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COMBINING SUSTAINABLE VALUE STREAM MAPPING AND SIMULATION TO ASSESS MANUFACTURING SUPPLY CHAIN NETWORK PERFORMANCE

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THESIS

A thesis submitted in partial fulfillment of the
requirements for the degree of Master of Science in
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By

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ABSTRACT OF THESIS

COMBINING SUSTAINABLE VALUE STREAM MAPPING AND SIMULATION TO ASSESS MANUFACTURING SUPPLY CHAIN PERFORMANCE

Sustainable Value Stream Mapping (Sus-VSM) builds upon traditional VSM to capture additional sustainability aspects of the product flow, such as environmental and societal aspects. This work presents research to expand the utility of Sus-VSM to supply chain networks, develop a general approach towards improving supply chain sustainability, and examine the benefits of implementing simulation and a design of experiments (DOE) style analysis. Metrics are identified to assess economic, environmental, and societal sustainability for supply chain networks and visual symbols are developed for the Supply Chain Sus-VSM (SC Sus-VSM) to allow users to easily identify locations where sustainability can be improved. A discrete event simulation (DES) model is developed to simulate the supply chain, allowing easier creation of future state maps, which are used to identify locations for sustainability improvement. A scoring methodology and DOE-style analysis are developed to collect more information from the supply chain. Results from the case study show that the SC Sus-VSM meets the goals desired, and that the DES model aids the goals of the map. It is also indicated that interventions in the supply chain should first focus on economic improvements, followed by societal and then environmental improvements to achieve the greatest supply chain sustainability.

KEYWORDS: Sustainable Manufacturing, Supply Chain Assessment, Value Stream Mapping, Sus-VSM, SC Sus-VSM

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May 22nd, 2014

COMBINING SUSTAINABLE VALUE STREAM MAPPING AND SIMULATION

TO ASSESS MANUFACTURING SUPPLY CHAIN NETWORK PERFORMANCE

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To my parents, Joseph and Janet Sparks

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CHAPTER I

Introduction

In manufacturing, there is a constant need and drive to improve production methods through new machining technology, processes that allow quicker production or new methods that improve the product safety and reliability. Periodically, however, the development of machines or processes for production stagnates, but the need for improvement still exists. In these instances, companies must seek other methods of improvement, such as through lean manufacturing. Lean manufacturing is a philosophy of continuous improvement that seeks to identify and eliminate a number of different wastes in the manufacturing system. The goal of eliminating these wastes is to reduce manufacturing costs, improve the quality of the product being manufactured, and to shorten the production lead time, allowing quicker delivery of the final product to the customer.

Lean manufacturing has become widespread throughout the manufacturing industry, and many lean tools have been developed to aid in creating this culture. One of the main tools used in identifying waste in the manufacturing system is value stream mapping (VSM). VSM is used to create a map of the manufacturing process line that captures important details, such as process cycle times, changeover times, uptime, value-added time, and the amount of inventory waiting at each process. The map also captures the production flow as well as the information flow through the manufacturing line. Once a map of the current state of the manufacturing line has been created using VSM, areas for potential improvement can be easily identified, such as bottleneck locations, poor uptimes, high cycle times or high changeover times. A future state map can then be developed using the potential improvements, thus visualizing the benefits that can be gained (Rother and Shook, 1999). Once improvements were identified and the benefits visualized, other lean tools could be used to implement the improvements.

More recently, however, there has been a drive for further improvements beyond just economic aspects. The National Council for Advanced Manufacturing expands the US Department of Commerce definition of sustainable manufacturing (US Department of Commerce, 2009) to include the manufacturing of "sustainable" products and the sustainable manufacturing of all products (NACFAM, 2014). Sustainable manufacturing seeks to improve the manufacturing process in three different areas, economic, environmental, and societal, with the overall goal of improving manufacturing while not decreasing the ability of future generations to live and do the same. As can be seen from growing environmental regulations, implementation of sustainable manufacturing is an increasing priority.

To successfully implement sustainable manufacturing, however, it is necessary to develop tools to evaluate the sustainability performance of a manufacturing system. Creating completely new evaluation tools can be costly and time consuming; but by adapting tools from other areas, such as lean manufacturing, an assessment tool can be created more easily. As a lean manufacturing tool, VSM only considers the economic aspect of sustainability; but by adapting VSM, a visual tool called sustainable value stream mapping (Sus-VSM) was developed to evaluate the sustainability performance of manufacturing systems (Faulkner et al., 2012). This work introduced new metrics to VSM, such as energy and water consumption, and work environment hazard ratings to assess the environmental and societal aspects of sustainability.

While VSM has long since proved its value as a lean manufacturing tool, and Sus-VSM is establishing its place in sustainability assessment, both possess the same limitation. Both traditional VSM and Sus-VSM focus on the process level of manufacturing, and capture the production line within a single manufacturing plant. While Sus-VSM is still a relatively new tool, VSM has been in use longer, and so attempts have been made to adapt VSM to evaluate an entire supply chain in order to aid in establishment of a lean culture throughout (Dolcemascolo 2006). These attempts at achieving supply chain leanness have met with varying degrees of success, but they all lack environmental and societal considerations, and the metrics used provide an amount of detail that is difficult to manage at the supply chain level.

Thus, as sustainable manufacturing begins to supersede lean manufacturing, it is important to develop tools that can assess the sustainability performance of a supply chain. By assessing the sustainability of the supply chain and having all members of the supply chain work together to improve sustainability, substantial benefits can be recognized and the overall supply chain performance can be improved as much as possible. As before, creating entirely new tools requires time and other resources, while adapting existing tools is far easier. Sus-VSM is already capable of capturing sustainability performance at the process level, and has the potential to be adapted for the supply chain level, similar to VSM. The work presented in this thesis is the result of efforts to meet this growing need and develop a methodology and tool for sustainability assessment at the supply chain level. Additionally, this work presents a general approach towards improving sustainability such that aspects that provide the greatest benefit to sustainability are prioritized first.

Adapting Sus-VSM to the supply chain level entails some unique challenges, one of which is the creation of future state maps. Sus-VSM is a pencil and paper tool, where future state maps are developed using estimations from those knowledgeable of the manufacturing process. Due to the complex nature of supply chains, however, it is difficult to estimate what effects changes will have, as a change in one branch of the supply chain can have an effect on a seemingly unrelated branch. Another shortcoming of creating future state maps by hand is the time necessary to assess numerous potential future states, as estimates must be made and the map created for each scenario. Furthermore, the collection of data at the supply chain level presents a large difficulty, as supply chain members are likely unwilling to share operations information due to confidentiality concerns. To counteract these three challenges, the implementation of a simulation model to aid the process presents significant potential. Discrete event simulation (DES) in particular lends itself for use in evaluating manufacturing systems. Finally, given the high-level view required when evaluating the supply chain, the information provided by the adapted Sus-VSM can be somewhat lacking in detail, so a method of further analyzing the results of the adapted Sus-VSM, such as a design of experiments (DOE) type analysis, could potentially increase the usefulness of the tool. Montevechi et al. (2012) present work that combines DOE with simulation to reduce the amount of trial and error needed with the simulation as well as to capture interactions between input variables that might be disregarded otherwise.

Based on the importance of evaluating the sustainability performance of supply chains, this thesis presents work that attempts to answer a number of research questions that would help overcome the challenges faced when trying to achieve sustainability.

- How can Sus-VSM be adapted to the supply chain level to identify potential improvements to supply chain sustainability performance?
- What general approach towards improving sustainability produces the greatest benefit in supply chain sustainability performance?
- What advantage does the use of DES grant when used in conjunction with Sus-VSM?
- What advantage is gained by implementing a DOE style analysis with supply chain Sus-VSM?

The remainder of this thesis will be presented in the following manner. Chapter II will provide a general literature review of research on traditional VSM and how it has been applied to the supply chain level. It will also cover efforts that have been made to develop metrics that capture sustainability and how they have been implemented into assessment tools. Finally, it will cover how simulation models have been used in conjunction with traditional VSM to provide additional benefits. Chapter III will entail a more detailed review of Sus-VSM, as this thesis largely builds upon standard Sus-VSM (Faulkner and Badurdeen, 2014). It will discuss what metrics have been added to Sus-VSM and how they are visualized for the value stream maps. It also details what methods have been used to verify and validate Sus-VSM and what improvements to the methodology been developed. Chapter IV presents the proposed methodology and metrics for building a supply chain Sus-VSM (SC Sus-VSM) as well as an example of SC Sus-VSM. The details of the simulation model developed to simulate the supply chain and create the SC Sus-VSM are also presented. Chapter V details the case study performed using the simulation and the different scenarios considered. This chapter also details the sustainability index that was developed to measure the sustainability performance of the supply chain. The DOE style analysis implemented to capture the sensitivity of the sustainability index to different interventions is also presented. Chapter VI presents the results of all these case study efforts. Finally, conclusions and recommendations for future research will be presented in Chapter VII.

CHAPTER II

Literature Review

By reviewing literature and previous works, it is possible to determine the strengths and weaknesses of various mapping and simulation methods. Studying where and how these methods have succeeded and fallen short, efforts can be made to build upon successes of the past and avoid the shortcomings of previous works. This literature review examines how VSM has been applied and expanded, how efforts have been made to assess sustainability for various manufacturing systems, how simulation has been integrated with VSM and how VSM has been applied at the supply chain level, and finally it examines different types of simulation and how they are used at the supply chain level.

2.1 Value Stream Mapping and Expansion

VSM is a tool developed within the Toyota Production System by Rother and Shook (1999) that maps the "door-to-door" production flow inside a plant, from delivery of necessary parts and materials for production to final shipment to the customer. VSM is first used to identify sources of waste in the value stream and then to develop a future state map of improvements that are then implemented, after which the process is repeated for continuous improvement. Singh et al. (2011) provide a review of VSM, which has been applied extensively within manufacturing industries. The primary shortcoming of traditional VSM, however, is the lack of metrics to assess environmental and societal aspects of sustainability performance.

In efforts to build upon and improve traditional VSM and other lean techniques to consider more than economic aspects, the EPA in the US developed two toolkits: a lean and environmental toolkit (EPA 2007) and a lean and energy toolkit (EPA 2007). The first EPA toolkit seeks to reduce environmental waste, which is defined to include materials and resources in excess of customer needs, pollutants released into the environment, and any hazardous materials used in production. After defining metrics to capture these wastes, the toolkit proposes to record one or two of these metrics in a traditional VSM and to make use of EHS (Environmental, Health, and Safety) stamps to target lean improvements to the most beneficial areas. The second EPA toolkit also builds upon traditional VSM, but instead seeks to monitor energy consumption for each process in the manufacturing system. For each process, data is collected and the energy consumption is visualized using an energy dashboard. The energy dashboards can be used to evaluate the energy efficiency of the processes, allowing improvements to be targeted to necessary areas. However, while the energy dashboard provides useful information, it occupies a large area on the VSM, resulting in a cluttered map that is difficult to read. Finally, neither EPA toolkit addresses societal aspects of sustainability in any form, nor is water usage considered in either toolkit.

Torres and Gatti (2009) developed a tool called environmental VSM (E-VSM) to monitor water usage using process data which is analyzed and divided into numerous categories. Those categories include: activated water, used water, water added to the product, latent loss, real loss, latent/real loss, and intrinsic functional loss. While this level of detail provides a large amount of information that can better target areas for improvement, the expenditure of time and resources in collecting the data hinders the quickness with which VSM can be applied. Also, visualizing this level of detail in a VSM requires visual icons that are not fully compatible with standard VSM, and introduces a substantial amount of confusion. Work by Simons and Mason (2002) resulted in a tool called Sustainable Value Stream Mapping (SVSM), which captures GHG and CO_2 emissions to evaluate and enhance sustainability. While directly capturing economic and environmental metrics, they do not capture societal metrics; instead they assume that societal aspects will improve when economic and environmental improvements are made. Building upon this work and previous work by Norton (2007) into sustainability metrics, a different tool called sustainable value chain mapping (SVCM) was developed by Fearne and Norton (2009) to combine sustainability and VSM. A case study of the food industry in the UK was used to validate the SVCM methodology. SVCM adds metrics for water and energy usage, but due to difficulties in capturing these metrics for each activity in the case study, they were estimated using the economic allocation method from life cycle assessment by Guinee (2002). Societal improvements were assumed similar to Simons and Mason (2002).

Work by Braglia et al. (2006) sought to expand the use of VSM to more complex production systems with complex bills of material (BOM) using improved value stream mapping (IVSM). The IVSM procedure selects a product family, identifies machine sharing, identifies the main value stream, maps the critical path, identifies and analyzes wastes, maps the future state for critical/sub-critical path, identifies the new critical path and iterates the procedure. Also addressing the challenge of complex production systems, Irani and Zhou (2003) present value network mapping (VNM) to visualize and analyze interacting value streams within jobshops, where high variety and complex product flow mandate that VSM be altered. Instead of identifying product families, Keil et al. (2011) first identify essential products and then build flow families. They define a flow family as a chain of consecutive single process steps which are similar within different product process of records. By using flow families, entirely different products can be grouped based on their process steps.

Faulkner and Badurdeen (2012) present a methodology for capturing and visualizing sustainability at the manufacturing line level called Sustainable Value Stream Mapping (Sus-VSM). Sus-VSM retains the functionality of traditional VSM, but adds metrics that capture environmental and societal aspects of sustainability. Additional work by Faulkner and Badurdeen (2014) details further refinement of Sus-VSM, and also provides a thorough review of other studies to expand VSM to include sustainability and discusses their shortcomings. Subsequent work by Brown et al. (2014) explores the application of Sus-VSM to various manufacturing system configurations and how Sus-VSM can be adapted to deal with challenges that arise in these configurations. The work in these papers is discussed in greater detail in Chapter III.

2.2 Sustainability Assessment

Barbosa-Póvoa (2009) identifies four key challenges that face sustainable supply chains, with determination of metrics to assess supply chain sustainability performance being the most important. Metrics need to adequately capture environmental impacts, consequences to the social well-being of the population caused by the supply chain, and have data easily accessible. Other identified challenges include defining or redesigning supply chains to facilitate recycling and remanufacture of returned products, accounting for uncertainty within the supply chain, and how to balance the three aspects of sustainability.

Lainez et al. (2008) present a Life Cycle Assessment (LCA) based approach to evaluating environmental issues within a supply chain. LCA involves an approach that captures all stages in the life cycle and places environmental impacts into a consistent framework, regardless of when or where these impacts occur. A major drawback of LCA is the necessity of compiling a life cycle inventory (LCI) that contains data collected from every echelon of the supply chain. Compiling data for the LCI would require prohibitive amounts of time and resources, making an LCA-based approach unsuited for quickly assessing supply chain sustainability performance. Further, the proposed approach fails to consider environmental aspects such as water usage as well as societal metrics in any form.

