UNIVERSITY OF OKLAHOMA GRADUATE COLLEGE

SIMULATION BASED ASSESSMENT OF LEAN MANUFACTURING RESILIENCE AND PERFORMANCE

A THESIS

SUBMITTED TO THE GRADUATE FACULTY

In partial fulfillment of the requirements for the

Degree of

MASTER OF SCIENCE

By SHAGHAYEGH AHMADI

Norman, Oklahoma
2025

SIMULATION BASED ASSESSMENT OF LEAN MANUFACTURING RESILIENCE AND PERFORMANCE

A THESIS APPROVED FOR THE

SCHOOL OF INDUSTRIAL AND SYSTEMS ENGINEERING

BY THE COMMITTEE CONSISTING OF

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ACKNOWLEDGEMENTS

I would like to begin by expressing my deepest gratitude to all those who have supported and guided me throughout the course of my master's studies. This achievement would not have been possible without the encouragement, mentorship, and kindness I received from many individuals along the way.

I am especially grateful to my advisor, Dr. Kash Barker, whose unwavering support, guidance, and mentorship have been instrumental throughout my academic journey. His involvement extended far beyond the scope of academic supervision. Through his thoughtful feedback, high expectations, and structured mentorship, he not only helped me grow as a researcher but also shaped my approach to discipline, ethical responsibility, and academic professionalism. Dr. Barker consistently encouraged me to push my limits and develop competencies that will serve me well throughout my career. I am sincerely thankful for the opportunity to study under his guidance and to benefit from his wisdom, integrity, and vision.

I would also like to express my heartfelt appreciation to Dr. Fatah Chetouane, professor at the Université de Moncton, for his invaluable guidance and support in the simulation component of my thesis. Dr. Chetouane played a vital role in helping me design and build a robust and logically coherent simulation model, which served as a central element of my research. Despite the distance, he remained fully committed, generously sharing his expertise with patience, clarity, and enthusiasm. His dedication and thoughtful insights helped ensure the quality and rigor of my work, and his encouragement inspired me to approach challenges with confidence. I am truly thankful for his mentorship and for the significant impact he had on the success of this thesis.

My sincere thanks also go to Dr. Soheil Hemmati, a member of my thesis committee, for his constructive feedback and for helping me strengthen my analytical and critical thinking skills. The course ISE 5970: Network Optimization, which I had the privilege of taking with him, played a key role in shaping my ability to frame and solve complex problems, skills that directly supported the development of my research. I am grateful for his academic guidance and the thoughtful perspective he brought to my committee.

I would like to extend my appreciation to Dr. Ziho Kang, another valued member of my committee, for his contributions to my understanding of simulation through the course ISE 5663: System Analysis Using Simulation. His instruction provided a strong foundation for the simulation work in my thesis and deepened my understanding of system analysis principles. I am thankful for his support and the knowledge I gained from his course.

I am profoundly thankful to my family, whose love, encouragement, and belief in me have been my greatest source of strength. They instilled in me a deep respect for education and the pursuit of knowledge, making curiosity and learning an integral part of who I am. Their constant support through both challenges and achievements has meant the world to me, and I dedicate this milestone to them.

Finally, I would like to thank the School of Industrial and Systems Engineering at the University of Oklahoma for providing a welcoming, intellectually stimulating, and supportive environment. The faculty, staff, and fellow students created a space where ideas could flourish, and where I felt encouraged to grow both personally and professionally. I am grateful for the opportunities and experiences I have had as a part of this academic community.

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ABSTRACT

In today's increasingly uncertain industrial landscape, manufacturing systems must be both efficient and resilient. While lean manufacturing is widely adopted for reducing waste and optimizing performance, its impact on system resilience remains contested. This thesis investigates the dynamic relationship between lean implementation and system resilience through simulation-based experimentation. Using Discrete Event Simulation (DES), two versions of the same case study are modeled, one representing the system before lean implementation and the other after. Various disruption scenarios are introduced to evaluate how each system responds over time, with a focus on system performance degradation and recovery. The findings reveal that lean and resilience are not inherently in conflict. Instead, their relationship depends on system design, the nature and timing of disruptions, and operational constraints of the manufacturing setting. This thesis aims to offer a more balanced perspective on the tradeoffs between lean and resilience methodologies.

Keywords: Discrete Event Simulation- Value Stream Map- Resilience- Lean Manufacturing

CHAPTER 1

1 INTRODUCTION

1.1 Background and Context

In today's fast-paced and increasingly competitive industrial landscape, manufacturing companies face growing pressure to enhance operational efficiency and maintain profitability. The combined forces of globalization, rapid technological advancement, and evolving customer expectations have intensified competition and raised expectations for higher productivity and cost efficiency. To remain competitive and sustainable in such an environment, organizations must continuously improve their processes, minimize waste, and use available resources optimally.

Many industries have adopted Lean Manufacturing (LM), a philosophy that the Toyota Motor Corporation [1][2]developed to address market complexities and enhance competitiveness. Lean provides a structured framework for improving efficiency by identifying and eliminating non-value-adding activities such as overproduction, waiting, excessive transportation, inappropriate processing, excess inventory, unnecessary motion, and defects [3]. The widespread implementation of lean principles, particularly in the United States and other competitive markets, reflects their recognized value as a strategy to maintain competitiveness in a rapidly changing global market [4].

Moreover, today's dynamic and unpredictable global environment has increasingly exposed manufacturing industries to various disruptions that can occur at both operational and strategic levels. These disruptions take multiple forms, including small-scale events such as customer delays, equipment failures, labor shortages, and defective products, as well as large-scale shocks such as natural disasters like Hurricane Katrina, wildfires, and catastrophic events like 9/11[5].

Additionally, the widespread use of digital technologies and the surge in communication platforms have added further complexity to international markets, exposing them to risks like weaponized disinformation and making them more volatile and challenging to manage. For example, recent global events, including the COVID-19 pandemic and geopolitical conflicts such as the war in Ukraine, have further revealed the fragility of international supply chains [6]. As a result, the importance of developing resilient manufacturing systems in the face of such disruptions has become increasingly evident [7].

In the context of manufacturing, resilience refers to a system's ability to withstand unpredictable changes (robustness) and adapt and recover its performance following a disruption (adaptability) [7][8]. Long-term sustainability in today's volatile environment depends not only on how efficiently a system can operate under normal conditions but also on how effectively it can respond to and recover from disturbances. This growing recognition has increased scrutiny of traditional lean systems and their potential limitations in addressing resilience demands.

While lean manufacturing has proven highly effective in driving efficiency, its strong emphasis on efficiency and reducing inventory levels has raised concerns about its potential impact on system resilience. While lean practices aim to eliminate waste and enhance responsiveness, they often remove redundancies essential for absorbing shocks and maintaining operations during disruptions. This has led to a perceived tension between the efficiency goals promoted by lean and the flexibility required for resilience. In particular, lean systems that rely on just-in-time production and operate with minimal buffers may be especially vulnerable to unexpected disturbances [9][10][11].

Yet, this apparent contradiction between lean and resilience is not absolute. Recent research suggests that lean and resilience are not entirely contradictory; they share overlapping characteristics, such as organizational settings in lean manufacturing, that can help a system become more resilient [9]. Specific lean techniques such as 5S, continuous improvement, root cause analysis, visualization, Gemba, Kanban, lean six sigma, pull systems, standardization, and Value Stream Mapping (VSM) have been found to contribute positively to resilience by fostering organizational discipline, agility, and proactive risk management [6][9][12]. These methods foster a disciplined, responsive, and transparent production environment, enhancing a system's ability to react to disturbances.

Among these practices, VSM stands out as a widely used lean tool that visually maps the flow of materials and information throughout the production process from raw materials to final product delivery [13]. VSM is particularly valued for its simplicity and effectiveness in identifying waste and streamlining operations. By providing a comprehensive snapshot of current workflows, VSM helps organizations pinpoint inefficiencies and design more efficient future states. However, one of the key limitations of VSM lies in its static nature. Like a still image, a value stream map captures a fixed system snapshot. It does not reflect the variability, feedback loops, or dynamic behavior that unfolds over time. Although VSM is a highly effective tool for making a system lean, it is not well-suited for assessing resilience or capturing system behavior during disruptions.

This limitation becomes particularly important when evaluating resilience, which is inherently time-dependent and concerned with how a system performs before, during, and after a disruption.

Relying solely on static tools like VSM may lead to an incomplete understanding of a system's ability to recover and adapt. To gain a more comprehensive understanding of the resilience of a system after applying VSM, it is helpful to use a dynamic complementary tool, such as simulation. Simulation supports this analysis by modeling system behavior over time and offering insights into performance fluctuations and recovery patterns under disruptive scenarios.

1.2 Research Gap and Objective

As discussed in the previous section, lean manufacturing and system resilience are essential for ensuring manufacturing systems' long-term sustainability and competitiveness. While lean strategies focus on eliminating waste and improving efficiency, there is growing concern about their impact on system resilience. Specifically, questions remain about how lean implementation influences a system's vulnerability to disruptions and its capacity to recover afterward.

Although several studies have explored the relationship and trade-offs between lean practices and system characteristics such as agility, responsiveness, and resilience, most of these investigations rely heavily on empirical methods such as surveys or expert opinions. One reason for this is the inherent difficulty in quantifying resilience. Resilience has broad and context-dependent definitions, typically linked to a system's performance over time. Unlike efficiency metrics, resilience lacks a universally accepted measurement approach, making it challenging to evaluate using standard methods. As a result, existing studies examining the relationship between lean and resilience have predominantly taken qualitative or interpretive approaches.

However, in studies unrelated to lean, researchers have proposed various methods to quantify resilience in supply chains using analytical models and simulation-based techniques. Discrete Event Simulation (DES) has proven particularly effective in capturing dynamic system behavior before, during, and after disruptions. Simulation allows researchers to model complex systems using current data and to observe how performance evolves in response to hypothetical disruption scenarios. Simulation becomes a valuable tool for understanding and predicting system resilience in this context.

Simulation is also widely recognized as complementary to Value Stream Mapping (VSM). While VSM provides a static snapshot of material and information flows in a system, simulation offers a dynamic view of how the future state performs under varying conditions after applying lean principles. Previous studies have used simulation to evaluate post-lean implementation outcomes such as waste reduction and lead time improvement. However, there is currently a lack of research that integrates lean implementation with disruption scenarios to examine how lean systems perform when exposed to real-world disturbances.

Thus, the primary research gap lies in the quantitative assessment of how lean implementation, specifically through VSM, affects supply chain vulnerability and resilience in the face of disruptions. In other words, it remains unclear whether VSM-based lean manufacturing systems maintain their effectiveness during disruptive events or become more fragile due to removing redundancies.

To address this gap, this study proposes a simulation-based approach using Discrete Event Simulation (DES) to measure and compare system resilience before and after the implementation of VSM. While numerous disruptions can occur, this research will focus on two of the most common types affecting supply chains. Resilience will be quantified using a framework proposed by Bruneau et al. [14], which evaluates the degree of performance degradation and the time required for recovery. This approach aims to clarify whether lean systems remain robust under stress or require additional strategies to maintain resilience.

1.3 Proposed Approach

To achieve the research objectives, this study utilizes a well-known example from Learning to See by Rother et al. [13], a foundational text in Value Stream Mapping (VSM). The book is designed to teach VSM techniques through step-by-step application using real-world manufacturing scenarios. In its final chapter, the authors provide a comprehensive case study involving the production of "Steering Arms" by TWI Industries. This example includes a detailed current state map and a fully developed future state map based on applying lean principles and VSM techniques. The future state reflects recommended process changes to reduce waste and improve operational efficiency.

This case study offers a robust foundation for the present research, representing a complete lean transformation process supported by real data. Using this model, we can begin with a validated lean intervention framework and focus specifically on evaluating its impact on system performance under disruption.

To conduct this analysis, we will employ Arena simulation software to build dynamic models of the production system before and after applying VSM-based lean improvements. Simulation enables us to model the system's behavior over time, like system performance change in disruption scenarios, which cannot be captured through static tools like VSM. This allows for a more comprehensive analysis of how lean systems respond to disturbances and whether they retain their efficiency under stress.

The simulation results will be used to assess the system's vulnerability and resilience, applying the framework proposed by Bruneau et al. [14], which quantifies resilience based on performance degradation and recovery time. By comparing key performance indicators (KPIs) such as throughput and lead time, the study aims to evaluate how lean implementation affects the production system's vulnerability and resilience.

1.4 Research Contribution

This study advances the investigation of how lean principles influence system resilience by integrating simulation-based analysis with traditional lean methodologies. While lean tools like Value Stream Mapping (VSM) are commonly used to identify inefficiencies and guide process improvements, they do not capture dynamic system behavior or performance under disruption. By introducing Discrete-Event Simulation (DES) into the analysis, this research provides a time-based perspective on how lean modifications affect not only operational efficiency but also a system's ability to absorb and recover from disturbances. The interaction between lean principles and resilience is examined in depth, revealing that these two objectives are not inherently conflicting, but are shaped by factors such as disruption timing, resource constraints, and system responsiveness. For practitioners, this study offers practical implications by demonstrating how simulation can be used to extend the capabilities of VSM, enabling more informed decision-making and proactive planning in lean manufacturing environments.

1.5 Thesis Organization

The remainder of this paper is structured as follows: Section 2 reviews the existing literature on VSM, Discrete Event Simulation (DES), resilience, and the relationship and interaction between these three axes. Section 3 presents the proposed solution methodology aimed at addressing the research question. Section 4 presents a case study of the TWI company, as introduced by Rother et al. (1999) [13], to simulate its operations before and after the implementation of VSM and discuss computational results. In Section 5, the results will be interpreted and discussed, and finally, Section 6 provides concluding remarks and suggests potential avenues for future research.

CHAPTER 2

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2 LITERATURE REVIEW

2.1 Value Stream Mapping (VSM)

In recent years, the industrial landscape has seen a marked increase in competition, demanding businesses keep pace and continuously improve to maintain their market standing. Lean methodologies have been increasingly adopted to address these challenges and enhance system efficiency. This methodology emphasizes diminishing costs by eradicating actions that do not contribute to value creation[4].

Among the various techniques under the lean methodology umbrella, Value Stream Mapping (VSM) has gained significant traction across multiple industrial sectors. In the Value Stream Mapping (VSM) context, "value" refers to any activity or process step directly contributing to meeting customer requirements or expectations. Conversely, non-value-added activities, often called "waste," are steps that do not directly contribute to meeting customer needs or expectations. VSM is a straightforward tool used on paper to help understand and show the journey of materials and information as a product moves through the value stream. It simply traces the production route of a product from customer to supplier, vividly drawing every process involved in the material and information flow. Afterward, a "future state" map should be drawn by asking key questions to depict the ideal movement of value [13].

Identifying and eliminating non-value-added activities, in other words, “waste,” is the key objective of Value Stream Mapping, which aims to increase efficiency, reduce costs, and improve the overall process flow. According to [3], there are seven categories of waste within manufacturing processes: overproduction, waiting, transportation, inappropriate processing, excess inventory, unnecessary motion, and defects. In Value Stream Mapping, the first step involves drawing the current state map, which traces the product flow from raw material to finished product, documenting all processes it undergoes. After creating the current state map, lean methodologies and tools are applied to reduce waste and enhance process efficiency. Several lean methods can improve the current state map, such as aligning production with takt time, establishing continuous flow where feasible, managing production with 'supermarkets' when continuous flow isn't possible, directing the customer schedule to a single point in the production process, balancing the production mix and volume, and achieving the capability to produce every component at frequent intervals, ideally every shift or more frequently, especially before the pacemaker process [13]. After applying these improvements, a future state map is created, integrating lean methodologies and tools.

