the fabrication process due to material delay.

The model underwent 100 runs, leading to the generation of a statistical report. The report revealed that spool 1 would take 1,027 minutes, spool 2 would take 890 minutes, and spool 3 would take 970 minutes to complete. By prioritizing spool 3 in the model and allocating labor resources accordingly, the duration of spool 3 was reduced. A comparison of the run scenario to Liu et al.'s (2017) study in Simphony.NET showed that the shop floor was active for a total of 1,027 minutes. During this time, Table 3 indicated that the average utilization of the 2 fitters was 51.5%, while the 1 welder was 97.1%.

Through the practice of crew resource management (CRM) and experimenting with different crew sizes in various scenarios, the model was successful in predicting the crew's average productivity. This indicates that available resources were used effectively and idle time was minimized. In Scenario 2, where an additional welder was added, the fitters' productivity increased while the burden of having only one welder decreased. This led to a reduction in spool production duration and a 22% decrease in active shop use, enabling the shop floor to be cleared more quickly for subsequent jobs. However, Scenarios 3, 4, and 5, which involved further increases in crew size, did not demonstrate significant improvements in spool fabrication or shop utilization. Based on these findings, it can be concluded that Scenario 2 is the optimal solution for maximizing crew utilization, minimizing pipe spool fabrication time, and ensuring effective shop utilization.

Table 3: Simulation results of varying labor and its impacts on job and shop utilization.

	Crew Size		Utilization		Duration (minutes)			
Scenario	Fitters	Welders	Fitters	Welders	Spool 1	Spool 2	Spool 3	Active Shop Use
1	2	1	51.50%	97.10%	1027	890	970	1027
2	**2**	**2**	**70.20%**	**62.50%**	**798**	**423**	**797**	**798**
3	2	3	72.10%	45.60%	729	423	728	729
4	3	2	53.80%	76.60%	651	514	594	651
5	3	3	58.40%	55.40%	480	423	551	600

7 DISCUSSION

As previously discussed, simulation modeling is a valuable tool that replicates the behavior of real systems, allowing for the testing of various scenarios before implementation. This process provides a thorough understanding of the system and aids in decision-making. In the construction industry, accurately estimating project time, cost, resource needs, production rates, and carbon emissions are common challenges. Simulation modeling meets the accuracy requirement, making it an effective method for preparing reliable estimates for labor hours, equipment hours, required materials, and related costs. While the traditional benefits of simulation modeling in construction are well-documented, there are additional benefits to be gained from a sustainability and lean perspective.

Simulation modeling can play a significant role in achieving the 8th sustainable development goal of promoting "Decent Work and Economic Growth" from a sustainability standpoint. This goal focuses on fostering sustainable, inclusive, and continuous economic growth, full and productive employment, and decent work for all. By analyzing the labor resource utilization data from Table 3 in the previous section, we can demonstrate how simulation modeling can support this goal in construction operations. In scenario 2, hiring a second welder increased the utilization of the two fitters while relieving the first welder's burden, leading to the creation of more jobs in the construction industry. Moreover, reducing workload can enhance workers' physical and mental health, resulting in greater job satisfaction.

From a lean perspective, simulation modeling helps identify process inefficiencies, bottlenecks, and areas for improvement. By reducing waste and cost while increasing productivity and output, businesses can reap significant benefits. One key type of waste that should be noted is waiting time (non-value-added activities), which is a major type of waste that takes on various forms in lean principles. Examples include parts or assemblies waiting in queues for the next operation, personnel waiting for necessary materials, equipment, or tools, finished products waiting to be shipped or stored in inventory, and underutilized equipment.

To summarize, simulation modeling in construction provides precise estimation and also fosters sustainable development by promoting fair employment opportunities and economic growth. It also supports lean principles to optimize processes and efficiently utilize resources.

8 CONCLUSION

The research conducted a study using Simphony.NET software to improve resource utilization in pipe spool manufacturing facilities while prioritizing sustainable development. The study factored in the social aspects of sustainability, specifically human-related risk factors like workloads and labor productivity. The goal was to find the optimal balance of resources, utilization, and time. This research enhances our understanding of simulation modeling and optimization in industrial processes, with a focus on the social dimension of sustainability and human-related risk factors.

By utilizing a crew consisting of 2 fitters and 2 welders, the simulation model effectively reduced idle time and evenly distributed the workload. As a result, the overall fabrication time for all three spools was reduced, leading to a 22% decrease in active shop usage. This allowed subsequent jobs to commence earlier, giving the team more flexibility in meeting deadlines and addressing labor constraints. The model can serve as a tool for controlling time or labor constraints that the owner or shop manager may encounter. By making quick adjustments to the model's attributes, these constraints can be successfully eliminated.

The simulation model proved to be an invaluable tool for achieving sustainable pipe spool manufacturing by considering not only environmental and economic aspects but also the social aspects of sustainability. The results demonstrate the model's ability to significantly reduce resource utilization while also improving social sustainability.

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