Potential metrics for assessing sustainability within a supply chain can be determined by examining methods of product life-cycle assessment. Working together with the National Institute of Standards and Technology (NIST), Shuaib et al. (2014) present a methodology called the Product Sustainability Index (ProdSI) to assess a product's sustainability performance throughout all four stages of the product life-cycle.

This work builds upon the Product Sustainability Index (PSI) framework developed by Jawahir et al. (2006) which considers the total product life cycle and the triple bottom line (TBL). Although ProdSI and PSI both stand for Product Sustainability Index, different acronyms are used to differentiate between the two methods. Zhang et al. (2012) present an application of PSI, but for ProdSI, Shuaib et al. (2014) present a more systematic approach towards identifying a comprehensive list of economic, environmental, and societal metrics divided into clusters and sub-indices for assessing product sustainability. A numerical example of an automotive body-in-white (BIW) component was used to demonstrate the application of ProdSI. Metric measurements were first normalized, and then weighted and aggregated to determine the ProdSI score. This ProdSI score can then be used to compare the product sustainability of different scenarios. However, the normalization and weighting process is dependent on expert opinions, introducing subjectivity to the methodology, affecting the accuracy and sensitivity of the ProdSI assessment. In related work, Feng et al. (2010) present an infrastructure to assess the sustainability of a product throughout the product life-cycle. The infrastructure includes a repository of sustainability metrics, methods and guidelines for the measurement process, and performance analysis and evaluation. The authors also provide an overview of the strengths and weaknesses of various metric repositories, thus identifying areas requiring further metrics to properly assess sustainability.

Research by Wang et al. (2011) focuses on capturing societal aspects of sustainability and presents an interesting approach. Basic societal needs, such as housing, education, healthcare, and other basic needs are divided into units, such as a 'unit' of healthcare. The number of work hours to obtain each unit is then determined based on the geographic location being considered and the average wage in that location. By examining the number of work hours to produce a product, the number of units that can be purchased per product can be determined. For example in Germany, purchase of a unit of housing may require 20,000 work hours at an average wage of 10€/hour. If 7 hours of work are required to make an ingredient for detergent, production of that detergent ingredient contributes to 0.00035 units of housing in Germany. A case study considering traditional and modern manufacture of detergent was simulated to demonstrate the methodology. One shortcoming of this work, however, is that the societal metrics consider only the employee, and ignore other potential stakeholders.

2.3 VSM for Supply Chains

A number of studies investigate how to apply VSM at the supply chain level instead of the process level. Dolcemascolo (2006) deals with the practical application of VSM to the supply chain or extended value stream, but only in regard to economical considerations. The method, Extended VSM visualizes metrics and is performed similarly to standard VSM, however, standard VSM must be performed at each plant to collect the necessary data to create the extended VSM. This means that for a supply chain with an established lean culture where traditional VSM has already been performed, extended VSM would be a useful extension. However, for a supply chain that is just starting to attempt applying lean methods, extended VSM would be of very limited use in supply chain assessment. Furthermore, this extended VSM focuses only on the economic aspect of sustainability, and lacks any metrics to capture the environmental and societal aspects.

A different attempt at applying VSM at the supply chain level was made by Seth et al. (2008). This work examines the cottonseed oil industry in India, and attempts to identify different types of waste that should be eliminated. To collect the data necessary to build the VSM, a questionnaire was prepared and given to oil mill owners, traders and brokers, as well as machinery manufactures. The goal of the questionnaire was to collect information regarding details such as plant processes, processing costs, machines, and the markets. In order to map the supply chain, a modified version of VSM was used as shown in Figure 2.1. This map loses significant details, such as cycle times for the processes inside the plants, but it does still capture inventory and transport lead times.

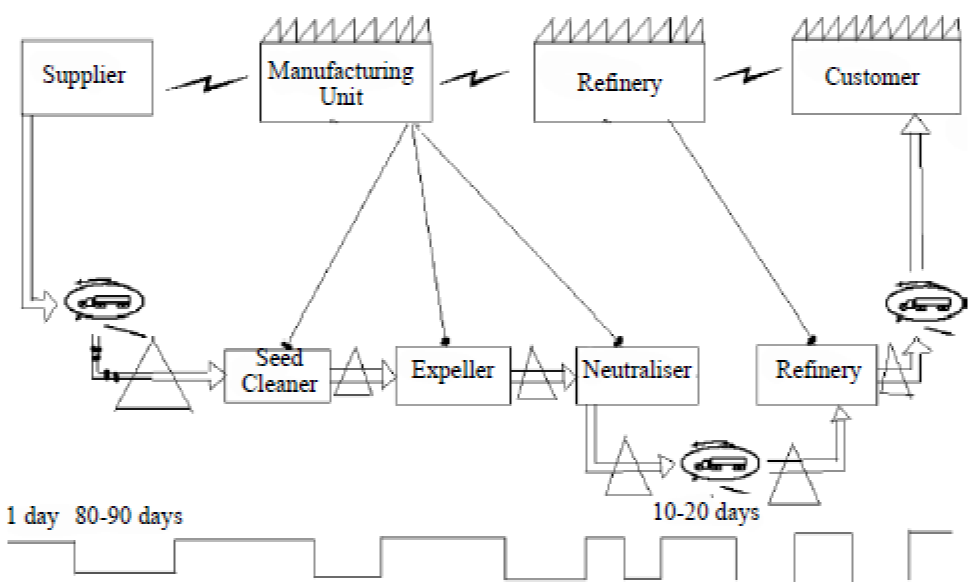

Figure 2.1: Example of VSM application at the Supply Chain level (Seth et al., 2008)

This modified VSM coupled with the questionnaire response allows many different waste types to be identified, including unnecessary transport and inappropriate processing caused by the use of outdated machinery. While this methodology is capable of identifying most wastes within a supply chain relatively quickly, it fails to capture the information that is shown in a standard VSM, such as value-added time within the plants, and the total lead time for each plant. Similar to Dolcemascolo (2006), this methodology captures only economic aspects of sustainability. While a basic picture of the supply chain can be developed to identify major types of waste, this methodology is less useful in identifying more subtle forms of waste. Work by Arbulu and Tommelein (2002) presents a VSM case study of a construction supply chain for pipe supports that captures each process in the supply chain and aids in waste identification. Visuals identify which processes are performed by the engineering firm and which are performed by a supplier, as well as the value added time for each process in man-hours. The VSM captures the total time spent between activities in the supply chain, allowing non value added time to be computed, but does not capture uptimes, changeover times, or any environmental or societal metrics. The case study considers a linear supply chain, instead of a branching system, further limiting the usefulness of the application.

Folinas et al. (2013) present work to develop an adaptation of VSM to assess environmental aspects of a food supply chain. This methodology does not propose a map that portrays the entire supply chain, but instead selects certain locations in the supply chain where VSM should be performed. This selection process is based on processes that require significant amounts of input, amounts of output, processes that consistently cause errors and delays, as well as processes that directly affect the customer or have high visibility. The methodology also suggests metrics that should be integrated into the VSM to capture the environmental impact, such as pounds of material and hazardous materials used, gallons of water used and consumed, watts and BTUs of energy used, solid waste and hazardous waste generated, pounds of air pollution emitted, and gallons of wastewater treated. However, the research does not suggest how these additional metrics could be visualized in the VSM. Additionally, the research requires that VSM be applied at multiple locations, and does not propose a method of visually capturing the supply chain as a whole. Further, while the proposed methodology would capture the environmental aspect of the supply chain, the societal aspect of sustainability is not considered. Finally, while the research proposes a VSM methodology that can assess the environmental aspect of a supply chain, it does not present a case study to verify that the proposed method will function as desired at the supply chain level.

2.4 DES and System Dynamics

The use of simulation to aid with the assessment and operation of manufacturing systems is by no means a new topic, with literature reviews on the topic containing vast amounts of material (Jahangirian et al. 2010). Two of the most popular types of modeling techniques are Discrete Event Simulation (DES) and System Dynamics (SD). As the name implies, DES models the operation being considered as a sequence of individual events in time, and several events can occur simultaneously (Seleim et al. 2012). DES also models the system as a network consisting of queues and flows and entities such as objects and people individually (Tako and Robinson 2012). SD, on the other hand, models the system using stocks and flows while the state of the system is changing in a continuous manner (Forrester 1961). Also, entities are not modeled individually, but as a continuous quantity within a stock. Further, DES tends to be more stochastic in nature with variable randomness being introduced through statistical distributions, while SD tends to be more deterministic in nature, with variables being represented by average values (Tako and Robinson 2012). Overall, both types of modeling are extremely useful, but one or the other will have an advantage, based on the situation. Given how VSM is used to map the production flow of a manufacturing system, and how processes are shown as activities with queues of individual entities waiting to go through the process, the DES method of modeling a system as a network of queues and activities lends itself particularly well to use with VSM. For example, entities do not arrive at processes in a continuous way, so there is a need to track individual entities and events in time, making DES better suited for modeling than SD. DES also allows randomness of the variables that represent VSM metrics, providing a more realistic model.

Research by Herrmann et al. (2000) seeks to measure the adaptability of a DES model in manufacturing applications. An adaptable model should be capable of addressing any changes in requirements or answers to be provided, internal and external changes in the production environment, and updated data provided by related information systems. Herrmann et al. (2000) propose to measure the adaptability of a new DES model using the ratio of the effort needed to upgrade from an existing model to the effort required to build the new model completely. Persson (2002) investigates the impact of different levels of detail in simulation models using three different models of a single manufacturing system. The models showed significant discrepancies in line utilization and blockage times, and inventory levels, indicating the importance of model detail, which also affects the validation process. Models should be validated using data for each output in the simulation, requiring expenditure of resources to collect data, meaning that selecting the appropriate level of model detail can result in less time required for data collection. Models with too little detail are inaccurate while models with too much detail are time consuming to run, so a middle ground for the level of detail would provide the best results. Negahban and Smith (2014) provide a comprehensive review of almost 300 DES publications from 2002 to 2013 with a focus on manufacturing applications.

Zhang et al. (2013) present a conceptual SD model to facilitate decision-making for sustainable manufacturing systems by highlighting relationships between factors and by simulating current functioning of the system and potential improvements to the system. The SD model would also provide a systems thinking approach to holistically solve problems in sustainable manufacturing. While the conceptual SD model addresses the three aspects of sustainability, an actual model must be built and validated to ensure that all aspects are captured correctly. While more detailed reviews of SD are available, they are not included, since DES is better suited for VSM simulation.

2.5 Application of Simulation to Study VSM

When exploring the possibility of combining lean tools with simulation, Solding and Gullander (2009), recognize that simulation is partially counterintuitive to lean tools, as lean tools are supposed to be simple in their use, while simulation is more complex in its application. However, upon reviewing the arguments presented by Standridge and Marvel (2006) in favor of combining simulation and lean tools, Solding and Gullander (2009) developed Simulation Based Value Stream Mapping (SBVSM) in an attempt to capture the potential benefits of a simulation/VSM pairing. SBVSM combines DES and VSM into a single tool, creating a dynamic VSM. In an effort to manage map complexity, SBVSM uses traditional VSM icons and visualization wherever possible. However, improvements were made when feasible, so SBVSM is able to capture multiple products simultaneously instead of only one product at a time. The results of these efforts can be seen in the SBVSM example shown in Figure 2.2.

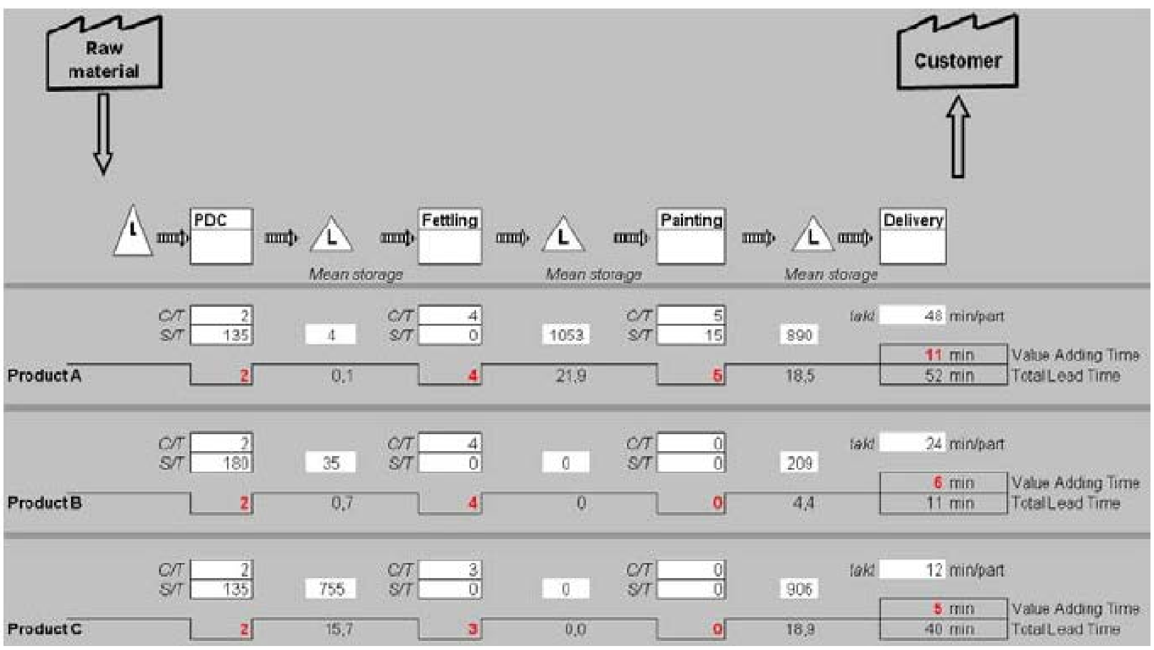

Figure 2.2: SBVSM representation with three products shown (Solding and Gullander, 2009)

Some of the changes made in visualizing SBVSM will make reading the map more confusing, given that the majority of the visuals are the same as standard VSM; however, this is a relatively minor obstacle. Also, this combination of DES and VSM allows the process line to be examined over a period of time instead of only in snapshots. For example, Solding and Gullander (2009) present charts that capture inventory fluctuation and resource utilization with respect to time, providing very useful information for assessing the manufacturing system. The setup used for the SBVSM process allows those familiar with lean concepts to quickly understand the process, even if they are not familiar with DES. While standard VSM is relatively easy to understand and apply, the development of a DES model is more complex. Thus, it requires someone who is knowledgeable in both VSM and DES to properly implement SBVSM. Furthermore, SBVSM was not developed for supply chains, and lacks environmental and societal indicators to assess sustainability.