Value Stream Mapping is an extremely popular technique in various industries due to its inherent adaptability and flexibility. This makes it particularly suitable for multiple sectors, from manufacturing to services. Implementing VSM can bring numerous benefits to a company. These include enhancing the flow of information to eliminate bottlenecks, significantly reducing excessive wait times, and overall enhancing the efficiency of business processes. The adaptability of VSM allows it to be tailored to the specific needs of each industry, thereby optimizing operations and improving resource utilization.

The number of literature reviews on Value Stream Mapping is quite limited. Among the few that exist, (Shou et al., 2017) stands out as one of the most comprehensive, offering a detailed topic exploration. Their study reviewed 131 journal articles from 1999 to 2016, scrutinizing the implementation cycle of VSM in industries. [15] A study shows that significant research efforts have been directed towards manufacturing. The paper showcases how the effectiveness of VSM implementations varies by context, classifying them into five business domains: manufacturing, healthcare, construction, product development, and service. It discussed the different metrics and lean tools used in each context for analyzing the Current State Map and improving the Future State Map.

Another literature review on VSM was conducted [16], which provided an extensive analysis explicitly focused on the service industry. This review examined 45 studies that applied VSM in various service sectors, including finance, healthcare, public services, transportation, etc. Their paper categorizes research objectives and implementations, emphasizing how VSM is adapted to meet the unique demands of the service industry, and, conversely, [17] analyzes the development of VSM within the Indian industrial context, reviewing 47 papers to categorize the research into conceptual, empirical, case studies, and surveys. They focused on the attributes of VSM used in the studies and demonstrated its effectiveness through a detailed case study.

Moreover, [18] the role of VSM in identifying non-value-added elements, reducing waste, and improving efficiencies like lead time and inventory management across various industries was discussed. In conclusion, reviewing the literature [19], we addressed the challenges in creating current state maps in VSM. They categorized articles based on their practical or theoretical approach and discussed frequent challenges such as poor process stability, unclear procedures, and difficulty measuring data. Additionally, they proposed guidelines to improve VSM effectiveness and suggested areas for further research.

2.2 Discrete-Event Simulation (DES) and VSM in Manufacturing

Discrete Event Simulation (DES) is a widely used decision-making technique in conjunction with Value Stream Mapping in practical applications. The two methods suggest distinct conceptual models of production, one involving a deterministic material flow and the other based on a stochastic queuing network [20]. While VSM enables us to visualize material and information flow and identify improvements, simulation provides a tool for assessing key performance indicators and exploring different system configurations, enhancing predictive accuracy and operational efficiency. Simulation is a complementary tool to VSM and enhances its capabilities by introducing a dynamic dimension [21].

The typical approach involves creating a current state map using VSM, simulating the process, and validating the simulation model with current system data. The modifications are applied to the simulation model after pinpointing non-value-added processes and determining remedies utilizing lean and VSM techniques. Observing the resultant changes provides a quantifiable comparison, serving as a persuasive instrument for building trust among managers who may be hesitant about change. Upon surveying additional literature, a noticeable pattern of encouraging the application of DES as a supplementary tool to VSM emerged.

Applying this integrated approach to a glass industry case was harnessed to address the long manufacturing lead times and imbalance in production lines at a Jordanian glass fabrication company. The incorporation of DES into VSM enabled the identification of bottlenecks and provided a means to dynamically evaluate the impact of potential process improvements. The study's success was measured through key performance indicators, including resource utilization, product cycle time, and manufacturing lead time, with results showing a 6% reduction in lead times and a 32% performance increase at primary bottlenecks.

[4] Extended the VSM-DES hybrid methodology to the process sector, tackling the challenges inherent in a large integrated steel mill known as AB Steel. Here, the methodology effectively addressed the barriers to lean manufacturing, such as large machinery and long setup times. Their dynamic simulations anticipated future issues, allowing them to assess the viability and effectiveness of lean interventions. The outcomes, which included reduced production lead times and lower work-in-progress inventory, highlighted the method's capability to improve operational efficiency significantly.

[22] Explored the integration of VSM and DES to refine lean manufacturing initiatives. By bringing time dynamics into play through DES, their approach allowed for an in-depth analysis of manufacturing processes, going beyond the reach of traditional VSM. This enabled the identification of hidden inefficiencies and the simulation of various improvement scenarios, with key performance indicators used to quantify the positive impacts.

Further showcasing the methodology's versatility, [23] the company employed VSM-DES integration to optimize the production system of a small and medium-scale enterprise (SME) within the industrialized construction sector in Sweden. Their approach proved beneficial for simulating and validating potential changes, resulting in improved operational efficiency, reduced lead times, and lower inventory costs.

Similarly, [24] the same methodology was applied to a Malawian pharmaceutical warehouse, targeting the reduction of lead times within the supply chain. Through this hybrid approach, they achieved notable improvements in operational performance, as demonstrated by a significant decrease in Total Process Lead Time.

[25] Investigated the truck manufacturing industry, employing the VSM-DES integration to address production line inefficiencies. Their findings showed a 4% increase in productivity and reduced cycle times, underlining the methodology's effectiveness in identifying and eliminating inefficiencies.

The adaptability of VSM and DES was also evident in a healthcare setting, where [26] they were applied to improve the efficiency of emergency departments in Istanbul, Turkey. The hybrid approach allowed for a comprehensive operations analysis, reducing patient waiting times and improving service efficiency.

[27] Explored the furniture manufacturing sector and demonstrated how VSM's integration with DES could address efficiency issues and waste reduction. The methodology facilitated the simulation of various scenarios, resulting in enhanced production efficiency and lead time reductions, thereby validating the combined approach as a comprehensive solution to complex and dynamic manufacturing challenges.

2.3 **Resilience in Lean Systems**

The contribution [15] provides a valuable cross-sector review of VSM applications (131 articles), highlighting its adaptability and sector-specific challenges. However, it focuses on static implementations and traditional metrics, overlooking dynamic system behavior and variability. While it advances understanding of VSM's broad applicability, it does not integrate DES or address resilience under disturbances.

The contribution [28] adopts a qualitative, organizational approach, using Revans' action learning process to enhance resilience, client satisfaction, and quality in mass-customization environments. While it effectively addresses human and organizational factors through cyclical problem-solving, it focuses on traditional lean-like practices. It does not explore the limitations of static methods like VSM or integrate dynamic tools like DES. The study's emphasis on adaptability and employee engagement aligns with your research objective but lacks a technical, system-level analysis of variability and disturbances.

The contribution [11] highlights the trade-off between lean strategies and supply chain resilience, emphasizing how cost reduction initiatives (e.g., zero stock policies) increase vulnerability to disruptions. It proposes a supply chain risk management model to balance efficiency and resilience, addressing a critical gap in lean implementations. While it provides valuable insights into lean systems' organizational and strategic challenges, it focuses on supply chain-level trade-offs rather than operational-level dynamics. The study does not explore tools like VSM or DES to quantify or validate resilience under disturbances.

The contribution [9] explores the resilience of hybrid supply chains (lean, agile, and green) and their ability to mitigate disruptions. It highlights the practical dominance of lean strategies due to their cost-saving benefits and organizational discipline, despite assumptions that agility is essential for resilience. The study identifies cognitive dissonances, such as the underrepresentation of lean and green attributes in resilience models, and emphasizes the need for trade-offs between efficiency and redundancy. While it provides valuable insights into the interplay of lean, agile, and green practices, it does not address operational-level tools like VSM or DES to quantify resilience under disturbances.

The contribution [29] uses Discrete-Event Simulation (DES) to model hospital emergency department (ED) resilience during disasters, focusing on patient waiting times as a key performance indicator. It develops a DES model and a simplified metamodel to predict ED performance under emergency conditions, demonstrating the effectiveness of emergency plans in reducing waiting times. While the study showcases the power of DES for dynamic system analysis and resilience assessment, it is limited to healthcare systems. It does not explore the integration of lean tools like Value Stream Mapping (VSM).

The contribution [12] explores using lean tools, such as Value Stream Mapping (VSM), SIPOC analysis, and fish-bone diagrams, to enhance resilience in Disaster Relief Operations (DROs). It demonstrates how lean transformation can improve responsiveness by identifying and eliminating non-value-added activities, as evidenced by a 14% reduction in time lost in an industrial fire case study. While the survey effectively applies lean principles to DROs, it focuses on qualitative and process-level improvements without integrating dynamic tools like Discrete-Event Simulation (DES) to quantify system behavior under disturbances.

The contribution [30] systematically reviews four decades of lean literature, identifying five phases of lean evolution and highlighting key knowledge gaps. While synthesizing lean principles and their applications, it underscores significant voids, such as the lack of theoretical connections to organizational change, systems thinking, and human resource development (HRD). The review emphasizes the need for deeper lean integration with HRD and organizational change theories, particularly in addressing lean transformations' "human factor" and dynamic aspects. However, it does not explore integrating lean tools like Value Stream Mapping (VSM) with dynamic methods such as Discrete-Event Simulation (DES) to address system variability and resilience.

The contribution [8] explores the impact of lean and agile supply chain strategies on robustness and resilience, using empirical data from 140 supply chain professionals. It finds that lean strategies significantly enhance robustness but not resilience, while agile strategies improve both. The study highlights the importance of market orientation (MO) and quality management (QM) as drivers for these strategies, with MO favoring agility and QM favoring lean. However, it does not address integrating lean tools like Value Stream Mapping (VSM) with dynamic methods such as Discrete-Event Simulation (DES) to quantify system behavior under disturbances.

The contribution [31] explores the impact of Lean Six Sigma (LSS) practices on supply chain resilience, proposing a conceptual framework based on interviews with 21 healthcare professionals. It identifies key themes such as IT management, risk management, and process reconfiguration, highlighting how LSS can enhance resilience through improved process efficiency and disruption readiness. While the study demonstrates the potential of LSS to address supply chain challenges, particularly in healthcare, it does not integrate dynamic tools like Discrete-Event Simulation (DES) to quantify system behavior under disturbances.

The contribution [32] explores the relationship between lean practices and resilience capabilities in the healthcare supply chain through a scoping review of 44 articles. It identifies synergies and divergences between lean and resilience, proposing a conceptual framework that links lean practices to resilience across different tiers and value streams in healthcare. While the study provides valuable insights into prioritizing lean practices for resilience, it does not address the integration of dynamic tools like Discrete-Event Simulation (DES) to quantify system behavior under disturbances.

The contribution [33] investigates the relationship between lean and resilient supply chain (SC) practices in the aerospace manufacturing sector, using Interpretive Structural Modeling (ISM) to identify linkages and their impact on SC performance. It finds that lean practices act as drivers for resilient practices, as lean implementations can increase SC vulnerability, necessitating resilience to mitigate disruptions. While lean practices significantly improve operational and economic performance, resilient practices have a more limited impact, except for "flexible supply base," which enhances both performance areas. However, the study does not explore the integration of dynamic tools like Discrete-Event Simulation (DES) to quantify system behavior under disturbances.

The contribution [34] demonstrates the application of Discrete-Event Simulation (DES) to optimize and enhance the resilience of healthcare delivery systems, specifically for HPV-based cervical cancer screening in Peru. The study uses DES to model "what-if" scenarios, evaluating system performance under resource constraints, variability, and disruptions. It highlights the trade-offs between efficiency and resilience, identifying critical resource requirements for scaling up and maintaining service delivery during disruptions. While the study effectively showcases DES as a tool for operational planning and resilience in healthcare, it does not integrate lean tools like Value Stream Mapping (VSM) to complement the dynamic analysis.

The contribution [7] comprehensively reviews resilience definitions and quantification approaches across organizational, social, economic, and engineering domains. It classifies resilience measures into qualitative (conceptual frameworks, semi-quantitative methods) and quantitative (general resilience measures, structural models) approaches, emphasizing the importance of planning and resource allocation for achieving resilience. While the review highlights the interdependence of infrastructure systems and the need for optimization models to balance vulnerability reduction and recoverability, it does not address the integration of lean tools like Value Stream Mapping (VSM) with dynamic methods such as Discrete-Event Simulation (DES).

The contribution [6] evaluates the resilience of lean production systems through a systematic literature review, investigating the correlation between lean principles and system resilience. It shows that specific lean methods, such as continuous improvement, Value Stream Mapping (VSM), and waste reduction, positively influence resilience, while others, like standardization, may have conflicting effects. The study highlights the need to adapt traditional lean concepts to enhance resilience in the face of disruptions, such as those caused by the COVID-19 pandemic. However, it does not explore the integration of dynamic tools like Discrete-Event Simulation (DES) to quantify system behavior under disturbances.

The contribution [35] evaluates the impact of resilience strategies, such as prepositioned inventory and backup suppliers, on supply chain (SC) resilience and financial performance during high-magnitude disruptions like the COVID-19 pandemic. Using AnyLogistix for discrete-event simulation (DES), the study quantifies resilience and demonstrates that prepositioned inventory increases resilience but at a significantly higher cost than backup suppliers. The study introduces a novel method for deriving quantitative resilience metrics from simulation, providing actionable insights for decision-makers to balance resilience and cost efficiency. However, it does not integrate lean tools like Value Stream Mapping (VSM) to complement the dynamic analysis.

The contribution [36] provides a systematic literature review of 53 articles to explore the integration of lean and resilience paradigms, addressing their application, compatibility, integration, and impact across various industries and organizational functions. Using the C-I-M-O (context-intervention-mechanism-outcome) framework, the study identifies four dominant research streams: application, compatibility, integration, and impact assessment. It highlights the synergies and divergences between lean and resilience, emphasizing the need for structured research on implemented practices and their benefits. While the study offers a comprehensive concept map to guide future research, it does not explore the integration of dynamic tools like Discrete-Event Simulation (DES) to quantify system behavior under disturbances.

The contribution [37] proposes a mathematical model using sigmoid functions to quantify and predict the resilience of systems during disruptions. The model captures the entire performance curve of a system, including preparation, absorption, recovery, and adaptation phases, and links model parameters directly to resilience capabilities. By applying the model to a traffic system, the study demonstrates how it can evaluate resilience-enhancing measures and account for uncertainties in system performance. While the model provides a robust framework for quantifying resilience, it does not integrate lean tools like Value Stream Mapping (VSM) or dynamic methods such as Discrete-Event Simulation (DES) to address operational efficiency and adaptability.

While Value Stream Mapping (VSM) is a widely used lean tool for identifying inefficiencies, it provides only a static view of system behavior. Discrete-event Simulation (DES) offers a dynamic framework for evaluating performance over time. Although several studies have integrated VSM and DES to support lean implementation, and others have used simulation to assess resilience, few have combined all three to examine how lean systems respond to disruptions. This gap highlights the need for a simulation-based approach that evaluates efficiency and quantifies resilience in lean production systems. The following chapter presents the methodology used to address this gap.

CHAPTER 3

3 METHODOLOGY

3.1 Research Design and Approach

This research investigates the impact of lean implementation on the resilience of a manufacturing system using a discrete event simulation approach. To achieve this, Arena simulation software was used to model the production process of a selected case study and analyze system behavior under various disruption scenarios. The goal is to assess whether a lean configured system, specifically one shaped by Value Stream Mapping (VSM), maintains its resilience when exposed to supply chain disturbances.

The research is organized into five stages, described below and visually represented in **Figure 1**.

1. In the first stage, the current production process described in the original VSM from Rother et al.[13] is translated into a discrete event simulation model using Arena. This model reflects the system's baseline performance before any lean interventions.

2. In the second stage, lean improvements inspired by the future state VSM in the same reference, combined with insights from the initial simulation model, are implemented. These include specific changes aimed at reducing waste and improving efficiency. After applying lean principles, a second simulation model is developed to represent the system.