Paju et al. (2010) present an application of a VSM-based assessment called Sustainable Manufacturing Mapping (SMM) that considers selected sustainability indicators. The methodology presented is also based on LCA and DES. Table 2.1 summarizes how VSM, LCA, and DES provide complimenting features for assessing a manufacturing system. The goal and scope definition in SMM is borrowed from LCA, the symbolic visualization is taken from VSM, and DES allows a dynamic assessment not based on average data. While SMM considers environmental indicators, no societal indicators are implemented, and while data is available for the environmental indicators, a lack of consistency in nomenclature and naming conventions is present. A lack of case studies indicates that further validation of the methodology is required.

Table 2.1: Characteristics of VSM, LCA, and DES used in SMM, preferred features italicized (Paju et al., 2010)

Feature	VSM	LCA	DES
Dynamic Assessment	Deterministic, standard or average parameter	Deterministic, standard or average parameter	*Dynamic event relationships, probabilistic parameters*
Publicly Available Data		*Public LCA data available*	
Visualization	2D process map	Limited process view	*3D visualization and animation*
Simplified	*User-friendly tool*	Experts tool	Experts tool
Standardized	Industrial de facto standard for lean manufacturing	*Standardized* ISO 14040, 14044	Partially
Framework for environmental impact analysis	Methodology has been presented	*The main tool*	Mostly research initiatives, also commercial solution entering the market

Research by Lian and Landeghem (2002) also seeks to improve on traditional VSM by introducing DES, and suggests four phases that can be used in the integration process. The first phase consists of only using standard VSM to create the current and future state maps for a single product. The DES model is introduced in the second phase where it is used to simulate the current and future state maps from the first phase. Comparing the DES model with the current state map validates the model and instills trust in the users. For the third phase, Lian and Landghem (2002) suggest using the DES model to examine the use of VSM for multiple products, and also to investigate different conditions and operating parameters. In the fourth and final phase, it is suggested that the DES model can be used for future state documentation and also as a training tool for operators. A case study performed by Jarkko et al. (2013) on a small-sized enterprise in the construction field explores a similar framework for DES and VSM. The DES model is built and verified using the current state VSM, and then it is used to explore and simulate what will occur in future state maps. The case study focuses on a small-sized enterprise because such companies often cannot economically afford to apply potential improvements through a trial and error method and need a more concrete confirmation the benefits of the proposed improvement. However, utilizing DES requires the employment of personnel specialized in the use of simulation software, which could be prohibitively expensive for a small enterprise. Abdulmalek and Rajgopal (2007) present another case study combining VSM and DES to highlight the ability to contrast before and after scenarios in detail to illustrate potential benefits to management.

2.6 Simulation Modeling for Supply Chains

Fowler and Rose (2004) present research into 'grand challenges' faced when applying simulation models to supply chains. A grand challenge is defined as a problem that is difficult with a solution that involves at least one order-of-magnitude improvement in capability along at least one dimension, is not provably unsolvable, and has a solution with significant economical or social impact. The first grand challenge involves the shortening of problem solving cycles through model design, development, and deployment. The second grand challenge concerns the development of real-time, simulation-based, problem-solving capability to assess the supply chain if sudden changes occur. The third grand challenge addresses the interoperability of simulation models within a specific application domain. A fourth challenge presented as a 'big' challenge is greater acceptance of simulation and modeling within industry.

While creating future state VSM at the process level is not difficult, the interactions between facilities at the supply chain level add complexity. According to an extensive review by Terzi and Cavalieri (2004), the use of simulation for supply chains allows what-if scenarios to be analyzed, facilitates comparison of alternatives without interrupting operations, and speeds the process through time compression. They also note, however, that the communication needed to collect the data for the simulation can be greatly hindered by geographical distance and if independent enterprises are involved in a single supply chain. Sarimveis et al. (2008) also provide a comprehensive review of various dynamic models for control of supply chains, citing almost 200 works from various areas.

Research by Higuchi and Troutt (2004) illustrates how an SD model could have prevented the manufacturer of the Tamagotchi digital pet suffering from the bullwhip effect. The initial rate of production was unable to meet demands for the toy, so production facilities were expanded. After expanding, however, demand declined sharply, leaving the manufacturer with large amounts of unsold inventory. The SD model illustrated that the bullwhip effect was likely to occur, and that further analysis should have been performed, given the short life-cycle of the product. Fleisch and Tellcamp (2005) use simulation to illustrate the effect of inventory inaccuracies caused by poor process quality, theft, and items becoming unsalable. Even if the sources of inventory inaccuracy remain unchanged, reducing these inaccuracies using the simulation would result in reduced supply chain costs and the level of out-of-stock. If the sources of inventory inaccuracies are also reduced, the benefits are even greater. Fleisch's and

Tellcamp's (2005) research is limited to a supply chain with one-product, however, and uses specific parameter estimates, so further case studies are advised.

Wan et al. (2003) present a simulation based optimization framework that is used to investigate and analyze complex supply chains. The framework uses deterministic math models that ignore randomness in the supply chain to provide efficient resource allocation across time and different products. These results are used as guidelines for the simulation model, accounting for uncertainties and providing performance measure information for the stochastic optimization model, which seeks to optimize the performance of the entire supply chain. The framework is general enough to be applied to varying supply chains with relative ease, but steps involved result in increased complexity.

Since supply chains are neither fully discrete nor continuous, Lee et al. (2002) present a combined discrete event and continuous simulation architecture to evaluate supply chains more accurately. For exceedingly complex supply chains, DES requires large quantities of input data and application requires increasing amounts of time. By introducing continuous components into the model, some supply chain features are simpler to express and model, reducing the amount of input data and time needed, without reducing the accuracy of the supply chain model. Supply chain elements are classified as discrete or continuous based on their attributes, with the discrete-continuous combined model accounting for interactions between the elements. A case study comparing DES with the combined model resulted in higher inventory levels in the DES model, indicating that the DES model overestimated inventory levels.

There exists a large amount of research literature on the use of simulation for assessing and improving supply chains, as it has been a topic of interest for some time now. Table 2.2 provides a partial summary of the literature reviewed in this section.

It should be noted that while many aspects such as applying VSM to supply chains, combining VSM and simulation, and developing methods to assess sustainability in different manufacturing systems have been studied previously, there has not been an effort to combine these tools. Sus-VSM captures and visualizes the economic, environmental, and societal aspects of sustainability, but is not adapted for supply chain application and lacks a dynamic model. Dynamic models that capture environmental aspects have been developed by combining VSM and DES, but societal metrics are difficult to capture and only the process level can be simulated. Supply chains have been modeled using DES, but not all sustainability aspects are considered and visualization via mapping is lacking. A tool that captures and visualizes supply chain sustainability performance using a DES model would meet many of these shortcomings.

Table 2.2: Partial Summary of Literature

Topic	Author(s)	Title	Year
SC Assessment	Barbosa-Póvoa	Sustainable Supply Chains: Key Challenges	2009
Sustainability Assessment	Feng et al.	Development Overview of Sustainable Manufacturing Metrics	2010
VSM in SC	Lainez et al.	Mapping Environmental Issues within Supply Chains: a LCA based Approach	2008
	Arbulu and Tommelein	Value Stream Analysis of Construction Supply Chains: Case Study on Pipe Supports Used in Power Plants	2002
DES and SD	Seleim et al.	Simulation Methods for Changeable Manufacturing	2012
SD	Zhang et al.	A Conceptual Model for Assisting Sustainable Manufacturing Through System Dynamics	2013
DES	Herrmann et al.	Adaptable Simulation Models for Manufacturing	2000
	Persson	The Impact of Different Levels of Detail in Manufacturing Systems Simulation Models	2002
	Negahban and Smith	Simulation for Manufacturing System Design and Operation: Literature Review and Analysis	2014
DES in SC	Lee et al.	Supply Chain Simulation with discrete-continuous Combined Modeling	2002
SD in SC	Higuchi and Troutt	Dynamic Simulation of the Supply Chain for a Short Life Cycle Product- Lessons from the Tamagotchi Case	2004
Simulation in SC	Fleisch and Tellcamp	Inventory Inaccuracy and Supply Chain Performance: a Simulation Study of a Retail Supply Chain	2005
	Wan et al.	A Simulation Based Optimization Framework to Analyze and Investigate Complex Supply Chains	2003
	Fowler and Rose	Grand Challenges in Modeling and Simulation of Complex Manufacturing Systems	2004

CHAPTER III

Sustainable Value Stream Mapping (Sus-VSM) Review

SC Sus-VSM builds on traditional VSM and particularly Sus-VSM, so a more detailed examination will highlight the benefits and shortcomings of Sus-VSM that SC Sus-VSM builds upon and seeks to improve. This chapter provides a review of the Sus-VSM methodology as well as its application to different manufacturing system configurations based on Faulkner et al. (2012), Faulkner and Badurdeen (2014), and Brown et al. (2014).

3.1 Sus-VSM Methodology

The Sus-VSM methodology extends traditional VSM by incorporating three metrics for environmental sustainability evaluation and two metrics for evaluating societal sustainability at the production line level (Faulkner and Badurdeen, 2014). The addition of these metrics allows all three aspects of sustainability to be evaluated for the production line, and for potential improvements to sustainability performance to be identified.

One added metric to aid in environmental assessment is process water usage. It was proposed that three aspects of process water usage be captured for each process: water needed, water used, and water lost. Water lost is defined as water that is not used for another process or recycled within the plant; therefore, water that is treated and exits the plant after the process, water that is spilled and water lost to evaporation are all included in the amount of water lost. Recycling as much water as possible within the plant is the easiest way to reduce the amount of water lost, as spillage and evaporation are harder to address. Faulkner et al. (2012) clarify that water added to the product itself is not captured by this metric, but is instead captured by the raw material usage metric, and although process water usage is defined for water, it can easily be used for oil or other coolants as well.

Another environmental metric introduced by Faulkner et al. (2012) is raw material usage which accounts for a large part of manufacturing costs and directly affects processing time, making it crucial to optimize the amount of material used. This metric captures both the original and final material masses for the process line as well as the amount of raw material added or subtracted at each process in the line. With only the original and final masses, it would be difficult to determine if material is being wasted, as one process could be adding material while another may be removing an equal amount, resulting in equal original and final masses for the production line.

The third environmental metric added is energy consumption, defined as the energy consumed by a process, not energy lost as heat or through machine inefficiencies. Faulkner et al. (2012) note that energy consumed by lights and environmental controls are not included in energy consumption, as they are independent of the process and the number of products made. The energy consumed by transporting the product between processes and any special heating or cooling storage chambers for the product can be determined using the energy density of the fuel used and converted to a common energy unit to visualize in the Sus-VSM.

Faulkner et al. (2012), also added metrics to assess societal sustainability of the process line in the Sus-VSM. These metrics focus on employee health and safety and include a physical work metric and work environment metrics. The physical work metric uses the Physical Load Index (PLI) introduced by Hollman et al. (1999) which has a score from 0-56 determined by a questionnaire which assesses factors such as different body positions, including arms, legs, and torso, and various loads lifted at those different body positions. The frequency with which various combinations of load and body position occur is also captured and used to develop the PLI score. This PLI score is captured for each process in the manufacturing line as well as between processes so that areas with a high score can be identified and evaluated for improvement efforts.

The work environment metrics focus on various hazards in the environment, such as Hazardous Chemicals/Materials Used (H), Electrical Systems (E), Pressurized Systems (P), and High-Speed Components (S). These are all given a risk rating from 1-5, determined by the likelihood of occurrence and magnitude of impact, as shown in Table 3.1. The ratings are captured within a circular icon for each process in the manufacturing line, so that potential risks can be identified and measures taken to protect employees.

Table 3.1: Risk Rating for Work Environment Metrics (Faulkner et al., 2012)

Potential Operator Risk	Description
--	Potential risk does not exist (DNE).
1	Risk is present but has low impact and probability of occurring.
2	Risk is present but has low impact and high probability or high impact and low probability of occurring.
3	Risk is present but has medium impact and medium probability of occurring.
4	Risk is present but has either medium impact and high probability of occurring or high impact and medium probability of occurring.
5	Risk is present but has high impact and high probability of occurring.

Another work environment metric that is captured is the noise levels at each process. Noise levels exceeding 80dBA pose a risk for operators, but lower noise levels for extended periods of time can also pose a hazard. To monitor these risks, the noise dose is determined using the ratio of time spent at a given noise level to the maximum permissible time at that noise level. Summing the partial doses allows the total daily dose to be determined. Using the noise dose, a time weighted average is used to determine the equivalent noise exposure for employees over a full 8-hour shift. This noise exposure is measured and recorded for each process in the manufacturing line, allowing noise cancellation or reduction measures to be put in place for processes that result in a high noise exposure for employees.

Overall, the addition of environmental and societal metrics to traditional VSM created a tool with much greater functionality. SC Sus-VSM builds upon Sus-VSM and uses the environmental metrics and visual icons with minor modifications, as discussed in Chapter IV. Sus-VSM retains all the capabilities of traditional VSM, but allows all aspects of sustainability to be visualized and evaluated, without reducing the legibility of the map.

3.2 Application Case Studies

A number of case studies with different manufacturing system configurations to further validate and assess the limitations of Sus-VSM have also been investigated (Falukner et al. 2012; Faulkner and Badurdeen, 2014; Brown et al. 2014). Collectively, three different manufacturing case studies are presented: high-volume with low-variety, low-volume with high-variety, and medium-volume with low-variety. Through cross-examination, these case studies provide insights into how Sus-VSM can be applied to different manufacturing configurations.

The first case study by Faulkner et al. (2012) considered a satellite dish manufacturer that operates with a high-volume and low-variety scenario. Collecting the data necessary to build the Sus-VSM proved difficult for some metrics, as not all metrics could be directly observed. For example, the authors detail how the energy usage per unit for an automated process where batches of the product travel along a conveyor belt was calculated using the rate of energy consumption, the length and speed of the conveyor belt, and the batch size. Thus, despite a lack of observable data for some metrics, the authors were able to adapt Sus-VSM to the situation by observing other parameters and applying the appropriate equations to capture the data necessary to complete the Sus-VSM, as shown in Figure 3.1.