3. In the third stage, predefined disruption scenarios are introduced to current and future (lean) models. These scenarios include delays in raw material deliveries, breakdown of the paint subcontractor, and a combined disruption scenario. Recovery strategies such as

sourcing alternative suppliers or utilizing contingency inventory are also implemented to evaluate system resilience.

4. In the fourth stage, the resilience of both systems (pre- and post-lean) is quantified using a measurement framework proposed by Bruneau et al. [14]. The simulation results extract key performance indicators (KPIs) such as throughput degradation and cycle time variation.

5. In the fifth and final stage, the resilience of the current and future state systems is compared. This analysis explores whether lean implementation, as defined by VSM-based improvements, enhances or reduces the system's ability to respond to and recover from disruptions.

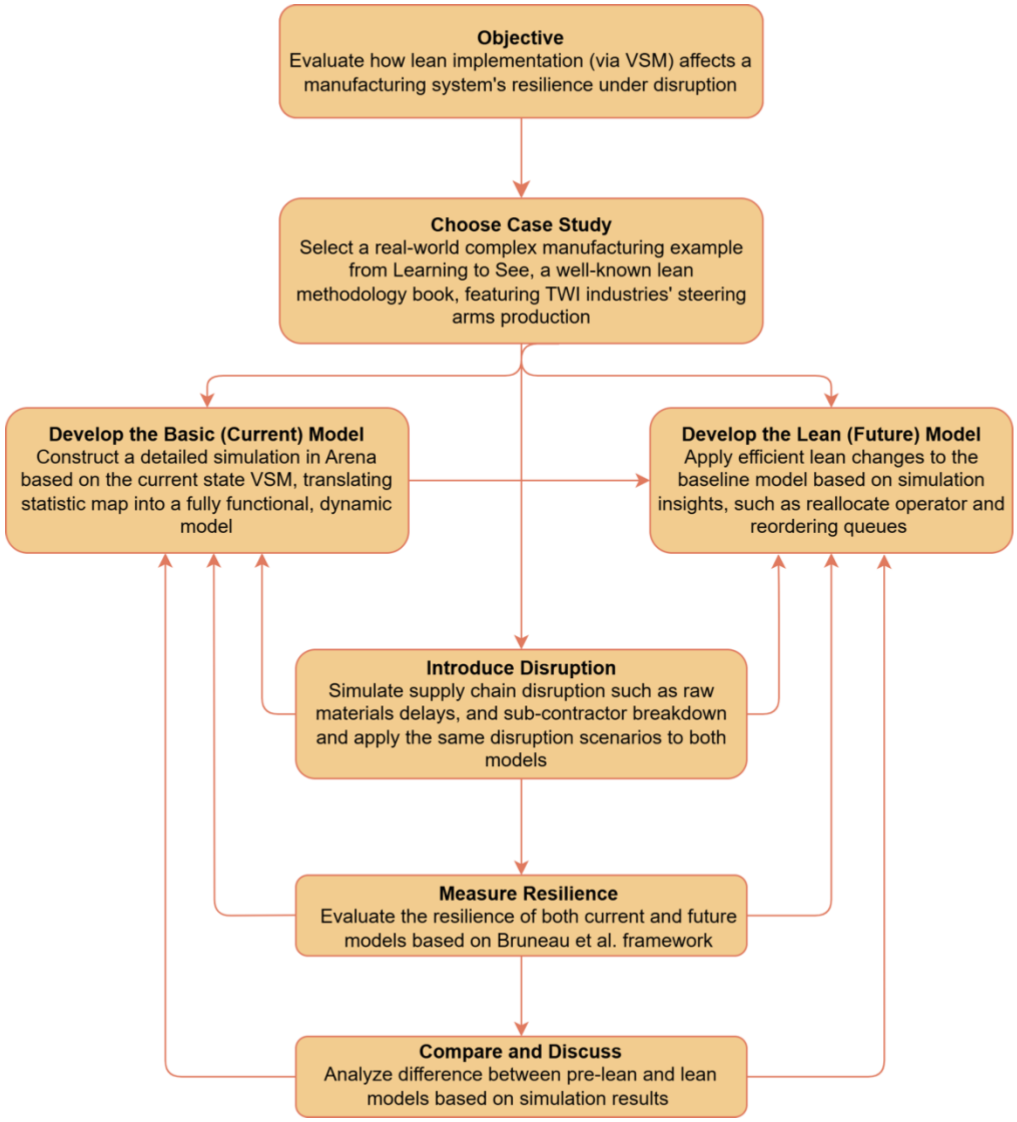

Figure 1: Research Methodology Flowchart

The boundaries of this research are explicitly focused on modeling system behavior under disruption, not optimizing lean tools themselves. The scope is limited to the selected case study, predefined disturbances, and recovery strategies. By combining lean principles using the VSM technique with Discrete Event Simulation, this study provides a structured approach to evaluate the intersection of efficiency and resilience in modern manufacturing systems.

3.2 Simulation of the Current State

The case study selected for this research is the production of "Steering Arms" by TWI Industries, originally presented in Learning to See by Rother et al. [13]. This book is widely recognized in the lean manufacturing literature as a foundational resource for learning Value Stream Mapping (VSM) techniques. It provides a comprehensive example that includes a detailed description of the production process, a current state map illustrating the flow from supplier to customers, and a future state map that demonstrates lean-based process improvements following the implementation of VSM.

A discrete event simulation model was developed using Arena to simulate the current model of the steering arm production system. This process involved transforming the static VSM built by Rother et al. [13] into a dynamic model by defining detailed process logic, incorporating batching behavior, modeling operator and resource constraints, and simulating external factors such as subcontractor involvement and raw material interarrival time. The simulation flow was built step by step to reflect real-world production dynamics, beginning with order generation and progressing through all primary production stages. The detailed explanation of the case study and production processes, with the subsequent sections, provides a detailed explanation of the simulation model structure, assumptions, and configuration, which is presented in Chapter 4.

3.3 Simulation of the Lean-Enhanced System: Future State

In this stage of the research, lean improvements inspired by the future state VSM presented in Rother et al. [13] and insights from simulation model results are applied to the production process. The goal is to translate these improvements into a future state simulation model using Arena software to evaluate the behavior of a lean-configured system under both normal and disruptive conditions.

Two key lean principles are incorporated into the model, each addressing specific inefficiencies observed in the current state. These modifications aim to reduce waste, improve flow, and ultimately make the system more responsive and efficient.

1. Produce to Takt Time

To address the overproduction observed at the assembly station, the number of operators is adjusted to align production output with takt time. Given a per-piece assembly time of 195 seconds and a per-shift demand of 600 pieces, the total assembly time required per shift is calculated in Equation **Error! Reference source not found.**), and the number of assembly operators needed for the production is calculated in Equation (2):

$$\text{Total assembly time per shift} = 195 \text{ seconds} \times 600 = 117000 \text{ seconds} = 32.5 \text{ hours} \qquad (1)$$

With 7.5 available work hours per shift per operator, the required number of operators is:

$$\text{Assembly operators needed} = \frac{32.5}{7.5} = 4.3 \text{ minutes per unit} = 4 \text{ operators (rounded)} \qquad (2)$$

2. Identify and address bottlenecks:

The forging process was identified as a potential bottleneck, indicated by the high utilization rate of the forge operator (96%) and a significant queue of 5,373 orders waiting for processing. To alleviate this bottleneck, one of the previously dismissed assembly operators was reassigned to support the forging station. This reallocation of labor aimed to reduce delays and improve overall system flow.

3. Reduce Changeover Times (non-value-added activities)

In the current process, changeover times at the end fitting and socket machining stages significantly contribute to downtime. To address this issue, the queue feeding into the forging station was restructured. Instead of using a traditional First-In-First-Out (FIFO) policy, the queue was reordered based on end fitting type. This change reduced variability between consecutive jobs and minimized changeover frequency, leading to a decrease in queue waiting times and improved process efficiency.

These three improvements, including reassigning assembly to the forging station, reducing idle assembly operators, and optimizing changeover through queue management, contribute to lower resource idleness while enhancing system flexibility. By implementing these lean strategies and incorporating them into the future state simulation model, the system is redesigned to operate more efficiently. This improved model is the second simulation model for evaluating resilience under disruption scenarios, enabling a performance comparison with the original simulation model that reflects the current state Value Stream Map (VSM).

3.4 **Introduction of Disruptions and Recovery Strategies**

The current and future simulation models introduce specific disruption scenarios, beginning at time t_0, with corresponding recovery strategies applied at time t_1 to mitigate their effects. Two common types of supply chain disruptions are considered:

- Raw Material Shortage: Simulating reduced availability of raw materials from individual or all suppliers, representing situations like supply shortages.

- Subcontractor Breakdown: Representing a subcontractor's failure or temporary unavailability, leading to interruptions in specific production processes.

Two of the most common strategies for a resilient supply chain are excess inventory and backup suppliers [38] [39]. This study implements backup suppliers and backup subcontractors as recovery strategies.

3.5 Evaluating Resilience

3.5.1 Performance metrics

KPIs- Selecting appropriate KPIs supports a comprehensive assessment of business performance [40], [41]. This study intends to investigate what happens after lean implementation at TWI's company and how it will affect system resiliency. One of the key performance indicators (KPIs) considered in this study is throughput. Since the objective is to capture the variability in the system following a disturbance, throughput was selected because it does not fluctuate significantly over time unless a disruption occurs. Throughput at each time point was calculated by dividing the number of orders shipped by the total operational time of the system.

3.5.2 Quantification Method

Measuring resilience is inherently complex. It is a multidisciplinary area that involves evaluating the magnitude of performance degradation and the time required for recovery. Several quantitative approaches exist for measuring a system's resiliency. In this study, resilience will be quantified using a framework proposed by Bruneau et al. [14]

Bruneau et al. [14] introduced an intuitive and widely accepted approach for quantifying the resiliency of a system based on the performance over time. They calculated resiliency as a function of system performance. If the performance of the system at time t is Q_t, and a disruption happens at t_0, and the system restoration happens through time and at time $t_1 > t_0$, the systems bounce back to its original performance [14] calculate the resilience of the system as shown in Equation (3):

$$R = \int_{t_0}^{t_1} [100 - Q(t)]\, dt \tag{3}$$

Figure 2 illustrates the performance track of a system following a disruption. The shaded triangular area between the disruption-free performance level and the actual performance curve is referred to as the resilience loss (R). A smaller triangular area indicates a more resilient system, either because the system recovers more quickly, the performance degradation is less severe, or both. Bruneau et al. [14] assume that in a disruption-free scenario, system performance remains at 100%, and that the system ultimately returns to its original performance level after recovery.

This resiliency measurement is highly intuitive and adaptable and can be used to measure the resiliency of different systems.

This study adopts this framework as it offers a foundational approach to measuring resilience. It is valued for its intuitive structure, flexibility, and broad applicability in assessing a system's ability to absorb disruptions and recover over time.

Figure 2: Representation of resilience loss measurement [7]

This chapter outlined the overall research design, including the simulation framework, lean implementation strategy, and disruption scenarios. The methodology integrates Value Stream Mapping (VSM) with Discrete-Event Simulation (DES) to assess efficiency and resilience. The following chapter presents the detailed case study of TWI Industries' steering arm production. The chapter also describes the development of the simulation models, key assumptions, input parameters, and model configuration used to evaluate system behavior under various conditions.

CHAPTER 4

4 Case Study and Model Development

4.1 Case Study: TWI Industries Steering Arm Production

This research is based on a detailed case study presented in *Learning to See* by Rother et al. [13], a foundational resource widely recognized in lean manufacturing and Value Stream Mapping (VSM). The example focuses on producing steering arms, a mechanical component used in tractor assemblies, manufactured by TWI Industries. This case is particularly valuable for simulation and resilience assessment due to its well-documented process structure, inherent complexity, and diverse product configurations.

A steering arm is a metal rod with forged fitting sockets welded to each end**. Figure 3** shows the structure of the steering arms.

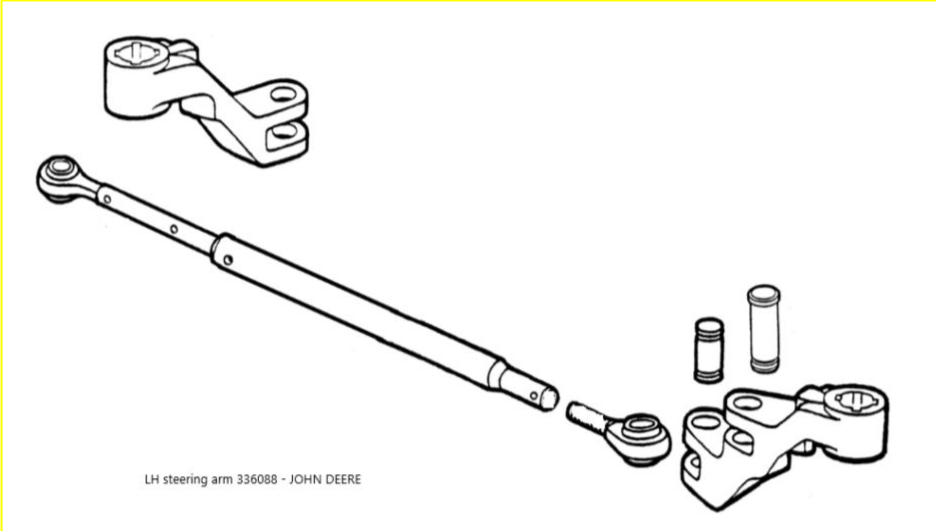

Figure 3: Steering Arm Structure

4.2 Process Description and Flow

The production process has seven main stages, each contributing to transforming raw materials into finished steering arms.

Figure 4 shows the process flows for producing steering arms, and the detailed production processes are as follows:

- Cutting: The rods from Michigan Steel Co. are manually cut to specific lengths using a saw. This process is operator-dependent and includes changeover time when switching between rod lengths or diameters.

- Machining of End Fittings and Sockets: The sockets and end fittings supplied by Indiana Castings undergo automated machining to ensure dimensional compatibility with the rods. This stage also involves a changeover time for handling different socket configurations.

- Welding (I): One end fitting is welded to one end of the rod. This is an automated process requiring operator supervision for loading and unloading. Changeovers are necessary when product dimensions vary.

- Welding (II): The second end fitting is welded to the opposite end, completing the main structural assembly. This process mirrors the conditions and requirements of Welding (I).

- Deflashing: An automated process that removes excess weld material to improve product quality and consistency. Changeover time is again relevant when switching between different product sizes.

- Painting: After deflashing, the steering arms are transported to an external painting facility. A daily truck service manages the outbound shipment of unpainted parts and the return of painted components.

- Assembly: The final step involves manually assembling the sockets to the painted rod.

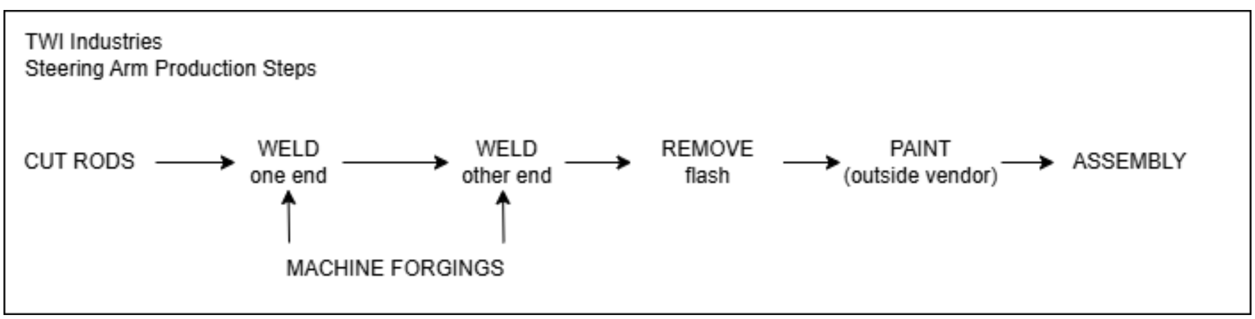

Figure 4: Steering Arm Production Process

4.3 **Data Collection and Parameters**

As **Figure 5** shows Steering Arms are offered in multiple configurations, with 20 different lengths, 2 diameters, and 3 types of end fittings. resulting in 240 possible product variants. This high level of customization requires frequent setup changes and flexible process planning, both characteristic of complex manufacturing systems and significant factors when assessing vulnerability to disruptions.

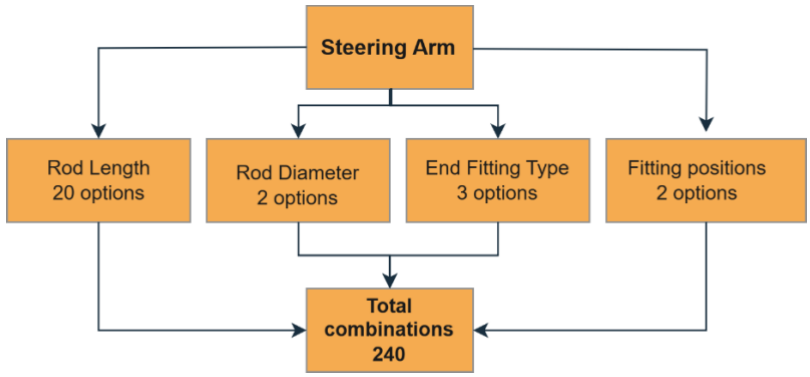

Figure 5: Steering Arm Configuration

The raw materials required for production are sourced from 2 different suppliers:

- Steel rods are procured from Michigan Steel Co., with a lead time of 16 weeks and 2 shipments per month.
- Forged end fittings and sockets are supplied by Indiana Castings, with a lead time of 12 weeks and two shipments per month.

In addition to internal processing steps, TWI Industries outsources the painting operation from a third-party subcontractor, extending the supply chain and introducing an additional layer of coordination and potential risk. The presence of multiple suppliers, external subcontracting, and long lead times makes this case a practical and realistic representation of supply chain structures in real-world manufacturing environments.

TWI Industries also operates under variable customer demand, receiving orders ranging from 25 to 200 units, with an average order size of 50 pieces. The monthly demand is approximately 24,000 units, packaged in boxes containing up to 5 steering arms. Shipments are made multiple times daily, with product specifications varying wildly between customer orders. However, all items within a single order share the same configuration.

The complexity of this system lies in several interrelated factors: the high mix of products, dependency on multiple external suppliers, subcontracted operations, and dynamic customer demand. These characteristics increase the system's exposure to potential disruptions and make it an ideal candidate for studying resilience in a lean manufacturing context. Furthermore, the case study provides a current and future state map following the implementation of lean practices using VSM. This makes it especially suitable for comparing the system's behavior before and after lean transformation and evaluating how lean implementation affects resilience under defined disruption scenarios.

The data such as process time, change over time, number of resources and their approximate utility for each production step is provided in **Table 1**. Fixture changeover is the time required when altering between different types of fittings.

Table 1: Steering Arm Production Process Data

Process Information	**Cutting**	**Machining**	**Welding (I)**	**Welding (II)**	**Deflash**	**Paint**	**Assembly**
Number of Operators	1	1	1	1	1	Painting is done outside with a 2-day lead time. Daily pickup and drop off.	6
Cycle Time (Seconds)	15	30	40	40	40		195
Change Over Time (Minutes)	Length: 15 Diameter: 60	End Fitting: 120	Length: 15 Diameter: 60	Length: 15 Diameter: 60	Length: 15 Diameter: 60		Fixed:10
Resource Utility	100%	100%	90%	80%	100%		100%

The operational schedule for the TWI industry follows a 5-day workweek. Each workday comprises 2 shifts, each lasting 8 hours. Within each shift, employees are allocated two 15-minute breaks.

Calculating Takt time:

Takt time represents how often the manufacturer should produce one part or product, based on the sales rate, to meet customer demands. Takt time is calculated by dividing the available production time per shift by the customer demand per shift (in units) [13]. The steering arms production takt time is calculated in Equation (4).

$$\text{Takt time } = \frac{\text{available production time per shift}}{\text{customer demand per shift}} \tag{4}$$

Given the monthly demand of 24,000 units. Assuming a 20-day working month with two shifts per day, the system demand per shift is calculated in Equation (5). So, the production system must produce:

$$\text{Deamands per shift} = \frac{24000 \text{ units}}{20 \text{ days} \times \text{ 2 shifts}} = 600 \text{ units per shift} \tag{5}$$

Considering each shift has 450 minutes of available working time (after deducting a 30-minute break from each 8-hour shift), the time of steering arm production is calculated in Equation (6).

$$\text{Takt time (TWI)} = \frac{450 \text{ minutes}}{600 \text{ units}} = 0.75 \text{ minutes per unit } = 45 \text{ seconds per unit} \tag{6}$$

This means that to meet customer demand, the TWI industry must produce one steering arm every 45 seconds during active production time.

4.4 Assumptions and Simplifications

Due to limitations in detailed real-time operational data, several assumptions and simplifications were made to complete the simulation setup. These are outlined below.

1. Product Configuration: It is assumed that each customer order contains steering arms with identical configurations (i.e., same rod length, diameter, and end fittings). However, these configurations vary between different customer orders.

2. Order Batching: Customer orders are represented as batches of steering arms, reflecting how production and shipping are handled in practice. Each customer order consists of a batch of final products, typically around 50 units.

3. Order Size Variability: To model variability in order size, a probability distribution is assumed: 10% of orders consist of 25 units, 80% consist of 50 units, and 10% consist of 200 units. This assumption captures the typical range and frequency of order sizes encountered in the actual system.

4. Order Arrival Distribution: The statistical distribution follows an exponential distribution based on average demand and working time calculations.

5. Order Interarrival Time Calculation: Based on customer demand of 24,000 units per month and an average order size of 50 units, the system is expected to receive:

$$\text{Orders Interarrival} = \frac{16000 \text{ hours per month}}{24000\text{Monthly orders}} = 0.67 \text{ hrs between receiving each order} \quad (6)$$

6. Raw material arrival: The lead time for supplying raw materials is 16 weeks for receiving steel rods from Michigan Steel Co. and 12 weeks for receiving sockets from Indiana

Castings. This lead time is considered only once for the first order and is not included for subsequent orders.

7. Lead time calculation: Assuming a working day consists of 16 hours and a week has 5 working days, the lead times for steel rods and sockets are calculated as written in Equation (7) and Equation (8).

$$\text{Steel lead time: } (16 \text{ weeks} \times \ 5 \text{ days per week} \times 16 \text{ hous per day}) = 1280 \text{ hours} \tag{7}$$

$$\text{Socket lead time: } (12 \text{ weeks} \times 5 \text{ days per week} \times 16 \text{ hours per day}) = 960 \text{ hours} \tag{8}$$

8. Raw material utilization: Since there is no data indicating how much steel is in a rod, one steel unit is assumed to be required for each rod.

9. Working Calendar and Operator Scheduling: It is assumed that operators work based on a working schedule with two 8-hour shifts per day, and each shift includes a 30-minute break. Total work time per shift and per day is calculated in Equation (9) and Equation (10)

$$\text{Total work time per shift: } (8 \ \times \ 60) - 30 \ = 450 \text{ minutes} \tag{9}$$

$$\text{Total work time per day (2 shifts)} : (2 \times 450) = 900 \text{ minutes} \tag{10}$$

10. Break Policy: Operator breaks are modeled using a wait policy. This means that if a break period begins while an operator is actively working on an item, processing will resume, and the break starts after the active entity process is completed.

11. Processing Steps: Both end fittings and end fitting sockets will undergo forging and deflashing processes.

12. Arena run setup: The simulation model's base time unit is the hour. The run time is 360 hours, the warm-up time is 70 hours, and the number of replications is 5.

4.5 Simulation Model (Arena)

To analyze the dynamic behavior of the manufacturing system under various disruption scenarios, a Discrete Event Simulation (DES) model was developed using Arena simulation software. The simulation model is the foundation for evaluating system performance before and after lean implementation and under different disturbance conditions. The model is based on the current-state Value Stream Map (VSM) of the steering arm production process provided by Rother et al. [13] and reflects the real-world flow of materials, information, and resources at TWI Industries.

The development of this model involved translating a high-level VSM into a fully functional simulation environment that captures the detailed behavior of each production step, including queue logic, batch processing, changeovers, operator scheduling, raw material supply delays, and external subcontractor coordination. Each entity in the system represents a steering arm with attributes such as rod length, diameter, end fitting type, order number, batch size, and arrival time, which govern routing decisions and setup logic across the system.

The simulation model includes the following features:

- Process level logic: Each of the seven main production stages (cutting, machining, welding I and II, deflashing, painting, assembly, and shipping) is modeled as a dedicated process, with logic blocks that reflect resource constraints, operator involvement, and process timing.

- Changeover setup rules: Setup times are applied when changing product dimensions (length, diameter) or switching end fittings. Setup is modeled to occur once per lot, with appropriate decision logic based on the configuration attributes of incoming parts.
- Batching behavior: Orders are received as batches rather than individual parts. Batch size follows a probability distribution.
- Operator assignment and shift scheduling: Each process is served by a defined number of operators whose availability is modeled using shift calendars and resource schedules. Operator breaks are implemented with a wait policy: breaks begin only after a task in progress is completed.
- Subcontractor logic: The painting stage, performed by an external vendor, is modeled with truck pickups and drop-offs, a 2-day turnaround time, and inventory queuing behavior.
- Supply chain delays: The initial lead times for raw material procurement (16 weeks for rods, 12 weeks for forged sockets) are included in the model, though they are assumed to affect only the first-order cycle.
- Material matching logic in several steps ensures that appropriate end fittings and sockets are paired during the welding stages and assembly.

In configuring the model, several Arena-specific elements were used:

- Create and Assign modules to generate orders with random sizes and different configurations

- Seize, Delay, and Release modules to model workstation logic and changeovers
- Decide and Batch blocks to handle the routing and assembly of parts with compatible attributes
- Record and Statistics modules to capture key performance indicators (e.g., Number of fulfilled orders, cycle time, etc.)
- Global variables and expressions to manage queues, order attributes, and simulation control

Each part of the system was rigorously tested and refined to ensure it behaved in accordance with real-world assumptions and VSM structure.

Figures in the appendices will present selected screenshots of the Arena simulation model, demonstrating the translation from conceptual flow (VSM) to executable simulation logic.

This model serves as the baseline (current state) for developing the lean version (future state). It is also used to implement disruption scenarios, assess their impact on system performance, and evaluate system resilience using quantitative indicators.

4.6 Simulation Model Visualization

To clearly illustrate the translation of the Value Stream Map into simulation logic, **Figure 6** presents a high-level flowchart representing the overall logic of the Arena simulation model. This flowchart outlines how entities flow through the system, interact with resources, and follow rules such as changeovers capturing the essential structure without delving into module level detail.

While the flowchart serves as a simplified representation, detailed screenshots of the actual Arena model, including individual modules and process-specific configurations, are provided in the

Appendices. These images offer a comprehensive view of how each production process was modeled using Arena's process-oriented modules, particularly concerning operator schedule, inventory management, and production constraints.

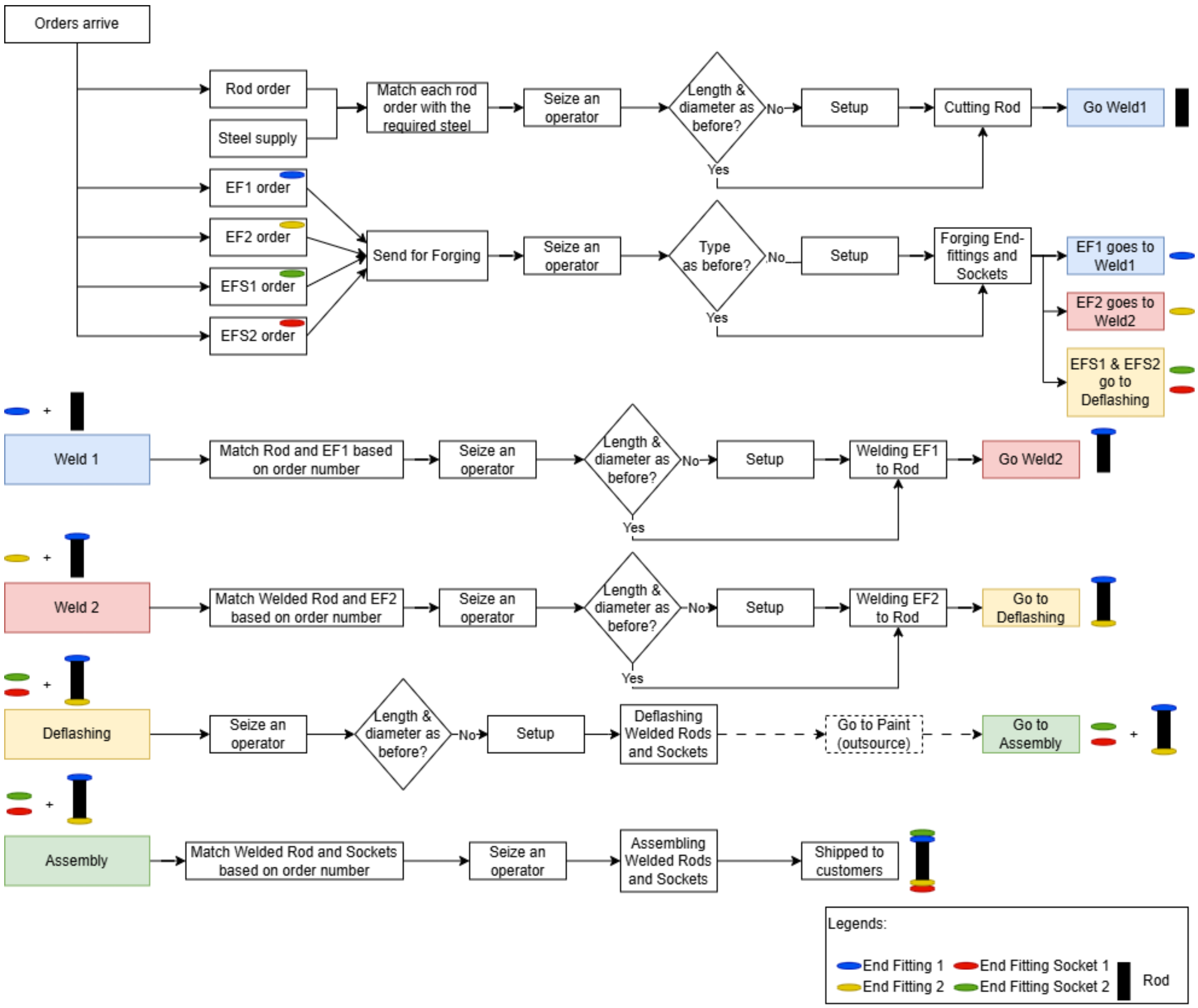

Figure 6: Simulation Model Flowchart

4.7 Disruption Simulation

Figure 7 illustrates the simulation process used to activate disturbance scenarios. To model a disruption in the simulation, a Create module is triggered at time t_0, which modifies a system variable, for example, reducing the quantity of raw material shipments to simulate a shortage scenario.