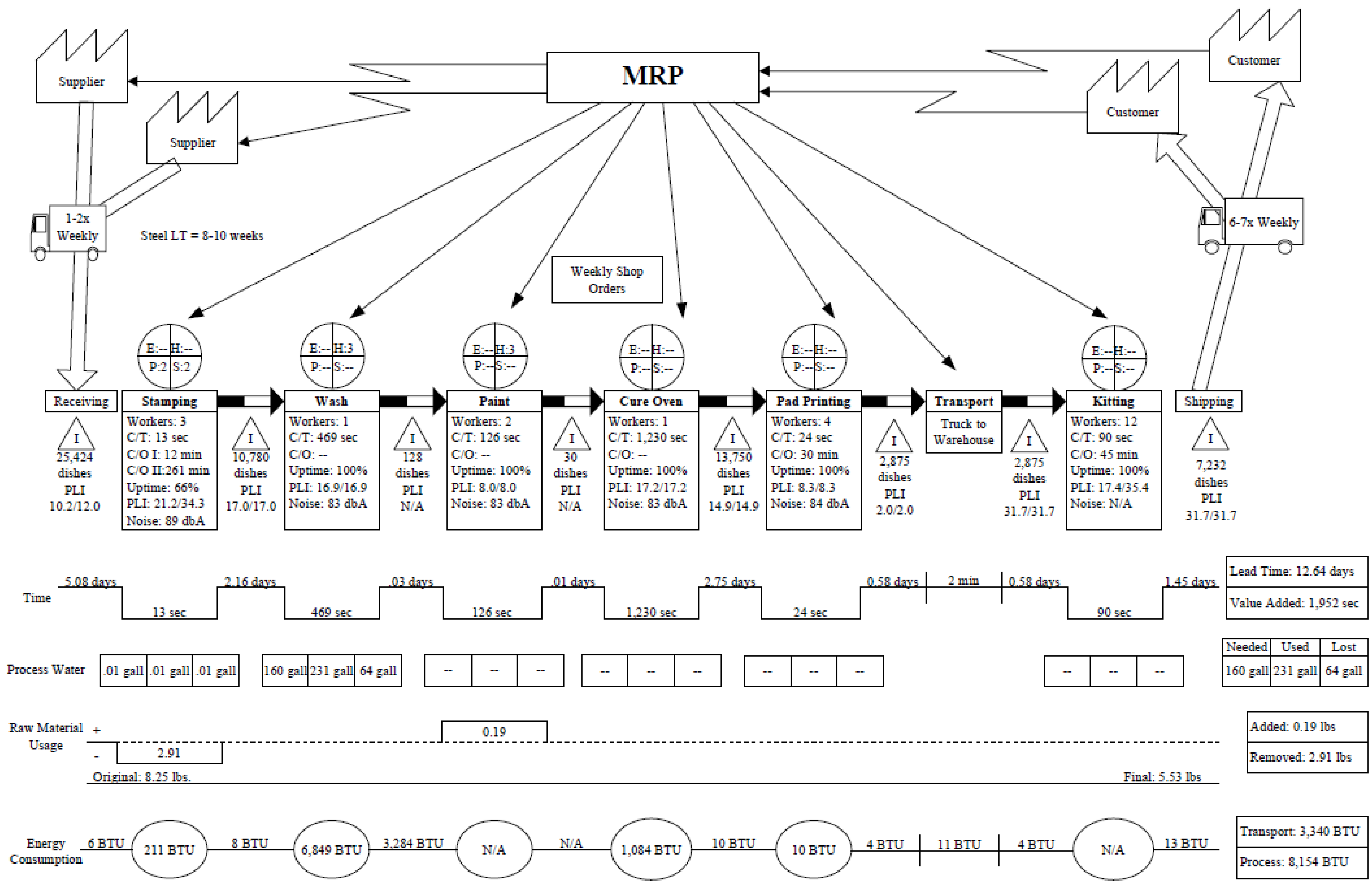

Figure 3.1: Example standard Sus-VSM for a Manufacturing Line (Faulkner et al. 2012)

The second case study reported by Brown et al. (2014) covers a low-volume, high-variety scenario for a manufacturer of dispenser cathode assemblies. This scenario is difficult to assess when using traditional VSM due to the high number of product types being manufactured and the often complex routing of the manufacturing line. This difficulty is compounded for Sus-VSM due to additional environmental and societal metrics. To solve this problem, Brown et al. (2014) focused the Sus-VSM application to areas of interest in the manufacturing line instead of capturing the entire complex system. While capturing the entire manufacturing line is desirable, the main goal of Sus-VSM is to identify opportunities for sustainability improvement in the system, which the authors still accomplish.

Another problem encountered by Brown et al. (2014) in this scenario is product variation and associated routing variation through the manufacturing line. Capturing the variation in lead times and other metrics and mapping the different product routes within a single Sus-VSM is unfeasible. To overcome this difficulty, Brown et al. (2014) designed three test parts of varying sizes that followed identical routes to represent product families that could be more easily evaluated, and suggested that metrics for a product family could be reported as averages if significant variation was present. While the test parts were simplified from actual production parts, the authors sought to use the results as a basis for modeling metrics such as energy consumption and establish a relationship between part size and energy consumption.

In this case study, Brown et al. (2014) also discovered that the PLI methodology was unable to accurately assess the physical strain on employee due to the fine, detailed nature of the work. The authors suggest that substituting a different methodology better suited for this type of work would allow proper assessment. Also, during discussions with the company, Brown et al. (2014) adapted the work environment metrics to be displayed as two ratings from 1-5, with the first rating assessing the likelihood of a risk event occurring, while the second rating evaluates the impact if that risk event occurs.

The third case study examined by Brown et al. (2014) focused on the manufacturing process for a contract to produce and deliver approximately 60,000 mortar fins, defined by the terms of the contract as a medium-volume with low-variety scenario. One obstacle encountered in this case study was the lack of inline flow meters to measure the water used and lost for the processes in the manufacturing line. The authors solved this problem using equipment literature and frequency of water or cutting fluid replacement to estimate water usage. Process energy consumption was determined from the machine power ratings, providing a high-end estimate of the actual energy consumption.

Another issue Brown et al. (2014) identified through direct observation was the PLI metric underestimating the physical strain experienced by employees during certain processes due to the nature of the PLI methodology. If the PLI questionnaires had been completed without direct observation of the manufacturing line, this issue may not have been identified. To correct this problem, the authors suggested that direct observation be utilized with standard PLI to avoid the subjective nature of the PLI questionnaires, but this correction was not implemented due to time constraints during the case study.

A summary of the challenges encountered and information learned in the case studies investigated by Faulkner et al. (2012) and Brown et al. (2014) can be found in Table 3.2.

Table 3.2: Summary of challenges encountered and information learned in case studies (Brown et al., 2014)

	Case Study 1	Case Study 2	Case Study 3
Manufacturing System Description	High Volume, Low Variety	Low Volume, High Variety	Med.Volume, Low variety
Challenges Encountered in Application of Sus-VSM	Allocation of water and energy consumption for continuous, automated process	Complex part routings and configurations	Unstable production schedule due to contract delays; limited number of team members for data collection
Relevance of Sus-VSM Metrics	All metrics were relevant	PLI metric could be replaced due to relative prevalence of small, tedious work	Additional metrics could highlight other ergonomic improvement opportunities
Key Learning	Sus-VSM is easily adapted to processes with continuous automated sections	Engineered parts can provide a baseline for systems with high levels of complexity	Sus-VSM is easily adapted to contracted manufacturing scenarios

In relation to SC Sus-VSM, the case studies examined by Faulkner and Badurdeen (2014) and Brown et al. (2014) for Sus-VSM highlight different methods for overcoming challenges faced when applying Sus-VSM. The first and third case studies illustrated different ways to calculate metric values when direct observation is not feasible; these methods can be useful when applying SC Sus-VSM, as direct observation and data collection becomes more difficult at the supply chain level. The second case study used methods for mitigating the complexity of the considered manufacturing line while still achieving the Sus-VSM goal of identifying locations for sustainability improvements. Due to the often complex nature of supply chains and the possibility of numerous branches, these methods can bring significant benefit to SC Sus-VSM by allowing simplifications to the map while still identifying potential improvements to supply chain sustainability performance.

Overall, the case studies examined by Faulkner and Badurdeen (2014) and Brown et al. (2014) highlight the use of different methods to adapt Sus-VSM to a range of different manufacturing system configurations. With some alterations, these methods can be applied when applying SC Sus-VSM, allowing for a wider range of supply chain configurations to be considered, increasing the usefulness of the tool.

CHAPTER IV

Methodology

This chapter details the methodology used in addressing the research questions considered in this thesis. The process followed has numerous steps which can be divided into four different phases. The first phase details the methods used to research potential metrics for SC Sus-VSM, and how those potential metrics were screened to identify the final metrics for inclusion in the SC Sus-VSM. Phase 2 discusses the creation of visuals to represent each of the metrics in the SC Sus-VSM and how they were incorporated to build the overall map. Phase 3 details the development of a DES model to simulate the SC Sus-VSM. The approach used to develop each plant model in the supply chain, model transportation between plants, as well as data collection for SC Sus-VSM development is discussed. Phase 4 consists of the development of a DES simulation model for the case study, identifying scenarios for future state map development and the analysis and comparison of the results. The methodology framework in Figure 4.1 shows the overall flow of the development process.

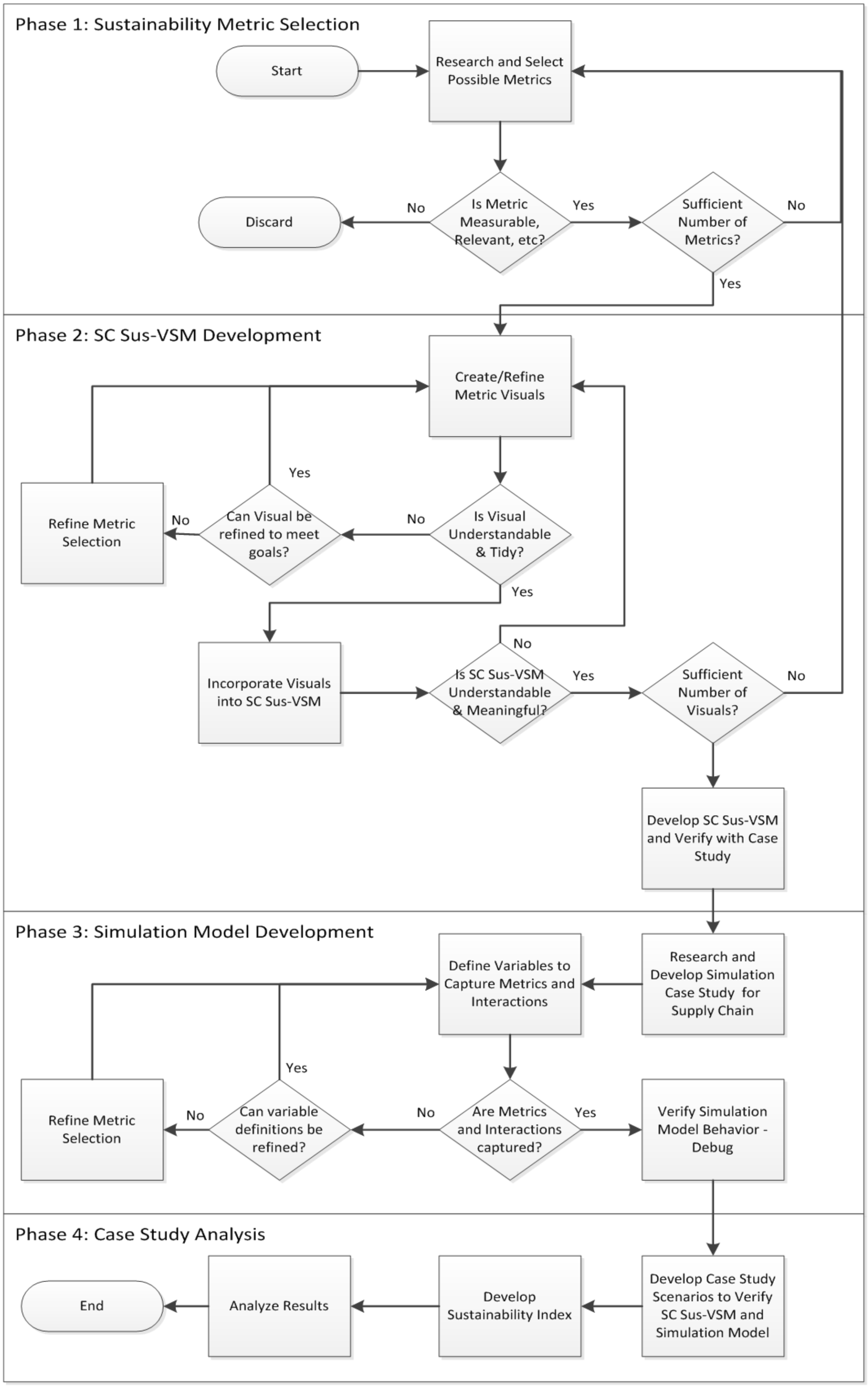

Figure 4.1: Methodology Framework

PHASE 1: Sustainability Metric Selection

Traditional VSM is used to quickly identify opportunities for kaizen, while standard Sus-VSM incorporates additional metrics to visualize sustainability performance and determine improvement opportunities at the manufacturing line level. SC Sus-VSM must accomplish the same goals as standard Sus-VSM, but requires metrics to accurately capture economic, environmental, and societal sustainability at the supply chain level. These new metrics were identified while ensuring compatibility with standard Sus-VSM and adapting sustainability metrics from the Sustainable Manufacturing Indicators Repository of the National Institute of Standards and Technology (NIST) (2010) and the Global Reporting Initiative (GRI) (2011). The NIST repository contains metrics for economic growth, environmental stewardship, and social well-being, and while metrics such as paid bribes were immediately deemed irrelevant for SC Sus-VSM, further consideration was given to other metrics such as total generated waste and recordable injury rate. The GRI presents guidelines with sustainability indicators that can be flexibly implemented by organizations to assess sustainability performance in key areas. The GRI guidelines contain metrics such as habitats protected or restored that are irrelevant to SC Sus-VSM, but metrics such as employee diversity ratio and number of hazardous spills that could be beneficial. The ProdSI developed by Shuaib et al. (2014) presents numerous economic, environmental, and societal metrics to assess product sustainability throughout the life-cycle of the product. While metrics such as product reparability and maintainability are specific to products and not applicable to SC Sus-VSM, metrics such as product defect ratio and mass of solid waste landfilled are more relevant for SC Sus-VSM. Chen and Johnson (2011) present a method of various scopes that can be used to assess both direct and indirect greenhouse gas (GHG) emissions, making the method ideal for SC Sus-VSM application. Table 4.1 presents a sample of potential metrics for SC Sus-VSM, with the final metric selections highlighted in green. Metrics were taken directly or adapted from NIST (2010), GRI (2011), ProdSI (Shuaib et al., 2014), Sus-VSM (Faulkner et al., 2012), and Chen and Johnson (2011) as indicated.