A similar approach is used to implement the recovery strategy. At time t_1, another Create module is activated, representing the arrival of the recovery action. Upon its arrival, the previously altered variable is reset to its original value, restoring the system to its pre-disruption state.

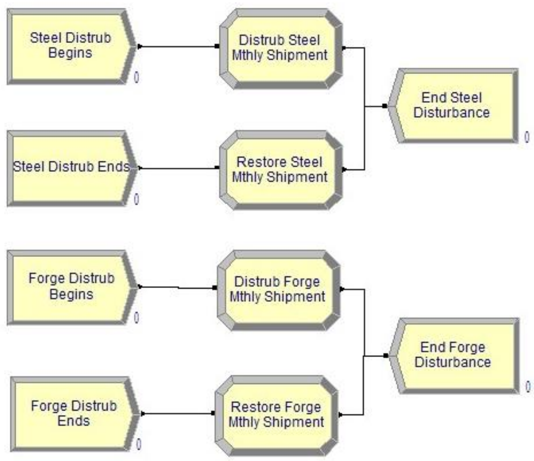

Figure 7: Disruption Simulation

This chapter provided a detailed explanation of the selected case study, including the production process, product complexity, and associated data. It also outlined the development of both the current-state and future-state simulation models, describing key assumptions, simplifications, and the configuration of disruption scenarios. The next chapter presents the results of these simulations, comparing key performance indicators across models and analyzing how each system responds to disruptions in terms of efficiency and resilience.

CHAPTER 5

5 RESULTS AND ANALYSIS

5.1 Current and Future Model Performance without any Disruption

As discussed in Chapter 3, the lean model was developed through three key changes: reducing the number of assembly operators by at two, reallocating one assembly operator to the forging process, and changing the queue policy from First-In-First-Out (FIFO) to attribute-based sequencing. Both models run for 360 days, assuming each day consists of 16 working hours, the total simulation time amounts to 5,760 hours. **Table 2** shows a comparison of the key simulation results of both models.

Table 2: Current Map Model vs. Future Map Model Performance

Metric	Current Model	Future Model	Improvements
Average Orders Shipped	743	894.8	20% increase in output with lean changes
Average Queue Waiting Time	570.0	503.8	12% reduction in delay
Operator Busy	28.4%	39.8%	11.4% increase in operators' utilization
Operator Idle	72.3%	61.3%	11 % reduction in operators' wasted time

The simulation results in **Table 2** provide strong evidence that the future model is a leaner and more efficient system. One of the most telling indicators is the reduction in average queue waiting time, from 570.0 hours in the current model to 503.84 hours in the future model. This reduction signals a smoother and more continuous flow of materials or tasks through the system, a fundamental principle of lean thinking. The system reduces non-value-added activities by minimizing time spent in queues, which translates directly into increased responsiveness and shorter lead times.

Furthermore, the future model exhibits improvements in operator utilization: the average time operators spend performing productive work increases from 28.44% to 39.78%. This shift means that resources are engaged more efficiently, with less idle or wasted labor, reducing operational costs and reflecting a better alignment of labor with actual process demand. Perhaps most compelling is the increase in throughput, with 894.8 shipped orders in the future model versus 743 in the current model, demonstrating that the system is operating more smoothly and achieving more output with the same structure. Together, these factors, such as faster flow, better resource use, and higher productivity, are signs of a lean system, validating the conclusion that the future model embodies lean principles more effectively than the current one.

Figure 8 illustrates the throughput trends of the current and future (lean) models over time. The production rate of the lean model increases at a steeper slope. After reaching a stable state, the throughput of the lean model (0.16) surpasses that of the current model (0.12). As shown in **Figure 8**, order deliveries begin after 1,340 hours. This delay is due to the long lead times required for the initial supply of steel (1,280 hours) and sockets (960 hours). Furthermore, it can be observed that as time progresses and both systems warm up, the production rate stabilizes.

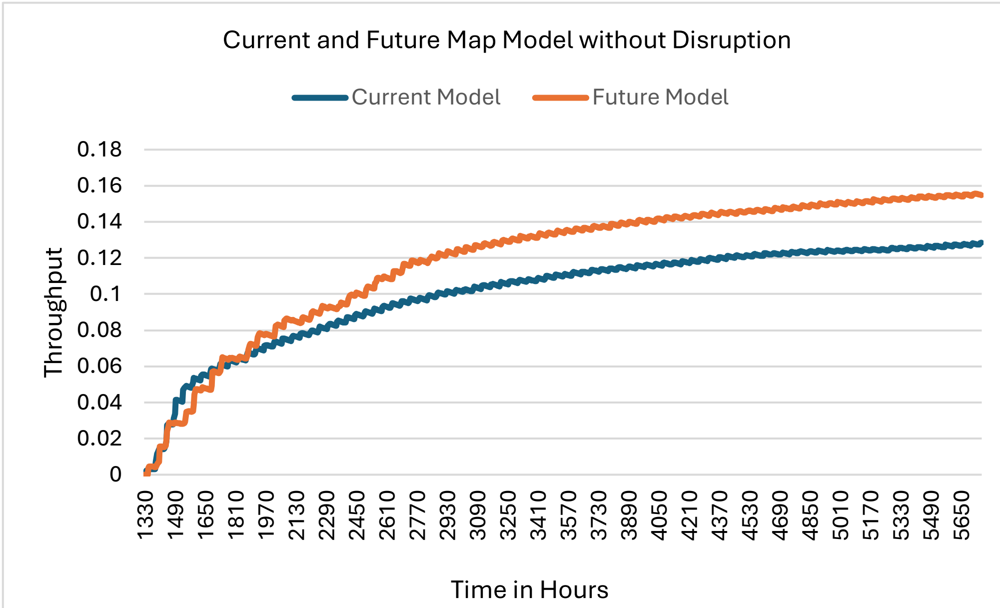

Figure 8: Current Map Model vs. Future Map Model Throughput

The performance of both models is initially suboptimal, primarily due to three main factors. First, the long raw material lead times cause the system to remain idle for an extended period. Additionally, performance is constrained by a limited number of operators. Each process (except for assembly) is staffed by only one operator, which is insufficient relative to the high demand of 480 orders per month. Furthermore, changeover times at each stage, particularly the two-hour changeover required in the forging process, lead to an additional decline in efficiency. Given the 240 possible product configurations, there is a high likelihood that consecutive orders will differ, leading to more frequent changeovers and increased non-value-added time.

5.2 Basic vs. Lean Model Performance under Disruption

5.2.1 Disruption Scenario 1: Disrupting the subcontractor

This scenario assumes that the subcontractor responsible for painting parts is affected by a disruption. Specifically, it is assumed that the subcontractor ceases operations or terminates its partnership with the company. However, this disruption is not permanent, as painting is essential for fulfilling orders. The recovery strategy in response to the subcontractor disruption involves contracting with a new painting company.

To better capture the effects of the disturbance, the disruption is introduced after 4,000 hours, once the system has reached a stable state. In this scenario, the disruption lasts a month (320 hours of working time). After this period, a new subcontractor is contracted to resume painting operations.

Figure 9 illustrates the current model's performance degradation following a disruption. Resilience is calculated based on the framework proposed by Bruneau et al. [14], assuming that model performance is measured by Equation (3) and that the system operates at 100% performance under a non-disrupted scenario. Under the subcontractor disruption scenario, the resilience of the current model is calculated as R = 2.784178.

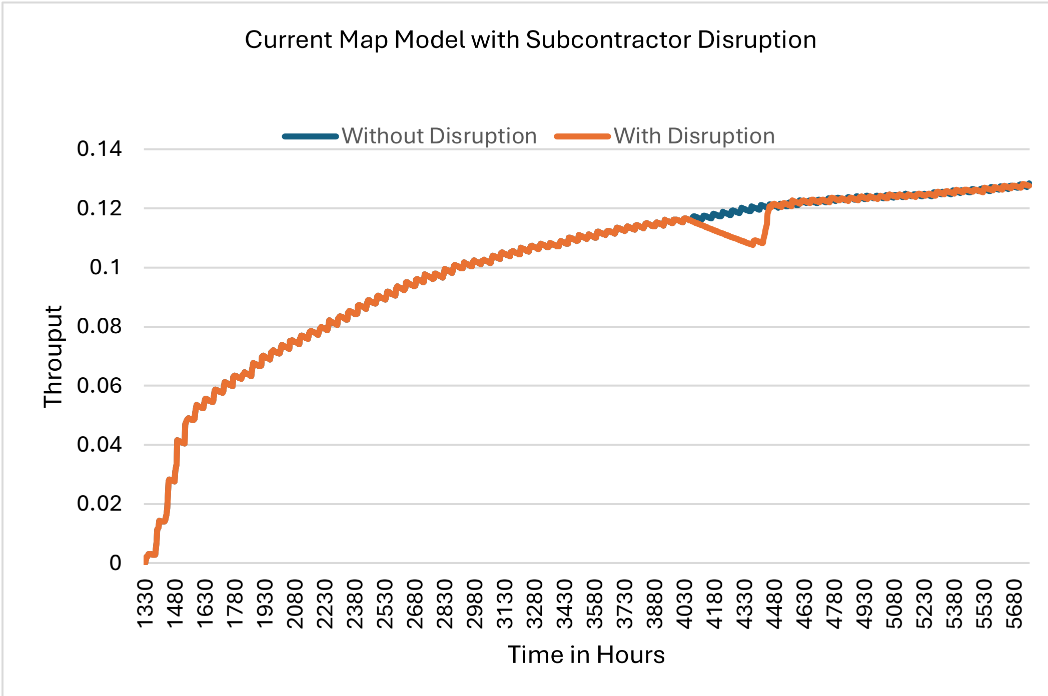

Figure 9: Current Map Model Throughput with Resource Failure

Figure 10 illustrates the performance degradation of the lean model following the same disturbance happening at the same time and continued for the same time as the current model. Based on the resilience calculation, the lean model exhibits a resilience value of R = 3.14134751 for this disruption scenario.

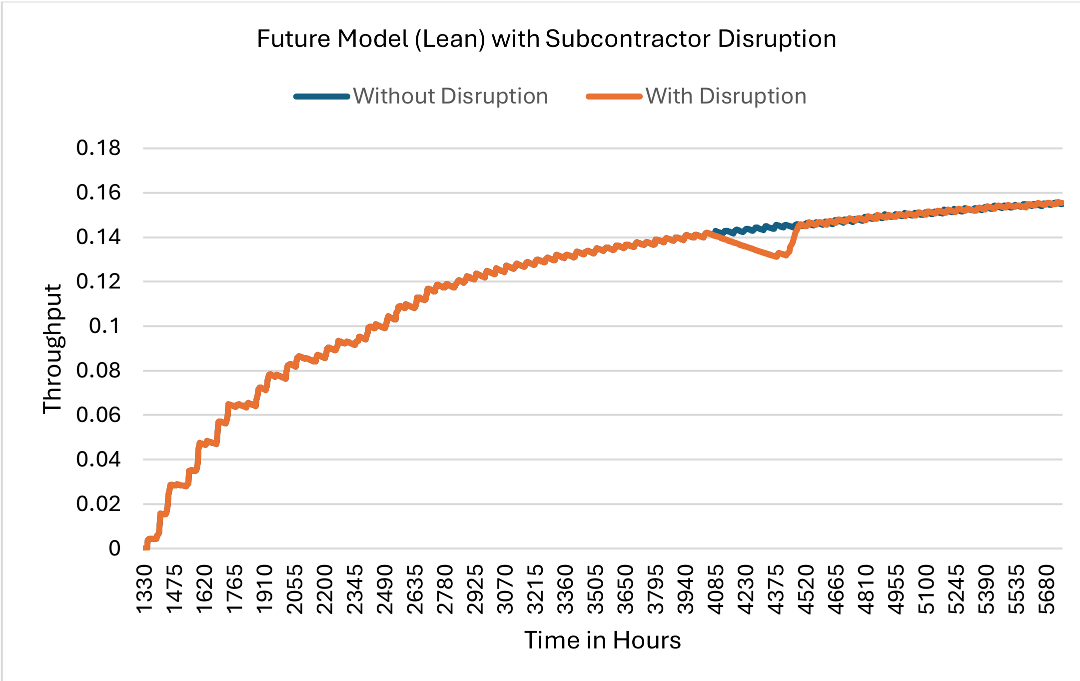

Figure 10: Future Map Model Throughput with Resource Failure

The disruption appears to affect both the current and lean models similarly. This is likely because the disruption occurs at the end of the production flow, when products have already progressed through most of the process. Furthermore, neither model fully utilizes the painting and assembly resources, 66.63% (paint subcontractor) and 9.3% (assembly operators) in the current model, and 66.77% and 10.75%, respectively, in the lean model. As a result, both systems are able to recover quickly by utilizing the idle time of resources and are only minimally affected by the disruption.

5.2.2 Disruption Scenario 2: Steel Disruption without Warehouse Capacity Constraint

This case study has two suppliers: Michigan Steel Co. and Indiana Castings. We introduce scenarios where the steel supplier gets disrupted and sends much less supply. The recovery strategy for the shortage of raw material in this model is to use a backup supplier. It is assumed that the backup supplier will provide raw material in a similar amount and frequency to the previous supplier.

In this scenario, Michigan Steel Co. supplies steel up to 100 orders per shipment, and Indian Castings supplies up to 400 orders of machine forgings per shipment. There is no limitation on receiving raw materials from Michigan Steel Co., meaning TWI's warehouse capacity is assumed to be unlimited.

The disturbance is defined as the Michigan Steel Co. reducing the supply to almost nothing (up to 1 order per shipment). The disruption is going to take 1000 hours, till TWI contract with a backup supplier, the worst-case scenario to observe the behavior of both models clearly and we study three period of times that disruption happens, one at the beginning of the production time, (starts after 2000 hours production), the second one in the middle of production time (starts after 3000 hours production), and the last one at the near the end of production time (starts after 4000 hours of production).

This scenario, applied to both the current and future models, simultaneously captures two things: first, comparing the resiliency of both models, and second, observing the effect of the disruption start time on the resiliency.

The current model's performance hasn't changed in this scenario in either of the periods. Although TWI is slow, it receives orders daily and gets the required steel from Michigan Steel Co. every two weeks. So, assuming that TWI's warehouse is unlimited, the company receive the required raw material of every order it received in two weeks, which is around 240 orders per two week and when the Michigan Steel Co. doesn't supply raw material any more, TWI current model still has a lot that doesn't feel affected at all.

Regarding the future model, **Figure 11**, **Figure 12**, and **Figure 13** illustrate the performance of future map model with the same disruption happening at different times.