Table 4.1: Potential SC Sus-VSM Metrics

Economic	Environmental	Societal
Lead Time/Plant Time (Faulkner et al., 2012)	Material Usage (Faulkner et al., 2012)	Product Defect Ratio (Shuaib et al., 2014)
Value Added Time (Faulkner et al., 2012)	Water Usage (Faulkner et al., 2012)	Recordable Injury Rate (National Institute of Standards and Technology, 2010)
Transport Time/Distance (Faulkner et al., 2012)	Energy Usage (Faulkner et al., 2012)	Employee Training Intensity (Shuaib et al., 2014)
WIP (Faulkner et al., 2012)	GHG Emissions (Chen and Johnson, 2011)	Hazardous Chemical/Materials (Faulkner et al., 2012)
Profit Generated (National Institute of Standards and Technology, 2010)	Total Generated Waste (National Institute of Standards and Technology, 2010)	Local Hiring Ratio (Global Reporting Initiative, 2011)
Government Subsidies (Global Reporting Initiative, 2011)	No. of Hazardous Spills (Global Reporting Initiative, 2011)	Diversity Ratio (Global Reporting Initiative, 2011)
Transportation Cost (Shuaib et al., 2014)	Environmental Protection Expenditures (Global Reporting Initiative, 2011)	Physical Load Index (Faulkner et al., 2012)
Use of Locally Based Suppliers (Global Reporting Initiative, 2011)	Fines for Non-compliance with Laws and Regulations (Global Reporting Initiative, 2011)	Electrical System Hazard (Faulkner et al., 2012)
Warranty Costs (Shuaib et al., 2014)	Weight of Waste by Type (Global Reporting Initiative, 2011)	Pressurized System Hazard (Faulkner et al., 2012)
Equipment Uptime (Faulkner et al., 2012)	Water Withdrawal by Source (Global Reporting Initiative, 2011)	High-Speed Components Hazard (Faulkner et al., 2012)
Storage Costs (National Institute of Standards and Technology, 2010)	Energy Saved by Improvements (Global Reporting Initiative, 2011)	Noise Hazard (Faulkner et al., 2012)
R & D Costs (National Institute of Standards and Technology, 2010)	Energy Usage by Source (Global Reporting Initiative, 2011)	Employee Hiring Rate (Global Reporting Initiative, 2011)
Packaging Cost (National Institute of Standards and Technology, 2010)	Mass Solid Waste Landfilled (Shuaib et al., 2014)	Employee Turnover Rate (Global Reporting Initiative, 2011)

4.1 Environmental Metrics

Three of the environmental metrics chosen for Sus-VSM for supply chain networks come directly from standard Sus-VSM work. Capturing raw material usage, water usage, and energy consumption is as useful for visualizing sustainability performance for supply chains as it is at the production line level. The additional metric of GHG emissions is selected to further improve sustainability assessment. How these metrics are measured and visualized in SC Sus-VSM and reasons for the metrics selections are provided in the following sections.

4.1.1 Raw Material Usage

For SC Sus-VSM, the procedure for capturing the raw material usage is similar to standard Sus-VSM, but is focused on covering the entire supply chain. The original material mass will be captured at the start of each branch in the supply chain while the final mass will be captured just before shipment to the customer. For the same reasons given above for standard Sus-VSM, the amount of material added or subtracted will be measured and visualized for each plant in the supply chain.

The raw material usage metric will be visualized similar to Sus-VSM (Faulkner and Badurdeen, 2014) using a dotted line to indicate the initial mass with mass added and removed mass recorded in boxes above and below the line, respectively, as shown in Figure 4.2. At plants where material is neither added nor removed, the dotted line for the initial mass will be used as an indicator. The sums of material added and removed will be recorded and displayed at the right-hand end of the SC Sus-VSM, similar to standard

Sus-VSM. Completed components from feeder plants are not considered as material added at the receiving plant.

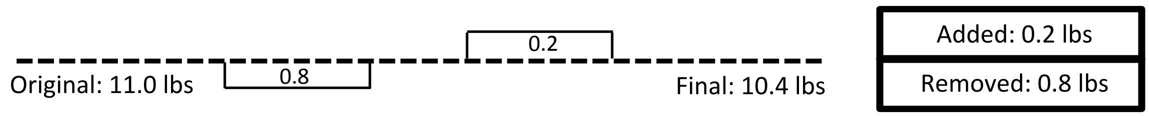

Figure 4.2: Example of Raw Material Usage SC Sus-VSM Visual

4.1.2 Water Usage

The use of water and other coolants is prevalent in manufacturing, and due to the large quantities commonly being used, this can have a significant environmental impact. The necessity of evaluating this impact is sufficient reason for water usage being selected as a metric for both Sus-VSM and SC Sus-VSM. For SC Sus-VSM, the definition of water lost will be water that is not recycled within the plant, similar to standard Sus-VSM, but water needed, used, and lost will be recorded at the plant level instead of the process level, and the sums of all three will be recorded at the right-hand end of the SC Sus-VSM. To visually capture water usage, the SC Sus-VSM utilizes the same three-box icon that was developed for Sus-VSM (Faulkner and Badurdeen, 2014), as seen in Figure 4.3.

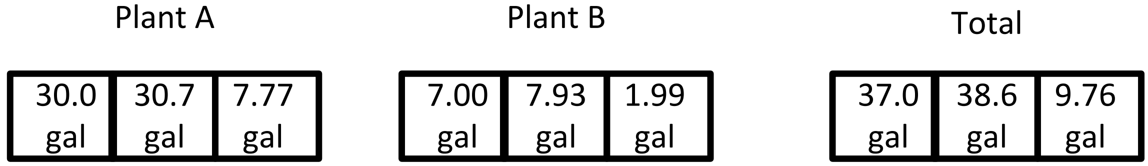

Figure 4.3: Example of Water Usage SC Sus-VSM Visual

4.1.3 Energy Consumption

Due to the use of non-renewable natural resources as well as production of GHG emissions, energy consumption is directly connected to environmental sustainability; it is also important from an economic standpoint. Measuring and visualizing the energy consumption allows areas of high consumption to be easily identified and more thoroughly investigated, thus focusing improvement efforts to the most beneficial areas.

The definitions of energy consumption for standard Sus-VSM can be easily used in SC Sus-VSM to adequately assess supply chain energy consumption. A major difference, however, is that the energy consumption due to transportation between plants will often be much larger than the consumption between processes. Thus, the transportation between processes within a plant will be presented collectively as a single measure of energy consumption for the plant. This value will be the sum of all the energy consumed by processes and for transportation between those processes but will not include lighting or environmental control, as these are not dependent on the product itself. Transportation between plants in the supply chain will be reported separately.

Despite the differences that will occur between Sus-VSM (Faulkner and Badurdeen, 2014) and SC Sus-VSM for the energy consumption metric, the visualization is almost identical, as shown in Figure 4.3. The energy consumed by the plant is measured and recorded within the circles while the transportation energy is recorded on the line between the circles.

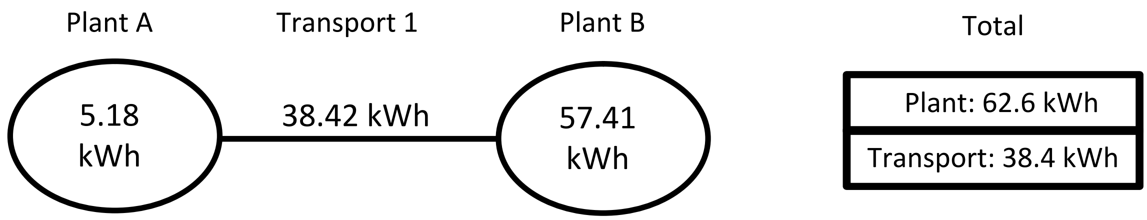

Figure 4.4: Example of Energy Consumption SC Sus-VSM Visual

4.1.4 GHG Emissions

With increasing regulations and public awareness of GHG emissions, there is a similarly growing need to develop a metric for Sus-VSM that can capture GHG emissions to evaluate environmental sustainability. By evaluating GHG emissions and making efforts to reduce those emissions, companies can be proactive in addressing changes that could potentially be regulated in the future.

The standard Sus-VSM (Faulkner and Badurdeen, 2014) does not have a metric to capture GHG emissions; while emissions from energy consumption can be calculated if the energy sources are known, direct GHG emissions from processes must be captured separately. For SC Sus-VSM, a metric to capture total GHG emissions from both direct and indirect sources would provide more information and increase visibility for potential improvements by providing a separate metric and visual in the SC Sus-VSM. Increased public awareness of GHG emissions and the potential to attract more customers with lower emissions give further reason to include this metric. Chen and Johnson (2011) present a method of evaluating GHG emissions using different scopes. Scope 1 considers only direct emissions, while Scope 2 additionally considers emissions from energy consumption. Scope 3 further includes emissions indirectly caused by company activities, such as waste disposal and employee commuting. For SC Sus-VSM, Scope 2 provides a detailed evaluation of GHG emissions, but does not require difficult data acquisition needed by further detail. Using Scope 2 has the additional benefit of further illustrating the direct connection between energy consumption and GHG emissions. It is proposed that this metric be measured in terms of mass of carbon dioxide generated directly from processes within the plant and from the energy consumed by those processes. GHG emissions generated by process energy consumption can be computed if the energy source and the amount of energy consumed are known. For example, if coal power plants are in the area, the GHG emissions can be calculated using the energy density and CO2 emissions of coal. The emissions from transportation between plants can be calculated using the amount of fuel combusted and the CO2 emissions per gallon of fuel.

GHG emissions will be visualized in a manner similar to that of energy consumption as shown in Figure 4.4. The emissions for each plant will be measured and recorded in the cloud icon while the emissions from transportation will be recorded on the line between cloud icons, as shown in Figure 4.5.

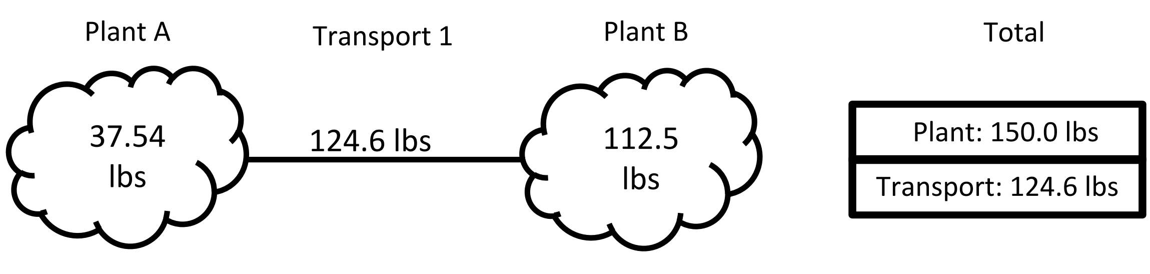

Figure 4.5: Example of GHG Emissions Supply Chain Sus-VSM Visual

4.2 Societal Metrics

To achieve true sustainability, it is not enough to consider only economic and environmental aspects. While standard Sus-VSM (Faulkner and Badurdeen, 2014) makes societal considerations for employees regarding health and safety, there are other stakeholders that deserve consideration when the supply chain is assessed; societal implications of business operations must also be considered. The local community surrounding the manufacturing plants and the customers who will be using the product are important stakeholders that should also be considered. For these reasons, a total of six societal metrics have been chosen to evaluate sustainability performance for supply chain Sus-VSM.

Selecting metrics that adequately capture the societal aspect of sustainability across the supply chain while still being measurable presents significant challenges. One of the challenges faced is identifying metrics that are relevant to all interested stakeholders, such as the employees, customers, local community, the company itself, and others. At the process level, only a few stakeholders are directly influenced, and relevant metrics can be identified easily. At the supply chain level, however, many more stakeholders are involved and metrics must be selected to evaluate impacts on as many stakeholders as possible. Another challenge faced is the availability and ease of gathering of data for selected metrics. Given the emphasis on a few stakeholders at the process level and because information relates only to internal operations, computing societal sustainability metrics for standard Sus-VSM is less difficult. At the supply chain level, however, there is a wider range of metrics, and data may need to be gathered from external partners, which is always difficult due to confidentiality reasons. For companies that exercise significant influence over suppliers, gathering data may be less difficult; for smaller companies that lack control over their supply chains, however, suppliers and downstream partners will be unwilling to share information. Metric selection can affect the difficulty of data acquisition, but cannot eliminate the problem; further, metric selection should foremost be based on relevancy to evaluating supply chain sustainability performance, so this problem should be addressed using other methods discussed later.

Another challenge encountered with societal metrics at the supply chain level is loss of relevancy, one of the main reasons some societal metrics were not retained from standard Sus-VSM. This is true for the work environment metric dealing with electrical, pressurized systems, and high-speed component hazards, but particularly with the Physical Load Index (PLI). The PLI uses questionnaires to assess the strain placed on employees while working, and is captured for each process in standard Sus-VSM. While it would be possible to aggregate a PLI score for the entire plant for supply chain Sus-VSM, it would be difficult to recognize if a problem were actually present. If a number of the processes in the plant have poor PLI scores, but a few have very good scores, examining the mean value of the scores will result in underestimating the problem. However, if the poorest PLI score is recorded for the plant, but there is only one process with a poor score, then the problem will be overestimated. The difficulty is similar for the other societal metrics from standard Sus-VSM. For these reasons, the societal metric selection needed to be reconsidered for the supply chain Sus-VSM, in order to select metrics that avoid these obstacles as best as possible.

4.2.1 Product Defect Ratio

While it is important to consider all the various societal stakeholders, it is equally important the metrics remain easy to use, visualize, and have collectable data, as SC Sus-VSM would otherwise become cumbersome. With these considerations in mind, the product defect ratio was selected to represent customer interest by providing an indicator of product quality, although other stakeholders are also interested in this metric. Data for this metric is already collected by most companies for their plants, and reflects the reliability of the product. Also, this metric does not lose any meaning at the plant level, as the number of defects can be summed for the whole plant. Identifying which processes within the plant have a high product defect ratio would require a more detailed examination of the plant individually.

A high product defect ratio indicates that the manufacturing process is not creating a reliable product, and since quality control is likely unable to identify all defective parts, there is a higher chance that the customer will receive a defective product. Not only does this create a bad reputation for the company, it can lead to expensive recalls of the product, and if a customer incurs injury from a defective product, costly lawsuits can result. Even if quality control can identify most of the defective parts, this results in rework and recycling, both of which can also be costly. Conversely, a low product defect ratio indicates that fewer parts will require rework or recycling, a good reputation will be built for the company, recalls of product will be less likely to occur, and lawsuits can be avoided. Given these benefits and the ability to be used at the supply chain level, product defect ratio is a useful metric to include in supply chain Sus-VSM.