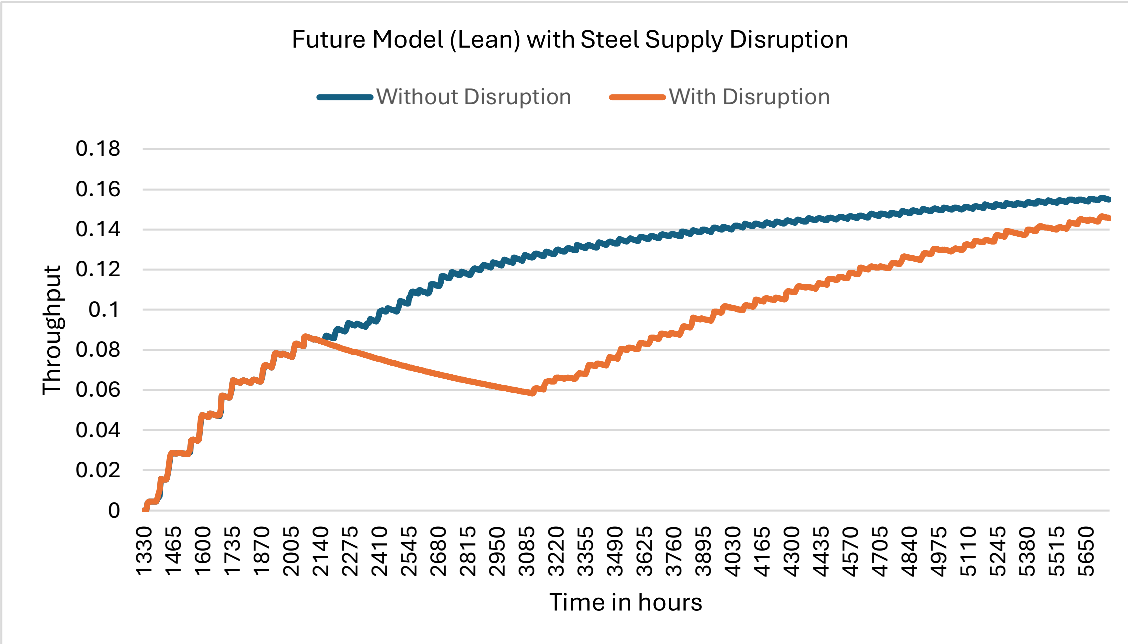

Figure 11: Future Map Model Throughput with Supply Disruption after 2000 hours

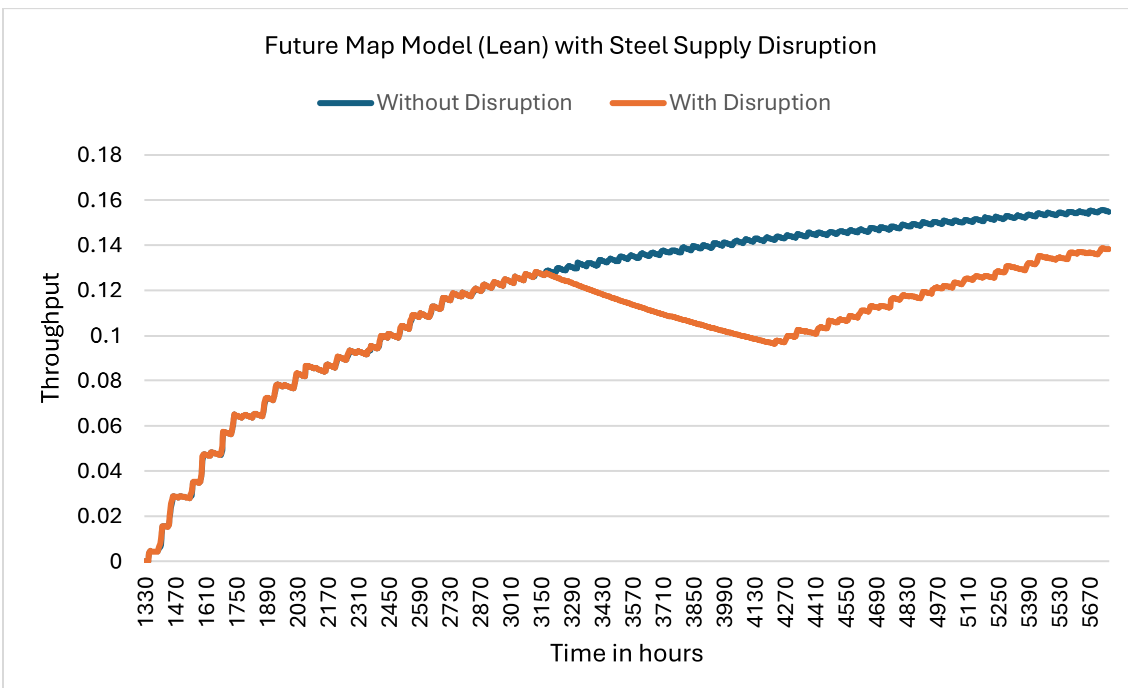

Figure 12: Future Map Model Throughput with Supply Disruption after 3000 Hours

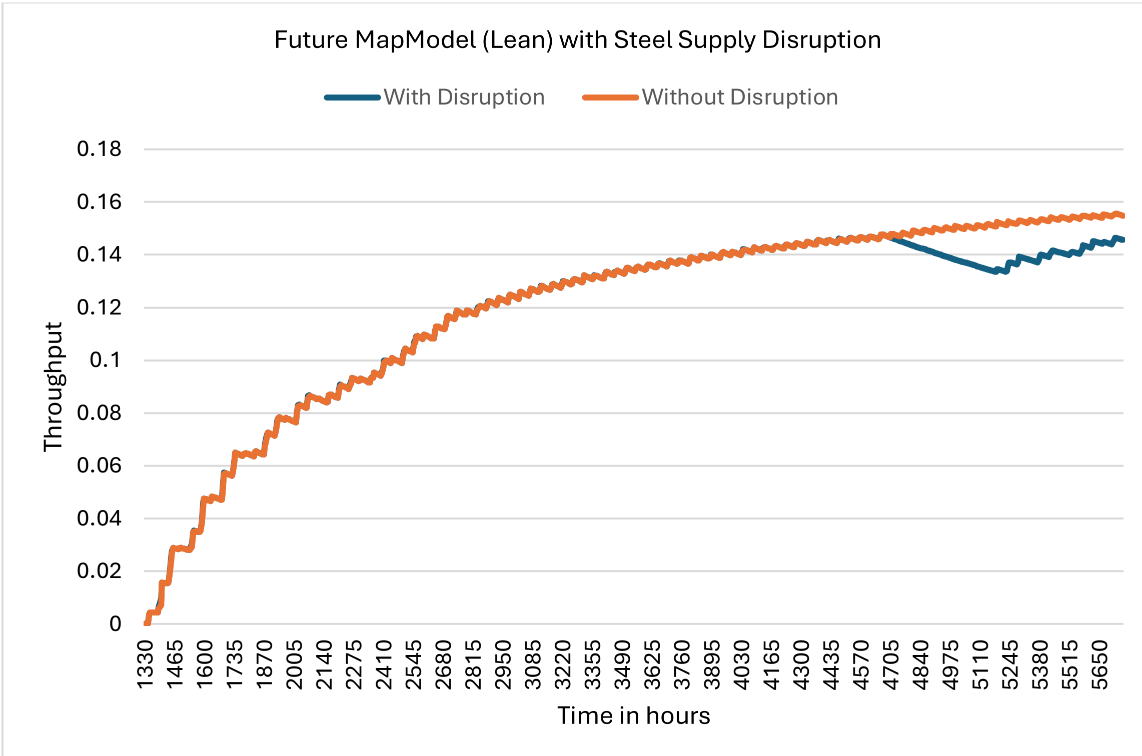

Figure 13: Future Map Model Throughput with Supply Disruption after 4000 Hours

It was observed that the future map model's resilience to the same disruption happens at different times is not the same. The resilience of the future map model increases when disruption occurs later. This can be interpreted that when the system stabilizes, the same disturbance scenario with the same duration would affect the model less. The lean model produces more product, so with the same amount of order and supply, it would have less inventory, especially at the beginning, when the production rate increases with a significant slope. The model is less resilient to supply shortage in the early production times.

5.2.3 Disruption Scenario 3: Steel Disruption without Warehouse Capacity Constraint

In this scenario, Michigan Steel Co supplies steel up to 100 orders per shipment, and Indian Castings supplies up to 400 orders of machine forgings per shipment. However, there is a limitation on receiving raw materials from Indiana Castings, meaning TWI's warehouse capacity is assumed to be limited.

The disturbance is defined as Michigan Steel Co reducing the supply to almost nothing (up to 1 order per shipment). The disruption happens after 3000 hours of production and lasts until TWI contracts with a backup supplier, which occurs at time 3640. This scenario will be simulated in both the current and future models to observe and compare their behavior.

The model is simulated so that TWI receives orders like before, but TWI looks at its warehouse capacity before shipping steel. If the shipment size exceeds the warehouse capacity, the surplus orders will wait, and the forge machining supply for those orders willn't be shipped.

Figure 14 shows the current map model performance under the disruption scenario 3, and **Figure 15** shows the future map model performance under disruption scenario 3.

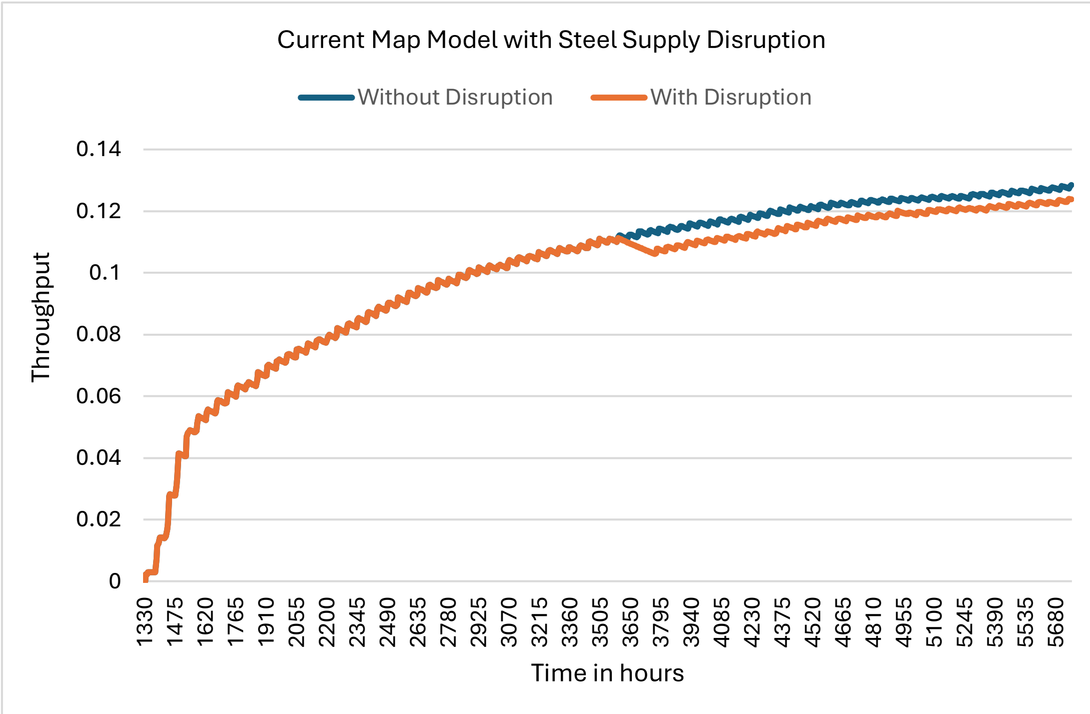

Figure 14: Current Map Model Throughput with Supply Disruption

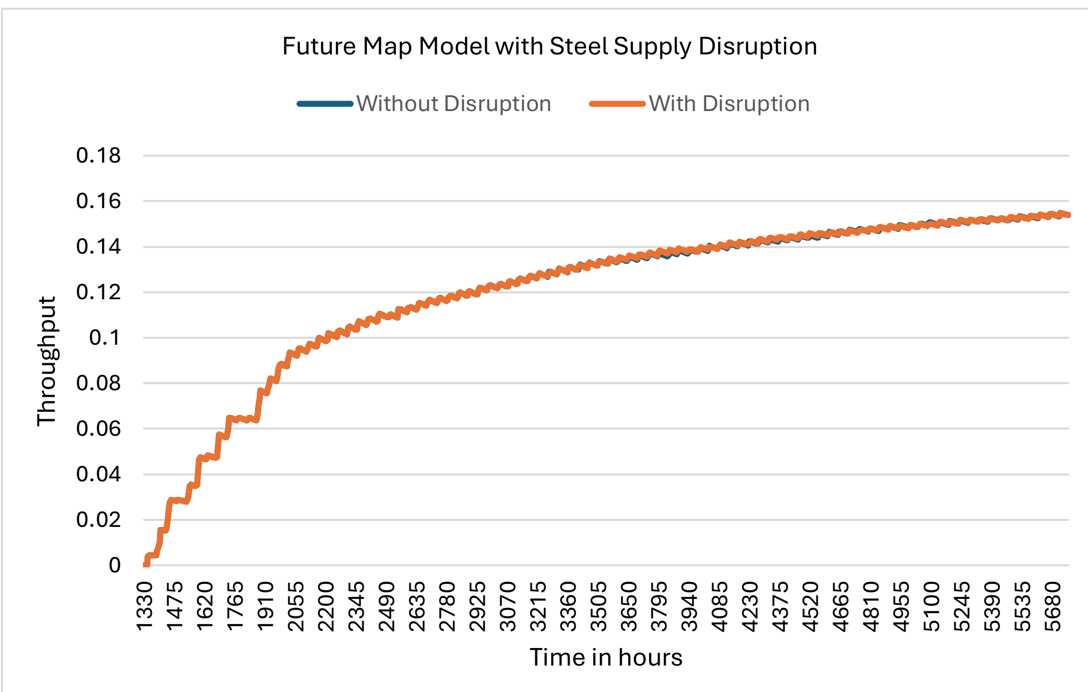

Figure 15: Future Map Model Throughput with Supply Disruption

Interestingly, the reaction of the current map and the future map model switched. Before introducing a capacity limit for the TWI warehouse, the current model was more resilient to the disruption of the steel supply. However, after setting a capacity limit for the TWI warehouse, the future model, which was leaner, became more resilient.

5.3 Key Insights from Simulation-Based Resilience Assessment

Simulation-based modeling provided critical insights into system behavior that could not have been observed through Value Stream Mapping (VSM) alone. While VSM is effective for visualizing process flow and identifying non-value-added activities, it cannot capture time-dependent behaviors such as performance degradation, recovery, and queuing under disruption. By integrating Discrete-Event Simulation (DES), this study was able to dynamically evaluate how lean implementation affected not only efficiency metrics but also system resilience in the face of supply chain disturbances. The simulation revealed that resilience is influenced not only by inventory levels but also by the system's structure, the timing and location of disruptions, and the specific lean strategies employed. For instance, under constrained warehouse conditions, the lean-enhanced model demonstrated faster recovery and higher throughput, challenging the assumption that lean systems are inherently less resilient. These findings emphasize the importance of using dynamic modeling tools to support strategic decision-making in lean system design.

CHAPTER 6

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6 CONCLUSION

An important insight emerged during the simulation experiments that challenges the common perception that lean systems are inherently more vulnerable to supply chain disruptions. It is often assumed that lean systems, due to minimal inventory and tight buffers, lack the flexibility to absorb shocks, particularly raw material shortages, and are therefore less resilient. Initial simulations seemed to support this idea: when both the baseline and lean models were subjected to the same disruption (e.g., a supply delay in forged sockets or steel rods), the lean model experienced a quicker decline in performance. This outcome reflected its lower work-in-progress (WIP) inventory and faster production speed, which meant the system had less raw material on hand to continue operating during the disruption.

However, this interpretation assumes that the baseline model's ability to maintain production is sustainable and unconstrained. In reality, no system can accumulate unlimited raw material without facing space or cost limitations. To address this, a warehouse capacity constraint was introduced in both models. When the warehouse reached its predefined capacity, incoming raw material orders were paused, and new customer orders were held until space became available. Under this more realistic condition, the resilience pattern shifted: the lean model, due to its higher processing speed and reduced backlog, was able to clear inventory (and so satisfy the customer order) more efficiently and recover performance after the disruption faster than the baseline model. In contrast, the baseline model experienced a more pronounced performance decline, as its slower throughput led to congestion and a longer time to recover once supply resumed.