This metric is visualized by a simple percentage shown within each plant box. This is easy to understand, and by not utilizing a larger icon, the SC Sus-VSM will remain uncluttered. If desired, the number of product defects in a certain time period can be recorded instead, such as the number of defects per work week.

4.2.2 Local Community Hiring Ratio

Accounting for effects on the local community is another consideration to promote sustainability, as abuse or neglect of the surrounding community will ultimately lead to an unsustainable method of production. The local community hiring ratio was selected as a metric since hiring information is readily available from human resources, and the metric highlights the number of jobs that are brought to the local community. Interestingly, this metric is one that would lose meaning at the process level more than the supply chain level, as knowing the local community hiring ratio for each process within the plant provides no more information than being capturing the metric for the plant as a whole. Hiring from the surrounding community fosters a positive relationship that will benefit both the company and the community, as the community will receive employment opportunities, and the company will build a good reputation and potentially gain loyal customers from the local community. This good reputation can later aid the company when seeking to expand, as other locations will be more amenable to the construction of a plant that will bring employment opportunities to the local community. This metric is shown on the SC Sus-VSM as a percentage within each plant box. It should be noted that each plant will be considering the community surrounding its own location.

4.2.3 Diversity Ratio

Similar to the local community hiring ratio, the diversity ratio takes into account the community, but in a broader sense than just the area surrounding the plant. The metric for diversity ratio captures the racial and gender diversity of the company's workforce. Again, the data for this metric should be readily available from the human resources division, and is captured as a ratio of minority employees to the total company workforce. This metric provides an indicator of how well the company is avoiding discrimination in hiring and shows a willingness to hire various members of society equally. By hiring a diverse workforce, the company can benefit from ideas and skills from numerous backgrounds and cultures. Further, having a diverse workforce builds rapport with society as a whole, providing the company with a greater and more loyal customer base. Given the demographics of certain areas, however, it may not be feasible for companies to achieve a high diversity ratio, as the local community may not be diverse, so balancing between with the local community hiring ratio and the diversity ratio may be required. Nevertheless, diversity is a criterion that still should be considered in order to promote societal sustainability. Similar to the product defect ratio and the local community hiring ratio, the diversity ratio is displayed as a percentage within the plant box on the SC Sus-VSM, being easy to understand and not causing clutter in the SC Sus-VSM.

4.2.4 Injury Rate Metric

As shown by the choice of metrics for standard Sus-VSM, employee well-being is an important aspect of societal sustainability that should be captured and evaluated, but metrics such as electrical hazards, high-pressure systems, etc. are too specific to be applied to supply chain Sus-VSM effectively. Instead, the injury rate metric is more easily measured and provides a general indication of where a more thorough investigation might be necessary to determine the cause of injuries. In addition, injury information at the plant level is readily available from human resources in the form of occupational health and safety records. Also, by tracking the injury rate at the plant, the company can hopefully avoid a great number of potential expenses. Whenever an injury occurs, the work flow of the plant is disrupted, causing delays and confusion. Also, injuries lead to employees being unable to return to work immediately, requiring replacement workers to be used, who may be less skilled. The company may also be responsible for paying the employees' medical bills related to treating the injury. Furthermore, if company manufacturing practices are found to be unsafe, there can be repercussions from regulating bodies as well as potential lawsuits from employees injured in an unsafe work environment. By monitoring the injury rate for each plant, companies can identify potential improvements to reduce the number of injuries, thereby reducing work disruptions, and showing employees that their welfare is one of the company's main concerns. As the other societal metrics, the injury rate is recorded within each plant box and displayed as the number of injuries in a given time period. This provides an easy to comprehend measure and does not clutter the SC Sus-VSM.

4.2.5 Hazardous Materials/Chemicals Metric

The hazardous materials metric was taken directly from standard Sus-VSM with few changes, as it is relevant and is easily assessed. As with the injury rate, this metric accounts for employee well-being as a societal aspect of sustainability. As with standard Sus-VSM, the hazardous materials metric is ranked based on likelihood of occurrence and level of impact, as seen in Table 3.1. Instead of this rating being assigned for each process, it is captured for each plant in the supply chain. If a plant is shown to have a high risk from hazardous materials, efforts can be made to improve safety regarding these materials, or possible substitutions can be explored to find a less hazardous material that still accomplishes the needed functions. A plant with a high hazardous materials risk may also be in violation of regulations concerning the use and disposal of hazardous materials and chemicals, so to avoid costly fines, it is highly necessary to monitor this metric.

Given that this metric is an assessment of the entire plant, a more thorough investigation might be required to identify exactly which processes are producing the hazardous material risk. Also, this metric is subjective in nature, given the way it is captured. More objective forms of this metric can also be used, but the data is more difficult to obtain, and the data collection process is more time consuming, reducing the speed with which the SC Sus-VSM can be applied. Once the hazardous material rating has been assigned, it is displayed in the plant box for each plant. This prevents clutter on the SC Sus-VSM, and once the rating method has been explained, is easy to understand.

4.2.6 Employee Training Intensity Metric

Similar to the local community hiring and diversity ratios, the employee training intensity is another way of capturing employee well-being. This metric is an indicator of how much training employees receive at the plant. By providing greater amounts of training to employees, a company is helping them develop skills that can be used to advance upwards within company, or can be used outside the workplace. Also, by providing training hours, the company can ensure that all employees meet a certain skill level for the tasks they need to perform. Further, by providing cross-training between different job positions in the plant, the company can make operations more resilient to employee call-offs or sick days, as there will be other employees available who can also perform the needed task. The data needed to capture the employee training intensity should be available from human resources, who will have a record of the number of training hours. Similar to the other societal metrics, the employee training intensity is recorded in the plant box for each plant. The metric is recorded as the number of training hours provided at the plant each week, which is easy for users to understand in the SC Sus-VSM.

PHASE 2: SC Sus-VSM Development

To build the SC Sus-VSM, it is necessary to incorporate the metric visuals for the supply chain. Each plant in the supply chain is visualized as a box, similar to the process boxes for standard Sus-VSM (Faulkner and Badurdeen, 2014), but containing different information. The defect ratio, injury rate, employee training intensity, local community hiring ratio, diversity ratio, and hazardous material/chemical rating are displayed within each plant box. In standard Sus-VSM, the amount of WIP is indicated using a triangle icon before each process in the production line, while in SC Sus-VSM the WIP for each plant is displayed using the same icon above the plant box. The amount of inventory waiting to be shipped is indicated above the transport icons using the same method. Transport between plants is visualized using an icon that represents the mode of transportation being used, such as a truck, plane, or boat, with the frequency of shipments and the travel time and distance displayed in the icon. Arrows indicate the direction of product flow through the supply chain.

Lead time, material usage, energy usage, water usage, and GHG emissions are all shown below the plant boxes and transport icons. For plants, the lead time line also captures the value-added time of the plant; the total plant lead time and the value-added time are displayed above and below the line, respectively. For transport icons, the travel time is displayed on the lead time line. On the right-hand end of the SC Sus-VSM, the total lead time and the total value-added time for the supply chain are displayed. Material usage, energy usage, water usage, and GHG emissions are displayed as discussed in the previous section, with the totals for each on the right-hand end of the SC Sus-VSM. Figure 4.6 shows an example of a developed current state SC Sus-VSM from one of the case study scenarios that will be addressed in Chapter V.

The SC Sus-VSM in Figure 4.6 shows the product flow from the feeder plants to the OEM and captures the selected metrics for each plant and transportation, with the metric totals for the supply chain displayed on the right-hand of the SC Sus-VSM. The SC Sus-VSM can be used to quickly visualize a supply chain and identify locations for potential sustainability improvements based on the metric values visualized in the map. For example, reading the SC Sus-VSM in Figure 4.6 shows that for a total lead time of

439.9 days, WIP at the drive train plant accounts for 231 days, indicating that further investigation of the drive train plant is needed. Similarly, the OEM accounts for more than half of the energy consumption from the plants, indicating energy conservation efforts should be focused on the OEM. After identifying locations that require further investigation, standard Sus-VSM can be used at the target plant for a more detailed examination that can pinpoint the factors causing a problem. A more detailed look can also be obtained by developing a simulation model for the SC Sus-VSM as discussed in Phase 3.

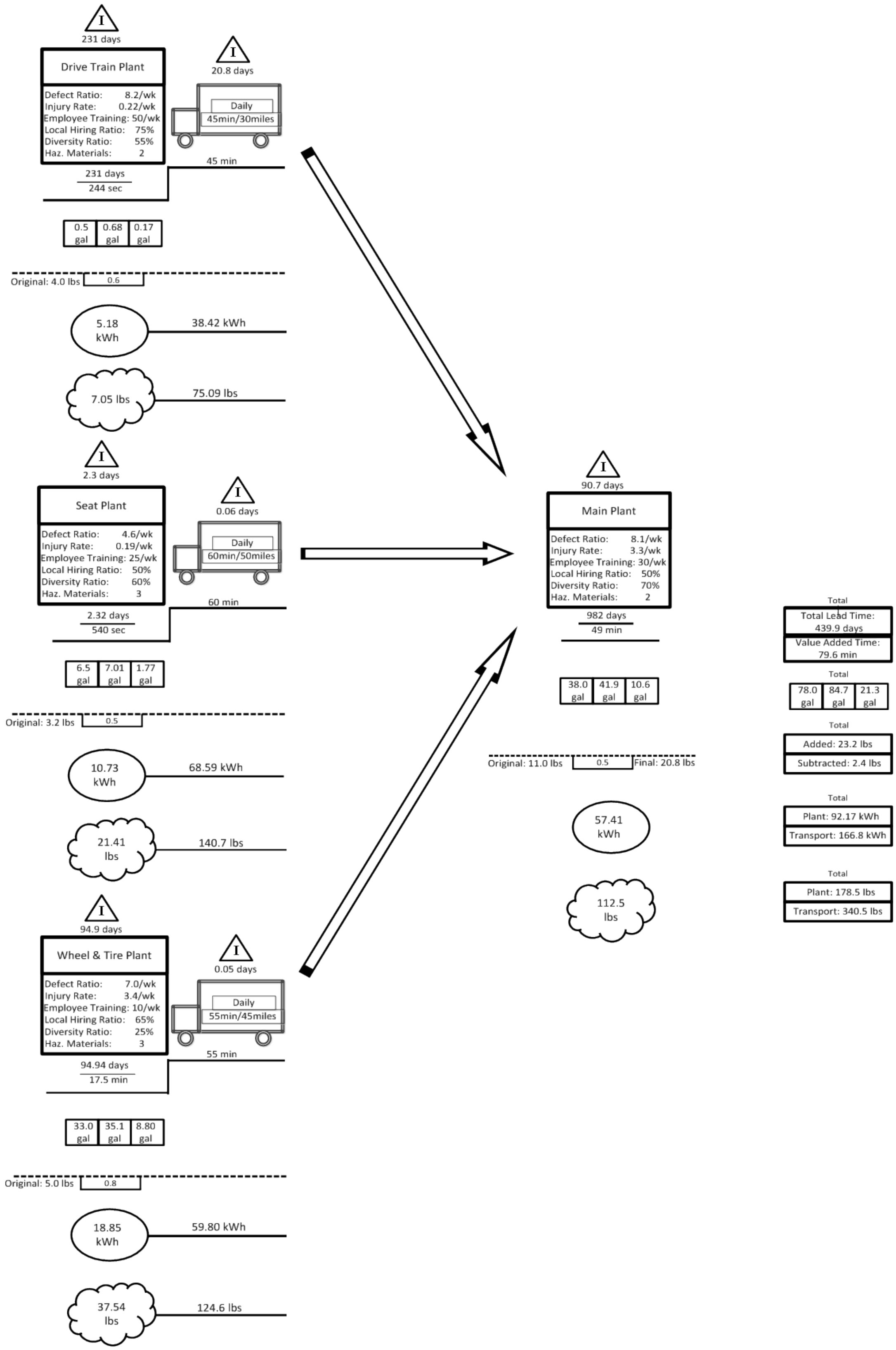

Figure 4.6: Example Current State SC Sus-VSM from Case Study

PHASE 3: Simulation Model Development

After the current state SC Sus-VSM has been created and areas have been targeted for kaizen improvement efforts, a simulation model can be used to simulate the proposed improvements and create a future state SC Sus-VSM. Simulating the future state maps eliminates some of the estimating and guesswork involved, as the simulation will capture any effects that a change in one branch will have on other locations in the supply chain. This allows multiple future state maps to be created and evaluated, and allows a company to move forward with the best improvements without investing excessive amounts of time or resources. Also, in a scenario where data is difficult to obtain for some locations in the supply chain, an estimate of the information can be used with the simulation model to help provide more accurate results for the sustainability assessment.

Using Rockwell's Arena simulation software, a discrete event simulation (DES) model was developed to simulate the metrics used in SC Sus-VSM. To model the supply chain, each plant is built as a sub-model containing various components. With the sub-model, each manufacturing process within the plant is modeled as a seize-delay-release process box, where the product entities are taken, delayed, and then allowed to continue on after waiting for the appropriate cycle time. In front of each process box is an assign box, where the variables for the process are defined. Immediately after the process box is the record sub-model, which contains a record box for each variable that was defined for that process. After the record sub-model is a decision node that acts as quality control by using the product defect ratio. If the product is found to be defective, the decision node will dispose of the defective product. After the decision node, the entity moves on to the next process within the plant. After the last plant process, the entity continues to transport. Transport is modeled as a sub-model that contains a seize-delay-release process box that delays the entity for the amount of time equal to the travel time. Before that process box, however, is a batch node, that groups entities together by the number of entities that is defined for each batch. This batch size is equal to the capacity of the transport vehicle. Between the batch node and the process box is an assign box to define the variables. Directly after the process box is a record sub-model that serves the same function as in the plant. After the transport record sub-model, the product batch moved is ungrouped into individual entities that move on to the next plant sub-model to continue processing. Plant and transports continue to be modeled in this way until the last plant, where entities leave and go to shipment, which is modeled as a dispose box.

Once the general layout for the simulation model has been created, it is necessary to define the metric variables carefully; otherwise, the model will not behave as desired and the metrics will not be captured accurately. The cycle time variables are based on the process they are defined for and are the most basic variable defined in the simulation model. Most of the other variables in the model are defined so that they are based on the cycle time variables. For example, the definition for the energy usage metric contains the process cycle time in the expression, so that if the cycle time increases, the energy usage will also increase. Similarly, the GHG emissions metric variable is based on the energy usage variable. Due to the nature of the simulation model, it is necessary to introduce a degree of randomness to the variables to more closely mirror a real life scenario. Firstly, this can be done at the basic level by defining the cycle times using mathematical distributions; exponential distributions can be used for process cycle times where the rate of production is fairly constant, while triangular distributions can be used for modeling processes with a minimum time, a mode time, and a maximum time (Kelton et al., 2009). This will provide some randomness to the cycle time and all the metrics based on it, but those metrics should also be more directly randomized. Once the initial distribution is selected to represent the part of the model in question, this initial distribution can be multiplied by a second distribution that has a mean of 1. This will allow the average of the initial distribution to remain relatively unchanged while still introducing another level of randomness. This degree of randomness within the model helps to simulate the variability that would occur in real life scenarios from delays and other factors, resulting in a more accurate simulation model.

To capture the product defect ratio and the injury rate, a counter was used to determine how many product defects and worker injuries occurred. This means that the variables for these two metrics need to be defined differently than the rest of the metric variables. This can be accomplished using a probability distribution that assigns a value of 0 or 1 based on the probability, with 0 indicating no defect and 1 indicating a defect has occurred. For example, to model a 10% defect rate, the probability distribution would be defined so that 10% of entities that pass through the process will be assigned a value of 1, indicating that a defect has occurred. Following this, the counter will track how many defects or injuries occurred during the simulation, which can then be translated into the number of defects or injuries per week.

The simulation model also contained visual gauges to capture the running average of the metric values for each process in real time. It should be noted, that not all metrics chosen for the supply chain Sus-VSM can be simulated in the DES model, as some of the metrics would require "forcing" the metric into the simulation in such a way that the result would be meaningless. For example, simulating the diversity or local community hiring ratios would not provide an additional benefit, as the variables to capture the changes in these metrics are not easy to incorporate into a DES model. The economic metrics and all the environmental metrics with the exception of raw material usage can be easily captured by the simulation. Of the societal metrics, product defect ratio, injury rate, and employee training intensity can be captured in the simulation.

PHASE 4: Case Study Analysis

In order to gain meaningful information from the DES model, it is necessary to analyze the results. A useful way of accomplishing this is to create a sustainability index that produces a normalized score for each metric. Using aggregation and weighting techniques, it is possible to eventually reach a single score that ranks the overall sustainability of the supply chain being considered. This sustainability index score can then be entered into a DOE style analysis to obtain information regarding the sensitivity of the supply chain to changes and interventions that are applied in an effort to improve the sustainability of the supply chain.

In order to normalize the data, it is necessary to have a benchmark simulation scenario that can be used to determine the score of the other scenarios that will be considered. For SC Sus-VSM, the current state scenario lends itself to being used as the benchmark for the normalization methodology. Once the metrics for a scenario have been normalized, they will all fall on a scale from 0 to 10, with the metrics from the benchmark scenario having a value of 5. The metrics from the other scenarios considered will be normalized using equation 4.1.

$$\overline{metric\ value} = 5 * \left(1 \pm \frac{metric\ value - benchmark\ value}{bench\ mark\ value}\right) \tag{4.1}$$

Within the parenthesis of this equation, addition is used if an increase in metric value has a positive effect on the supply chain sustainability, and subtraction is used if a decrease in metric value is an improvement.

The next analytical step was to create economic, environmental, and societal sub-indices. The scores for these sub-indices were determined by weighting and aggregating the normalized metric values based on importance. Ranking metrics based on importance is subjective in nature and will vary from application to application. As noted by Shuaib et al. (2014), there is no universal or standard weighting method for sustainability metrics, so the process will inherently be subjective. While expert opinions would also be subjective, they would provide a level of guidance for weighting of sustainability metrics and perhaps lead to a more standard weighting method. An equal weighting can also be used to provide a simpler method where it is clear what is occurring, but it does not accurately reflect the importance of metrics to each other.

Once the economic, environmental, and societal sub-indices have been created, the aggregation and weighting step must be repeated to create the overall sustainability index. Again, measures can be taken to reduce the subjectivity of the weighting at this step, but depending on what actions were taken in the previous step, this may not be as important. If the metrics in the previous step were weighted by importance, then equal weighting of the economic, environmental, and societal sub-indices should still provide accurate results. If equal weighting was used in the previous step, then more objective weighting of the sub-indices can help produce a more accurate overall sustainability index.

Once the sustainability index has been determined, a DOE style analysis can be performed by placing the sustainability index results from each scenario into a test matrix. The test matrix for the case study performed in this thesis can be found in Table 5.6. It should be noted that more than one replication must be performed for each scenario being considered, but this is easily accomplished using the simulation model. The DOE test matrix consists of various treatments that consider all the interventions and their combinations. For example, if three interventions are considered, one each for economic, environmental, and societal, there will be a total of 8 possible treatments: no interventions implemented (1), the interventions considered individually (3), the interactions between pairs of interventions (3), and all three interventions together (1). A plus-sign in the test matrix indicates that an intervention is being considered for that treatment, while a minus-sign indicates the opposite. For interactions, however, the plus-sign is determined by multiplying the sign's of the interventions that make up that interaction. For example, consider interventions A and B: if intervention A or B is considered individually, then interaction AB will have a minus-sign; if neither A or B is considered or if both are considered together, then interaction AB will have a plus-sign.

After the sustainability index scores have been entered into the DOE test matrix, a number of calculations must be performed to determine the significant interventions and the sensitivity of the sustainability index to those interventions. First, the sample variance for the treatment, S_{TR} was calculated using Equation 4.2 (Montgomery, 2005), where *n* is the number of replications, y_i is the response for replication *i*, and $\bar{y}$ is the average response for the replications.

$$S_{TR}^2 = \frac{1}{n-1}\sum_{i=1}^{n}(y_i - \bar{y})^2 \tag{4.2}$$

The standard deviation and the effective standard deviation were then calculated using Equation 4.3 and Equation 4.4 (Kenney, 1962), respectively. *TR* represents the number of treatments in the test matrix.

$$S_e = \sqrt{\frac{\sum S_{TR}^2}{TR}} \tag{4.3}$$

$$\sigma_{eff} = S_e\sqrt{\frac{4}{TR \cdot n}} \tag{4.4}$$

The number of degrees of freedom for the case study was then determined using Equation 4.5 (Stattrek, 2014).

$$DF = TR \cdot (n-1) \tag{4.5}$$

Once the number of degrees of freedom has been calculated, it is used with a standard *t*-table distribution to determine the *t*-value. In addition to the degrees of freedom, a confidence interval must also be selected, with a 95% confidence interval being a common standard. After the *t*-value is determined, it is used to calculate the decision limit that will be necessary to determine which interventions are significant. Equation 4.6 provides a sample of the calculation used for the decision limit.

$$DL = \left| t'_{(0.025,DF)} \cdot \sigma_{eff} \right| \tag{4.6}$$

To determine which interventions had a significant effect on the sustainability index, it is necessary to calculate the absolute effectiveness using Equation 4.7.

$$|E| = |\bar{y}^{+} - \bar{y}^{-}| \tag{4.7}$$

In this equation, y^+ represents the response values for which intervention y has been made, represented by a "+" in the test matrix. As an example, for the economic intervention, the y^+ values come from the economic, economic-environmental, and economic-societal treatments. Similar reasoning is used for y^-.

After determining the absolute effectiveness for each intervention and the decision limit, a Pareto chart can be built to show which interventions are significant. If a intervention falls above the decision limit, it is a significant intervention, but if it falls below, it cannot be distinguished statistically from noise in the experiment, so that intervention is considered insignificant. Once the significant interventions have been determined, response plots can be created for each to provide information on the sensitivity of the supply chain sustainability. Response plots are created by linearly plotting $\bar{y}^{-}$ and $\bar{y}^{+}$ for each intervention. For intervention pairs, one intervention is held constant at each value while the other intervention is plotted for those values, resulting in two lines on each intervention pair response plot. The same method is used for a triple interaction between three interventions, resulting in a total of four lines on the response plot.

When implementing a DOE style analysis for SC Sus-VSM and the DES model, difficulties with factor variability are present. In a typical DOE analysis, certain factors are changed for each treatment while the remaining factors are held constant. Due to the variability present in a supply chain, it is not possible to hold the factors completely constant. As discussed by Montevechi et al. (2012), simulation can be used to eliminate this randomness by holding each factor constant as needed. However, this approach results in the simulation model representing the real world less closely. For this thesis, an approach of capturing average values for cycle times, water usage, etc., is used to combat the amount of randomness present. This approach, however, produces an increased amount of experimental noise in the results of the DOE style analysis.

Following the methodology outlined in this section, the application of SC Sus-VSM combined with simulation to a supply chain should be straightforward. The SC Sus-VSM can be developed using pencil and paper following the part of the methodology for metric selection and visual development. Implementing the DES model provides a number of improvements to the process by allowing different scenarios to be considered quickly, and allowing possible gaps in data to be estimated and simulated, providing more accurate results. By analyzing the results in the method described, much useful information can be determined, such as which intervention provides the greatest increase to the sustainability of the supply chain and how sensitive the supply chain is to the each intervention. Overall, this methodology provides a useful tool for assessing the sustainability of a manufacturing supply chain.

CHAPTER V

Case Study

5.1 Case Study Parameters

To demonstrate the methodology developed for SC Sus-VSM, a hypothetical, single-tier bicycle supply chain was considered. Figure 5.1 illustrates which components of the bicycle are included in this case study and which components were considered but not included. The dotted lines indicate that the brakes and handlebars were not included in this case study.

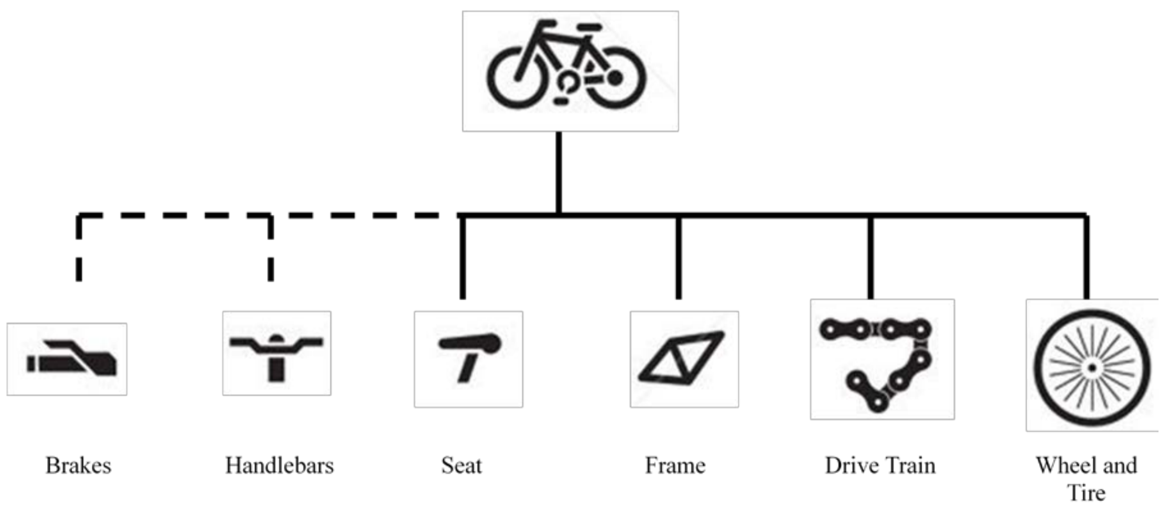

Figure 5.1: Bicycle components being considered and omitted for case study (based on image from Shutterstock, 2014)

The supply chain consists of a single plant which houses the frame manufacture and final assembly with three feeder plants supplying the drive train, the seat, and the wheel and tires, as shown in the supply chain map in Figure 5.2. Transportation between plants is accomplished via truck shipments. Although the entire bicycle could conceivably be manufactured in a single plant, additional plants were included to thoroughly test and evaluate the methodology presented in Chapter IV. Additionally, the feeder plants can be owned by different suppliers, and are not necessarily owned by the main manufacturer or original equipment manufacturer (OEM).

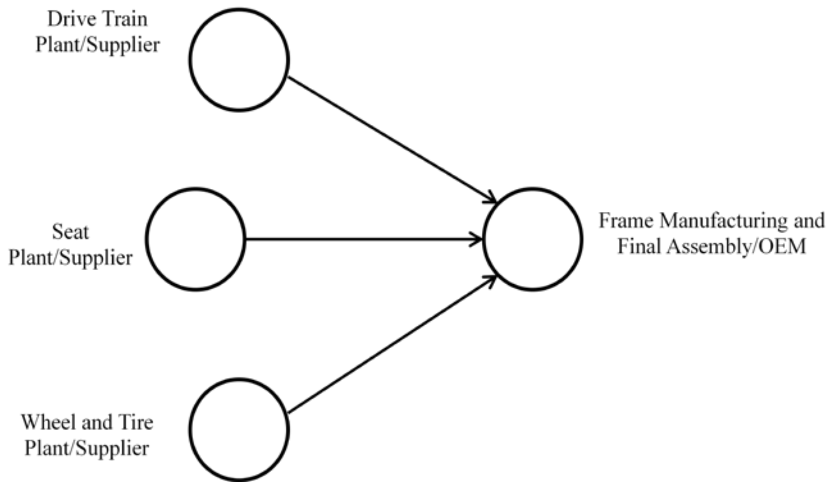

Figure 5.2: Bicycle Supply Chain Map

The process cycle times and the travels times used for the case study are presented in Table 5.1, which also provides the times used in the various scenarios considered with the simulation model in section 5.3. These times are based on knowledge of the equipment used in each process and estimated from the travel distance and speed.

Table 5.1: Process Cycle Times for Case Study Scenarios

Simulation Process Boxes		Current State Cycle Times		Economic Cycle Times		Environmental Cycle Times		Societal Cycle Times	
Drive Train Plant	Press	82	s	82	s	82	s	82	s
	Chain Assembly	162	s	110	s	162	s	162	s
	Transport 1	45	min	45	min	45	min	45	min
Frame Manufacture	Tube Drawing	600	s	300	s	600	s	600	s
	Frame Assembly	600	s	450	s	600	s	600	s
	Painting	600	s	600	s	700	s	600	s
Seat Plant	Seat Frame	300	s	300	s	300	s	300	s
	Fabric and Padding	240	s	240	s	240	s	240	s
	Transport 2	60	min	60	min	60	min	60	min
Seat Installation	Frame and Seat Assembly	120	s	120	s	120	s	120	s
	Decal Application	300	s	300	s	300	s	300	s
Wheel and Tire Plant	Tire Manufacture	180	s	180	s	180	s	180	s
	Manufacture	600	s	600	s	600	s	600	s
	Assembly	180	s	180	s	180	s	180	s
	Wheel and Tire Assembly	90	s	90	s	90	s	90	s
	Transport 3	55	min	55	min	55	min	55	min
Drive Train and Wheel Install	Drive Train Installation	480	s	480	s	480	s	480	s
	Wheel Installation	240	s	240	s	240	s	240	s

Tables 5.2 - 5.7 present the energy usage, water usage, raw material usage, and GHG emissions for each process and transport in the supply chain. These parameters are based on general knowledge of the processes with a focus on parameters being correct relative to each other, i.e. a painting oven consumes more energy than seat installation. For this case study, it is assumed that the main power source for the plants is coal, and the shipping trucks use diesel engines, therefore the energy usage and GHG emissions are based on the energy density and CO_2 emissions for these fuel types, which are shown in

Table 5.8. The capacity for Transport 1 is 10 units, while the capacity for Transports 2 and 3 is 20 units.