This finding highlights a key consideration in resilience analysis: resilience is not purely a function of inventory levels or redundancy; it also depends on system responsiveness and constraint management. When bounded by realistic warehouse or queue capacities, lean systems exhibit stronger resilience due to their agility and reduced waste. This suggests that the perceived trade-off between lean efficiency and resilience is not universal, and can be reversed under certain structural limitations.

This insight not only enhances the accuracy of the simulation but also strengthens the practical relevance of the findings. In real-world settings where warehouse space, cash flow, or perishability limits excessive inventory accumulation, lean systems may be better positioned to withstand and recover from disruptions. As such, resilience should be evaluated not only in terms of raw material buffers but also in terms of system throughput, responsiveness, and constraint-aware design.

6.1 Contextual Factors Influencing Resilience in Lean Systems

While simulation results provide quantitative insights into the performance and resilience of lean versus non-lean systems, it is essential to recognize that resilience is not a fixed property. It is a context-dependent concept. The study concludes that how a system responds to disruption depends on several critical factors beyond its lean structure. This section highlights three such criteria that must be considered when assessing the relationship between lean practices and system resilience:

6.1.1 The Location of the Disruption in the Supply Chain

The stage of the supply chain at which the disruption occurs significantly affects the outcome. If the disruption takes place in the early stages of the production process, such as raw material supply, its impact can cascade throughout the system. In such cases, a lean system may be more vulnerable due to limited inventory and lower buffering capacity. However, if the disruption occurs in the later stages of production (e.g., near assembly or shipping), the difference between lean and non-lean models may be negligible. This is because most processes have already been completed, and once recovery begins, both models can resume operations in a similar manner. Therefore, assessing resilience without considering where the disruption occurs can lead to misleading conclusions.

6.1.2 The Timing of the Disruption

The timing of the disruption relative to the system's operational timeline also plays a crucial role. Simulation results show that the lean model may be severely affected if a disruption occurs early in the production cycle, especially before the system has fully ramped up. During this early stage, the system lacks queued inventory and may stall entirely when the supply is interrupted. Conversely, if the same disruption occurs later, the impact may be minimal once production has stabilized and there is sufficient flow and throughput. This highlights that the same disruption, with the same duration and severity, can have vastly different effects depending on when it occurs. In lean systems, even minor disruptions at startup can lead to significant performance degradation, while similar disruptions introduced after the warm-up phase may be absorbed with little consequence.

6.1.3 The Specific Lean Principles Implemented

Not all lean improvements have the same implications for resilience. Some changes that increase efficiency may inadvertently reduce flexibility, depending on how aggressively they are applied. For example, in this study, assembly line efficiency was increased by reducing the number of operators and reallocating resources, raising utilization without reaching 100%. Under normal conditions, this change improved performance without compromising resilience. However, if operator utilization approaches full capacity, the system may lose its ability to respond quickly to fluctuations or recover from delays, especially if disruption frequency or duration increases. In contrast, other lean practices, such as reducing changeover time or sequencing orders to reduce setup frequency, enhance both efficiency and resilience by eliminating waste without reducing adaptability.

These observations highlight that evaluating the resilience of lean systems requires a nuanced understanding of how lean principles are implemented and when and where disruptions occur. A lean system's resilience is not inherently better or worse than a non-lean system's. It is contingent on operational context, system design choices, and real-world constraints such as warehouse capacity, supplier variability, and production flexibility. Therefore, future research and practical implementations should move beyond general assumptions about lean vulnerability and adopt a more scenario-specific approach to resilience assessment.

6.2 Contributions to Lean Manufacturing and Resilience Research

This research contributes to the growing body of literature at the intersection of lean manufacturing and system resilience by integrating Value Stream Mapping (VSM) with Discrete-Event Simulation (DES) to assess dynamic system behavior under disruption. While prior studies have primarily examined lean and resilience separately, this study demonstrates how lean improvements can influence both efficiency and the ability to recover from operational disturbances. The findings challenge the assumption that lean systems are inherently fragile, showing that resilience is not solely a function of inventory buffers but also of system responsiveness, resource allocation, and disruption timing. By applying simulation to model both pre- and post-lean implementation scenarios, this work provides a more nuanced understanding of how lean systems perform under stress and offers a practical framework for evaluating trade-offs between efficiency and adaptability in manufacturing.

6.3 Recommendations for Future Work

Building on the findings of this study, future research could further investigate the relationship between lean implementation and resilience using expanded modeling techniques and broader experimental conditions. One promising direction is to examine system behavior using a wider range of performance metrics, including service level, lead time variability, and recovery efficiency, to gain a more comprehensive view of resilience outcomes. Another valuable study area would be identifying a threshold or cut-off point for warehouse or buffer space capacity beyond which system resilience significantly declines or improves. Additionally, future work could involve simulating individual lean principles independently, such as takt time alignment, operator reallocation, or changeover time reduction, to assess the specific impact of each practice on resilience. This would help isolate which lean strategies support or hinder system adaptability under disruption. Finally, expanding the analysis to include probabilistic disruptions, multi-stage supply chains, or different industry settings could further validate the generalizability and practical relevance of simulation-based lean and resilience assessment.

CHAPTER 7

7 References

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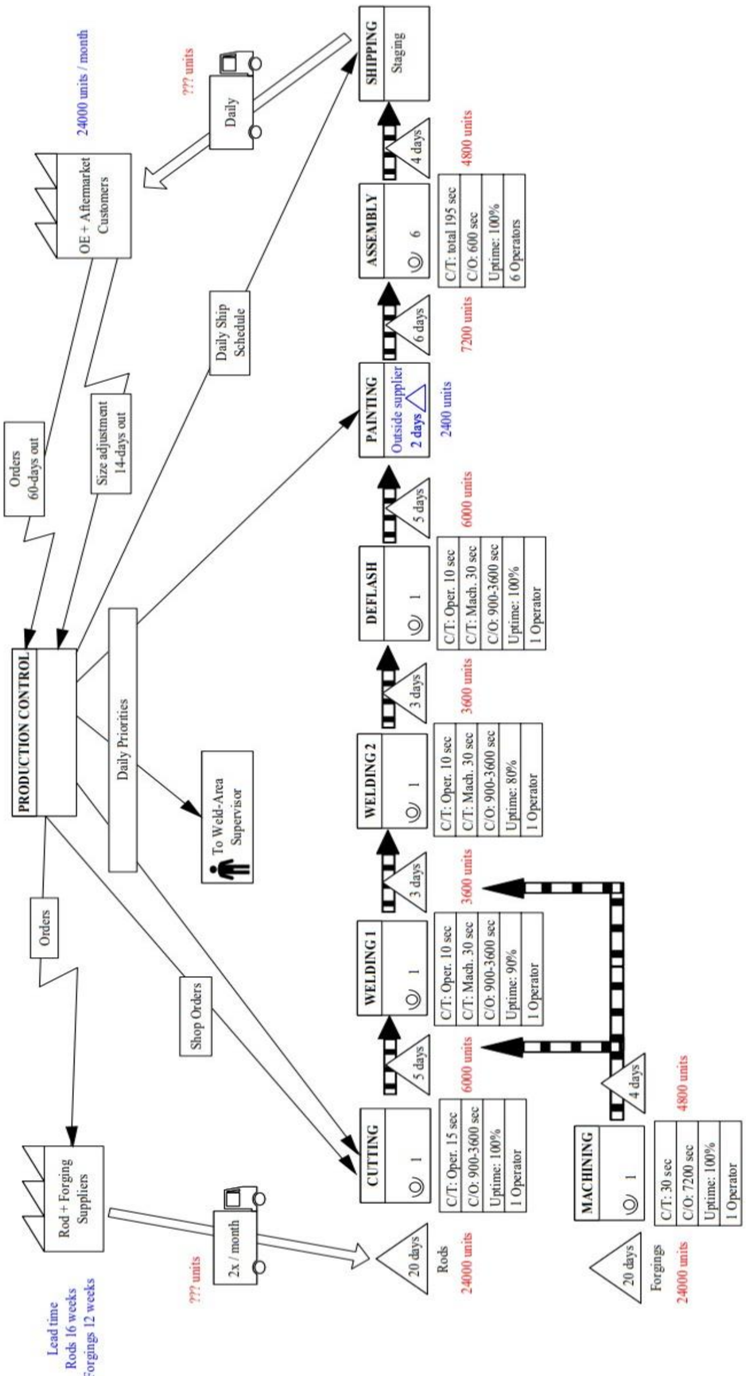
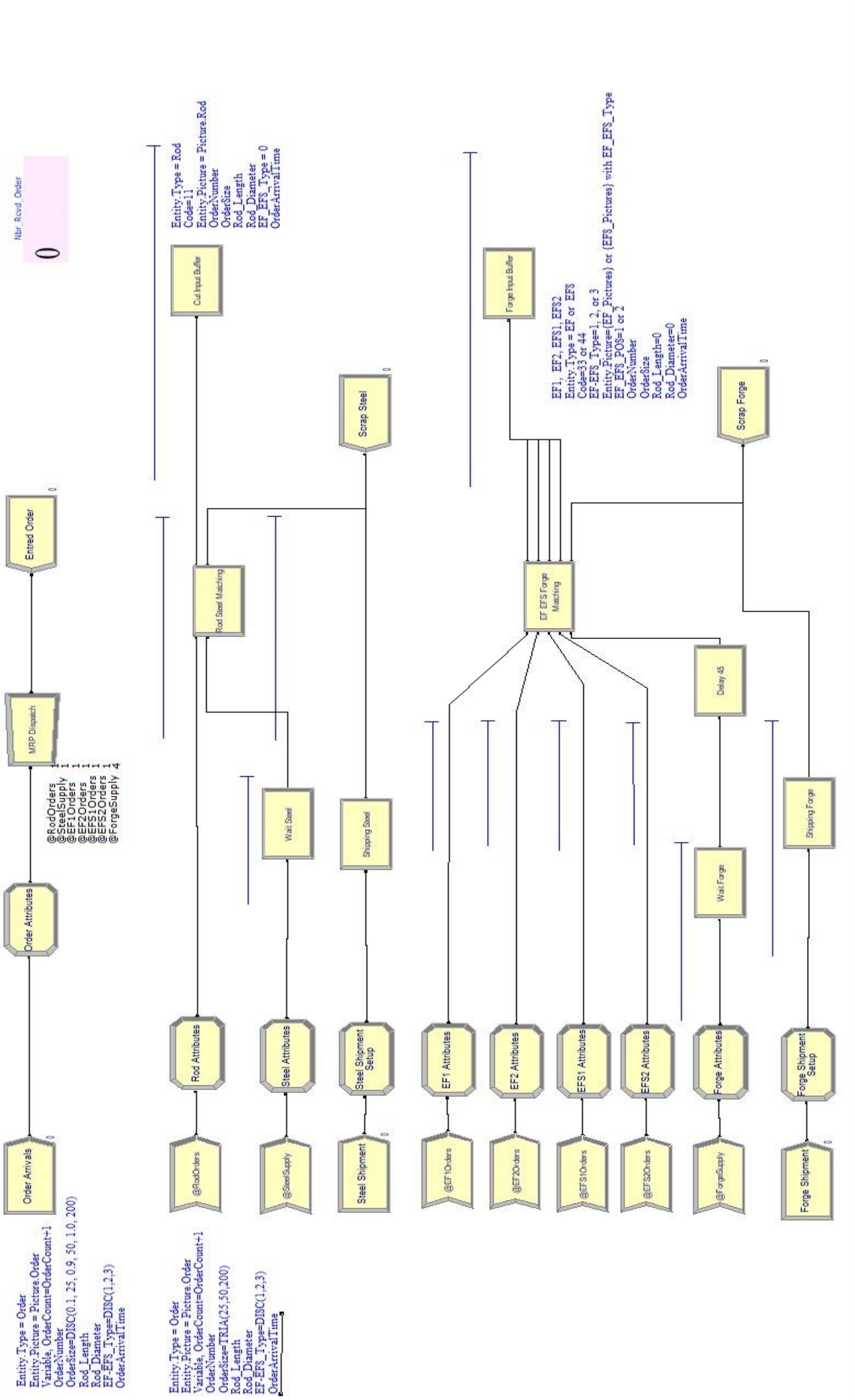
CHAPTER 8

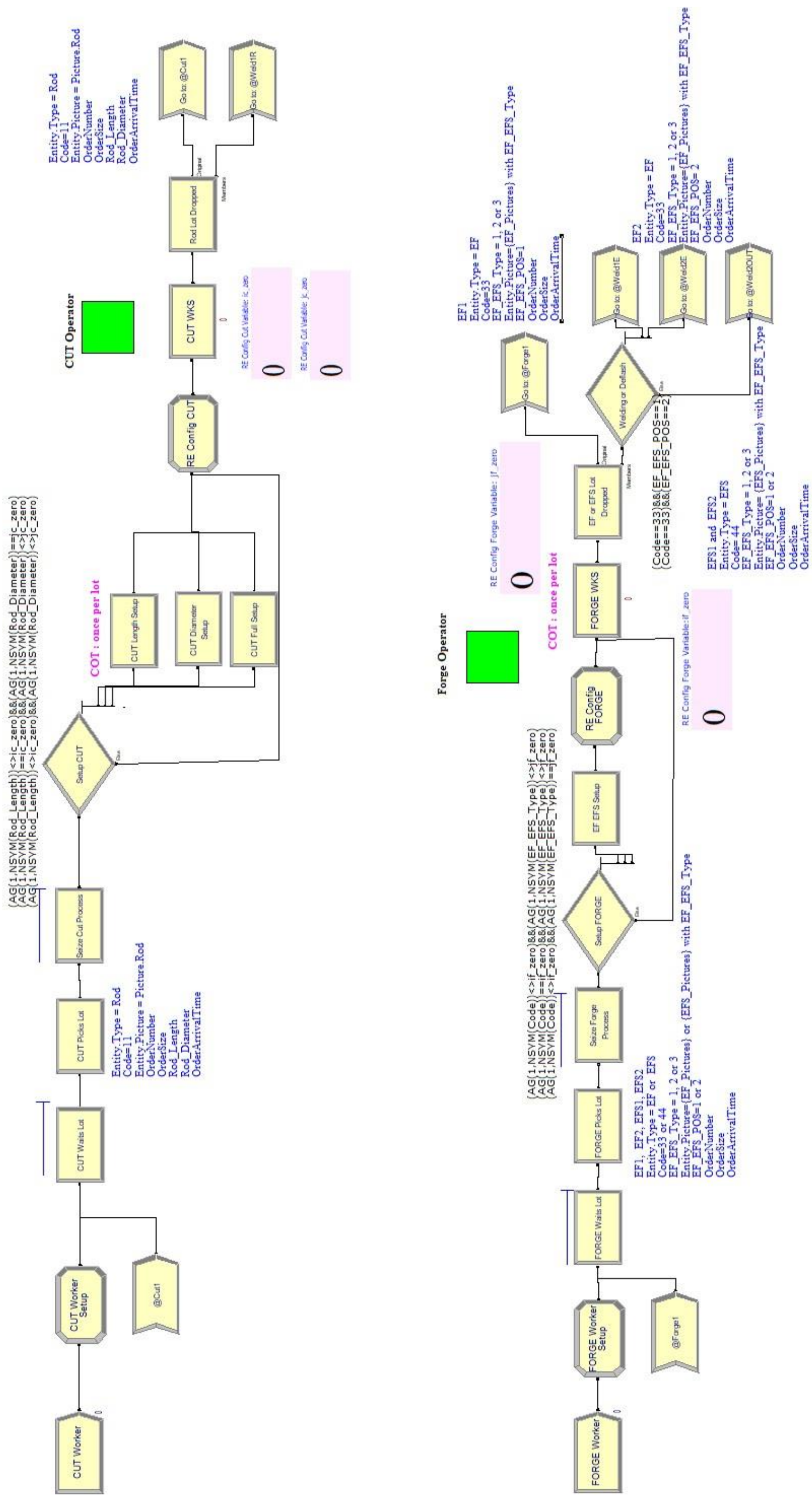
8 APPENDICES



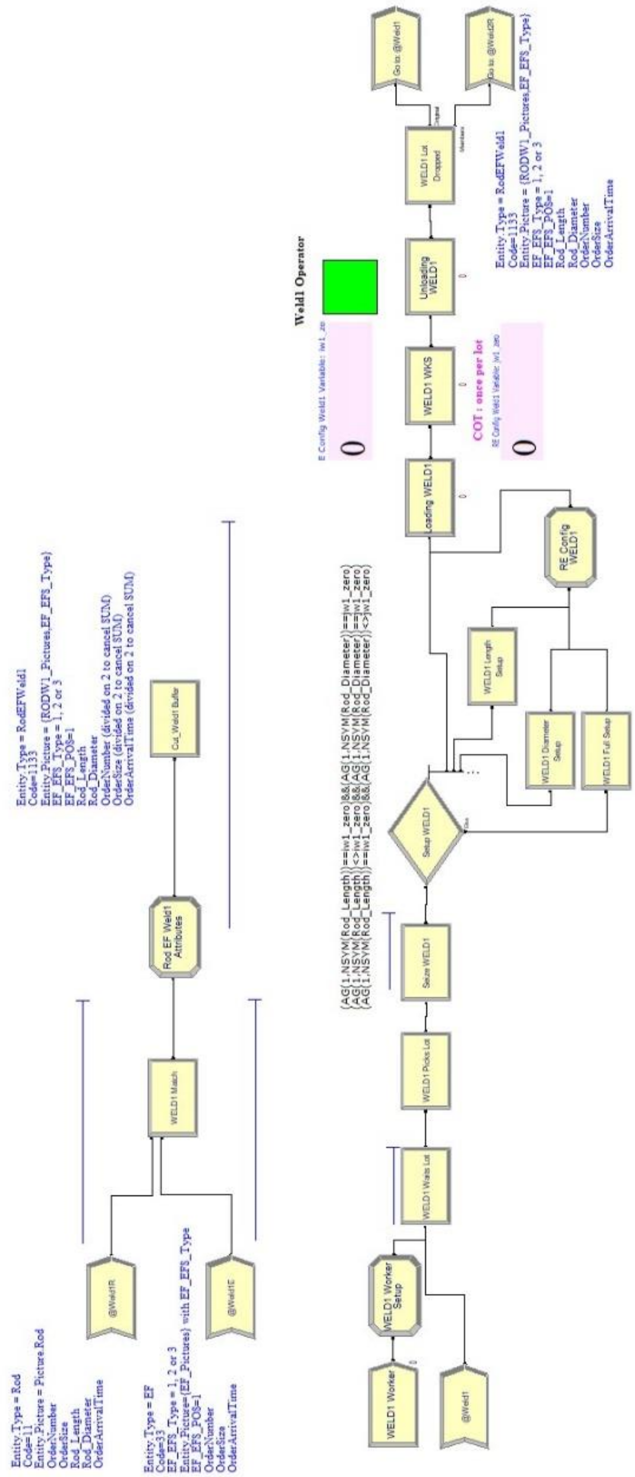
Appendix A Current Value Stream Map



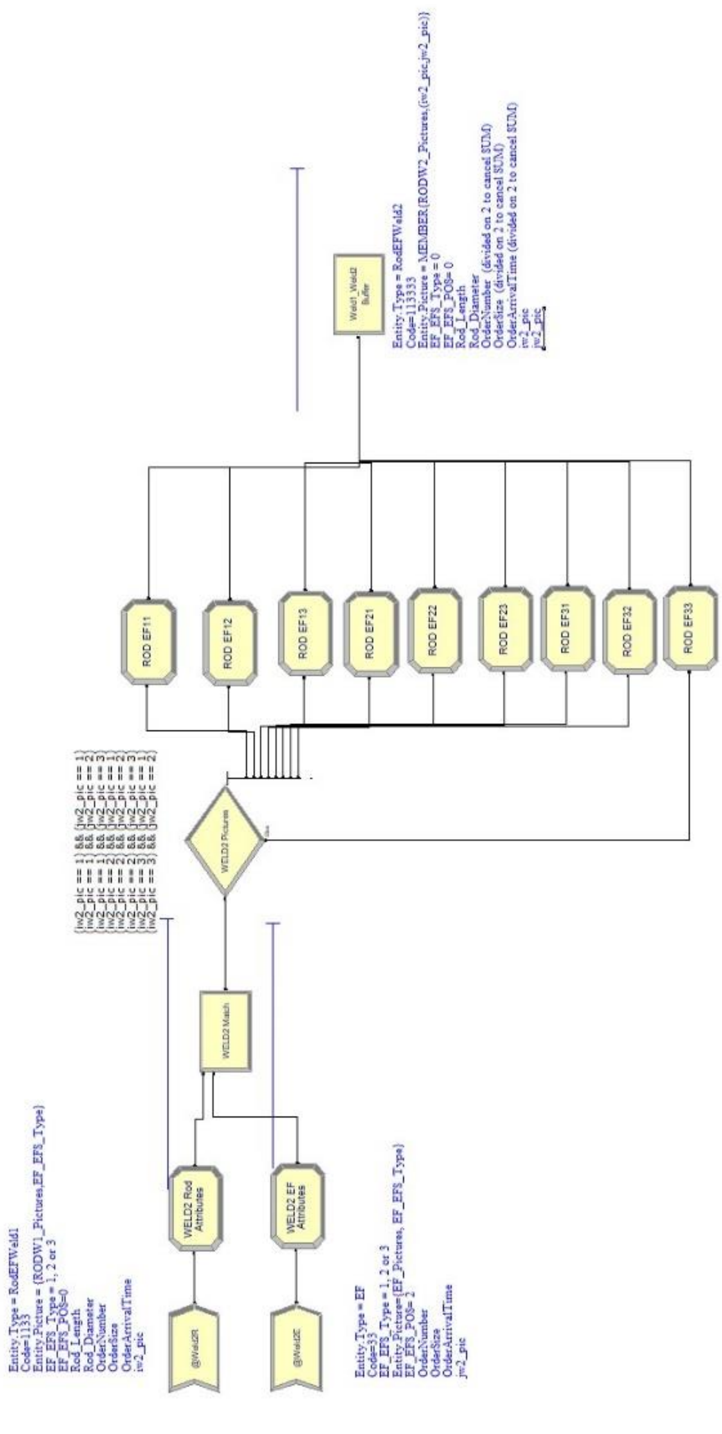
Appendix B Simulation of Order Arrivals (ARENA)



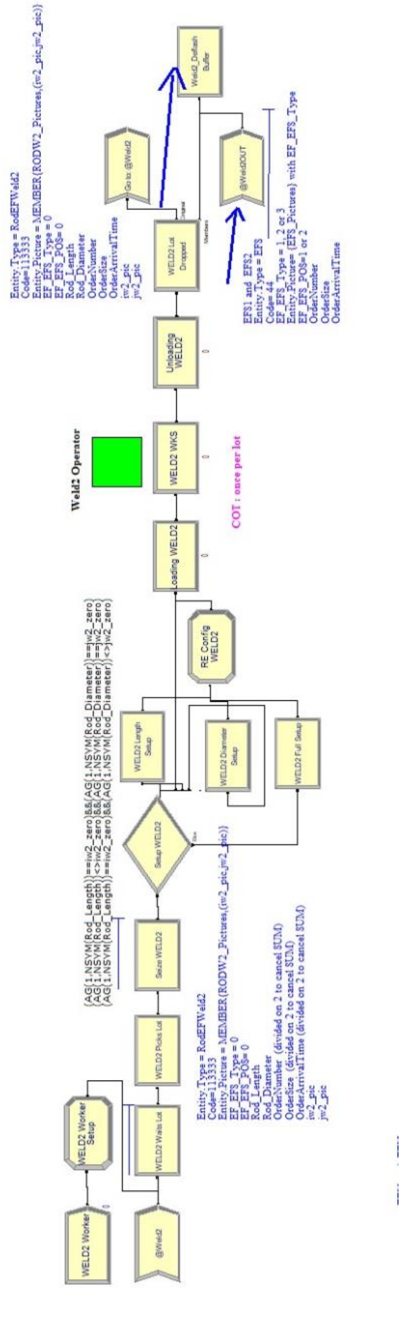
Appendix C Simulation of Cut and Forge Processes



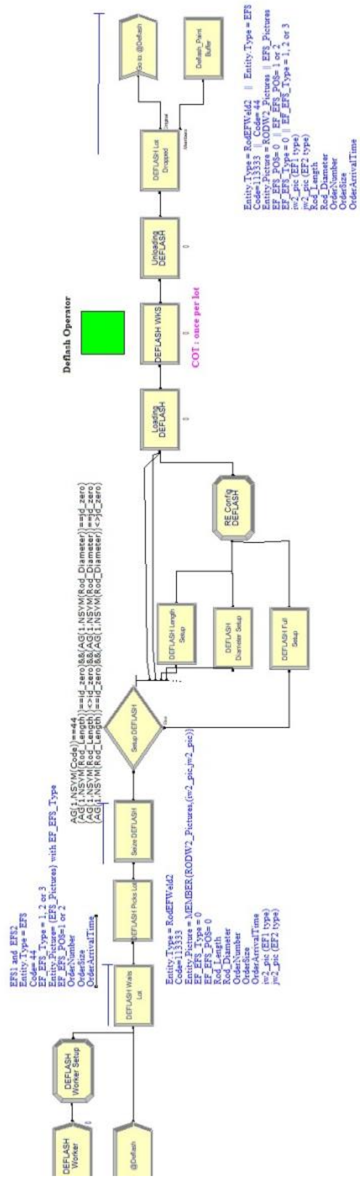
Appendix D Simulation of Weld 1 Process (ARENA)



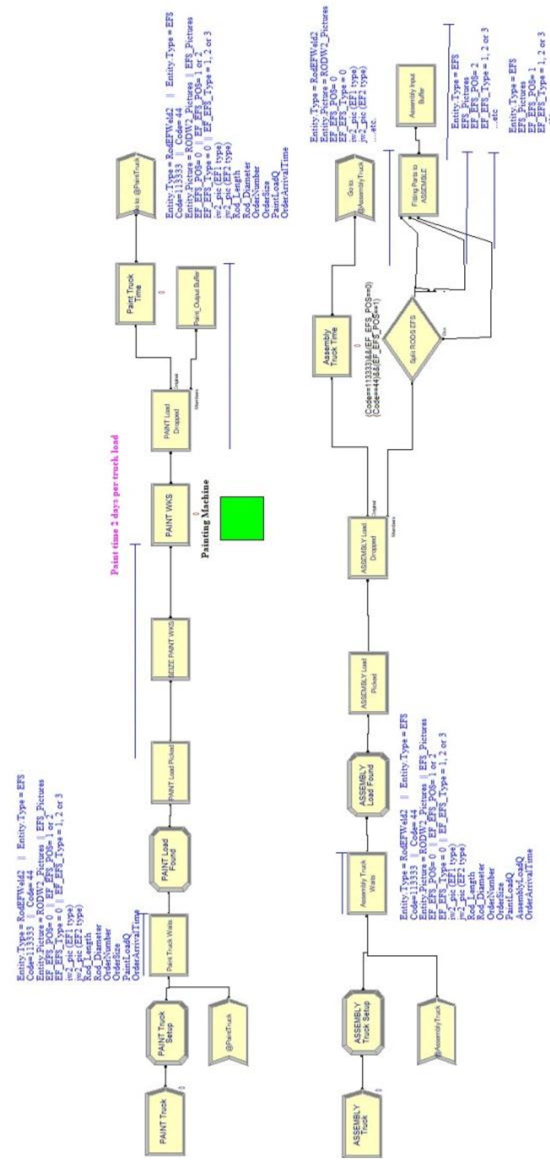
Appendix E Matching End-Fittings for Weld 2 Process (ARENA)



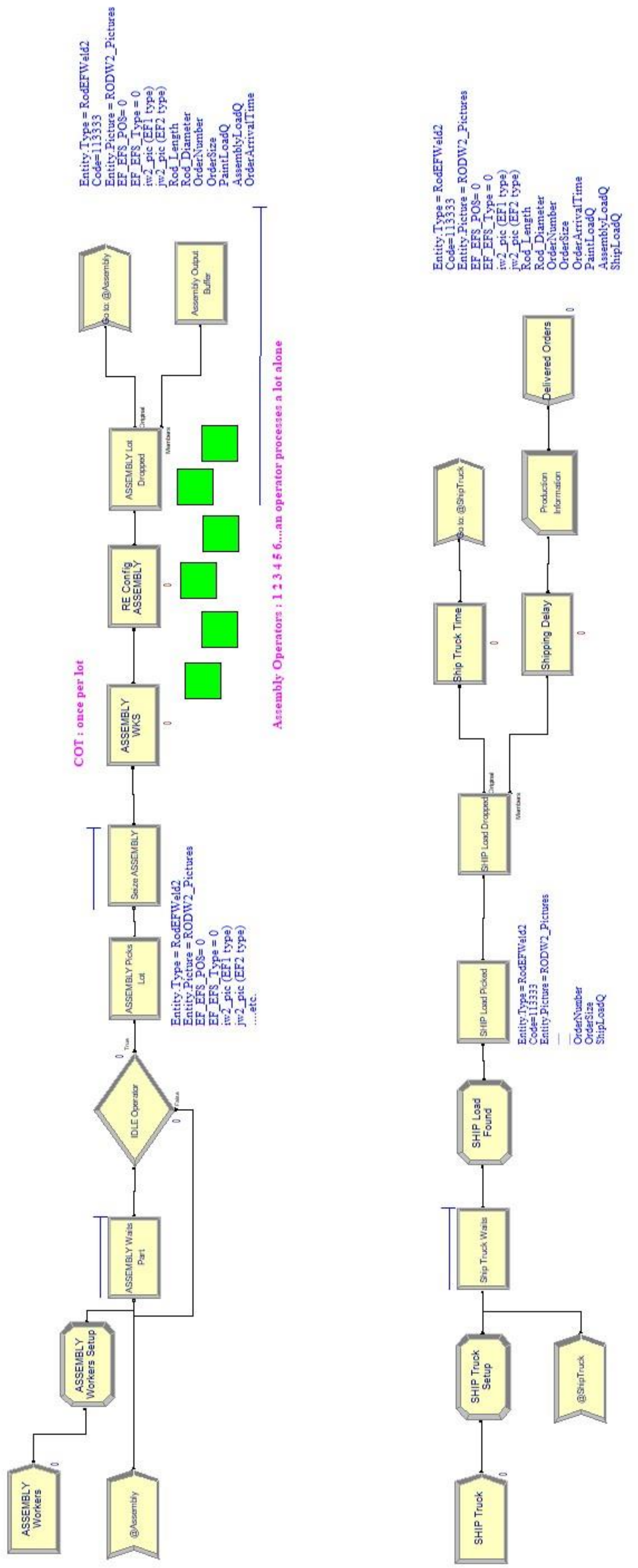
Appendix F Simulation of Weld 2 Process (ARENA)



Appendix G Simulation of Deflash Process (ARENA)



Appendix H Simulation of Painting Process (ARENA)



Appendix I Simulation of Assembly and Product Shipment (ARENA)