Table 5.2: Drive Train Plant Parameters

Drive Train Plant			
	Press	Chain Assembly	Transport 1
Energy	2.28 kWh	3.15 kWh	37.5 kWh
Water Used	0.68 gal	0 gal	0 gal
Water Lost	0.17 gal	0 gal	0 gal
GHG	4.56 lbs	2.7 lbs	75.0 lbs
Raw Material	-0.6 lbs	0.0 lbs	0.0 lbs
Injury	0.01%	0%	0%
PDR	0.50%	0%	0%

Table 5.3: Frame Manufacture Line Parameters within OEM

Frame Manufacture Line			
	Tube Drawing	Frame Assembly	Painting
Energy	13.33 kWh	10.0 kWh	16.67 kWh
Water Used	3.0 gal	0 gal	30.0 gal
Water Lost	0.75 gal	0 gal	7.5 gal
GHG	26.67 lbs	20.0 lbs	33.33 lbs
Raw Material	-0.8 lbs	0.2 lbs	0.0 lbs
Injury	0%	0.50%	0%
PDR	0.50%	0.50%	0.50%

Table 5.4: Seat Plant Parameters

Seat Plant			
	Seat Frame	Fabric and Padding	Transport 2
Energy	6.67 kWh	4.0 kWh	70.0 kWh
Water Used	5.0 gal	2 gal	0 gal
Water Lost	1.25 gal	0.5 gal	0 gal
GHG	13.33 lbs	8.0 lbs	140.0 lbs
Raw Material	-1.2 lbs	0.7 lbs	0.0 lbs
Injury	0%	0.05%	0%
PDR	0.50%	0.50%	0%

Table 5.5: Seat Installation Line Parameters within OEM

Seat Installation Line		
	Frame and Seat Assembly	Decal Application
Energy	1.0 kWh	5.0 kWh
Water Used	0 gal	7.5 gal
Water Lost	0 gal	1.88 gal
GHG	2.0 lbs	10.0 lbs
Raw Material	0.0 lbs	0.0 lbs
Injury	0.05%	0%
PDR	0.50%	0.50%

Table 5.6: Wheel and Tire Plant Parameters

Wheel and Tire Plant					
	Tire Manufacture	Wheel Manufacture	Wheel Assembly	Wheel and Tire Assembly	Transport 3
Energy	5.0 kWh	11.67 kWh	1.25 kWh	0.75 kWh	59.58 kWh
Water Used	10.0 gal	20.0 gal	0 gal	0 gal	0 gal
Water Lost	2.5 gal	5.0 gal	0 gal	0 gal	0 gal
GHG	6.67 lbs	23.33 lbs	2.5 lbs	1.5 lbs	119.2 lbs
Raw Material	0.4 lbs	-1.3 lbs	0.0 lbs	0.1 lbs	0.0 lbs
Injury	0.10%	0%	0.50%	0.50%	0%
PDR	0.50%	0.50%	0.50%	0.50%	0%

Table 5.7: Drive Train and Wheel Installation Line Parameters within OEM

Drive Train and Wheel Installation Line		
	Drive Train Installation	Wheel Installation
Energy	6.0 kWh	3.33 kWh
Water Used	0 gal	0 gal
Water Lost	0 gal	0 gal
GHG	12.0 lbs	6.67 lbs
Raw Material	0.0 lbs	0.0 lbs
Injury	0.50%	0.50%
PDR	0.50%	0.50%

Table 5.8: Diesel and Coal Energy Density and CO2 Emissions

Diesel	Energy Density		CO2 Emissions	
	135.8	MJ/gal	22.2	lbs/gal
Coal	Energy Density		CO2 Emissions	
	-		0.489	lbs/MJ

5.2 SC Sus-VSM for Case Study

Using the case study parameters, the current state SC Sus-VSM was developed as previously shown in Figure 4.6. The map shows the flow of the product through the supply chain, and highlights numerous locations where further investigation might provide details for improving the sustainability performance of the supply chain. Comparing the total lead time with the plant lead times and inventories highlights potential bottlenecks in the supply chain; for example, the drive train plant has 231 days of inventory, accounting for more than half the total lead time. Similarly, the energy usage at the OEM accounts for approximately 62% of the energy usage from plants in the supply chain. For metrics that are not totaled on the right-hand end of the SC Sus-VSM, comparisons between plants can illuminate potential problem areas, such as a diversity ratio of 25% at the wheel and tire plant compared to 70% at the OEM. Once the SC Sus-VSM is built, problem identification of this nature is straightforward and quickly performed, showing the effectiveness of the metrics and visuals developed for the SC Sus-VSM. After identifying these problems and implementing improvements, another SC Sus-VSM would be created and the methodology performed iteratively, promoting continuous sustainability improvement in the supply chain.

Due to the simplicity of the hypothetical supply chain considered, applying SC Sus-VSM was straightforward and presented few difficulties. A potential challenge that could be encountered when applying SC Sus-VSM, however, is effectively mapping a complex supply chain with numerous branches. For this case study, a OEM with three feeder plants was considered and presented little difficulty, but mapping additional feeder plants would negatively impact the legibility and usefulness of the SC Sus-VSM, as the map would be cluttered and difficult to follow. Methods of overcoming this challenge might include consolidating plants to reduce the number of branches or excluding minor feeder plants.

5.3 Case Study Simulation Model

The case study bicycle supply chain was modeled as three feeder plants flowing to the OEM where the frame manufacture and final assembly take place, as shown in Figure 5.3. The drive train, seat, and the wheels and tires are manufactured in the three feeder plants and shipped to the OEM via truck. Each plant in the supply chain is simulated using a sub-model containing the basic manufacturing processes with the running averages of the energy usage, water usage, and GHG emissions per entity displayed below each plant in the supply chain model. The feeder plant simulation sub-models are shown in Figures 5.4 - 5.6, where more details are discussed.

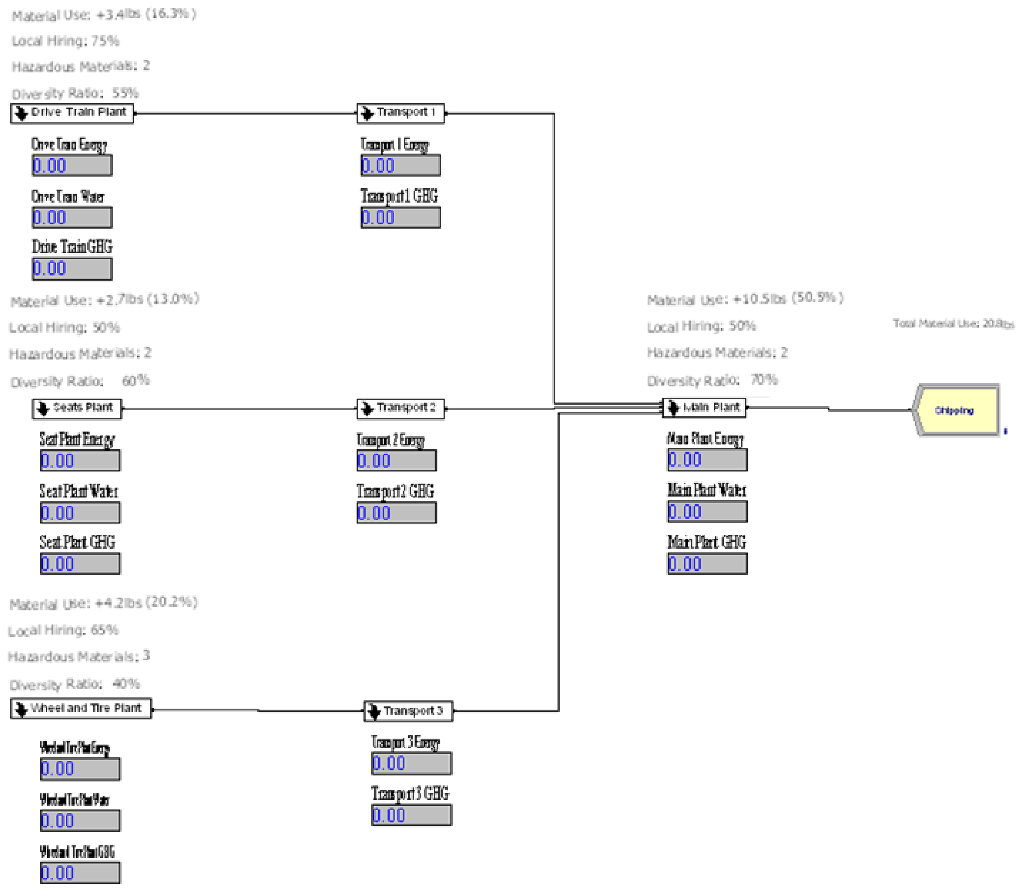

Figure 5.3: Simulation Model of Case Study Supply Chain

Figure 5.4 shows the simulation sub-model for the drive train manufacturing plant, where links for the chain are punched using a press, and then linked together to form the chain. The sub-model first creates the entity for the drive train which then undergoes the punch press process, after which the metric values are recorded for the entity in the record sub-model, which is discussed later in this section. After recording metric values, the entity passes through a decision box where defective parts are identified and disposed. The parts are next assigned a number to facilitate part matching for final assembly at the OEM. Parts are then routed through the chain assembly process, metrics are recorded, and completed drive trains move to the Transport 1 sub-model.

Due to software limitations, a single entity for the punch press does not represent a single chain link, but represents the number of links necessary to create a single chain.

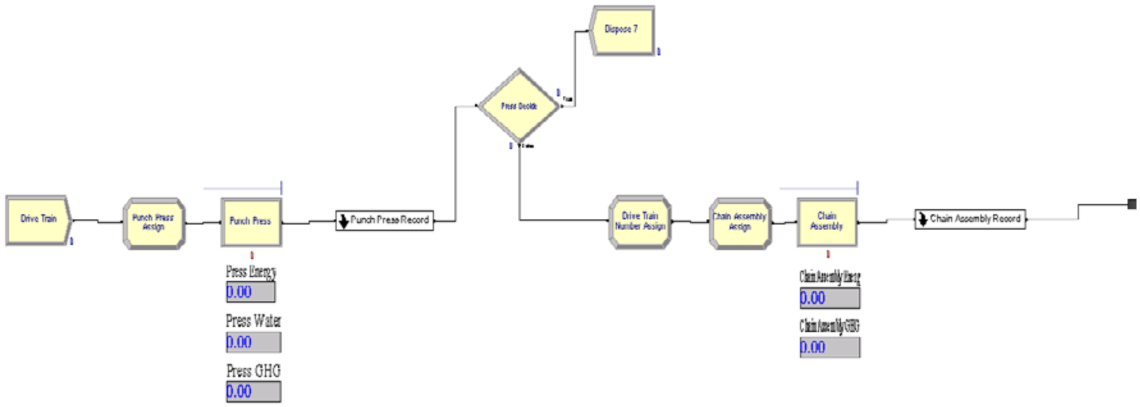

Figure 5.4: Drive Train Feeder Plant Simulation Sub-Model

Figure 5.5 details the simulation sub-model where the bicycle seats are manufactured. The seat entities are created and assigned a number for part matching during final assembly before undergoing the seat frame manufacturing process. The entities continue through a decision box to remove defective parts and are then routed through the fabric and padding process to complete the bicycle seat. Defective seats are the disposed using another decision box before moving to the Transport 2 sub-model.

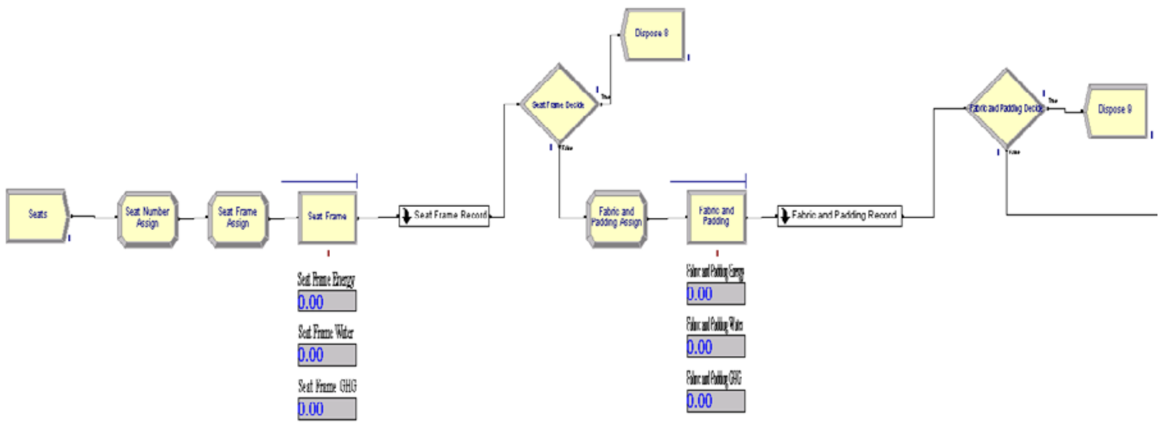

Figure 5.5: Seat Feeder Plant Simulation Sub-Model

The wheel and tire manufacturing plant sub-model is more complex than the other feeder plants, as shown in Figure 5.6. In the top branch, the tire entities are created and assigned a number to be matched with wheel entities later in the plant, and then sent through the tire manufacture process. After metric values are recorded, defective tires are disposed using the decision box while correct tires are sent to the match box to be paired with wheels. In the other branch, the wheel entities are created also assigned a number for matching before going through the manufacturing process for the hub, rim, and spokes. Defective parts are disposed while correct parts continue to the wheel assembly process after which defective wheels are again disposed before flow continues to the match box. Once a tire and wheel have been matched, they are permanently batched together and assigned a new number for matching during the final assembly before undergoing the wheel and tire assembly process. Finally, defective assemblies are discarded while correct wheel and tire assemblies continue to the Transport 3 sub-model.

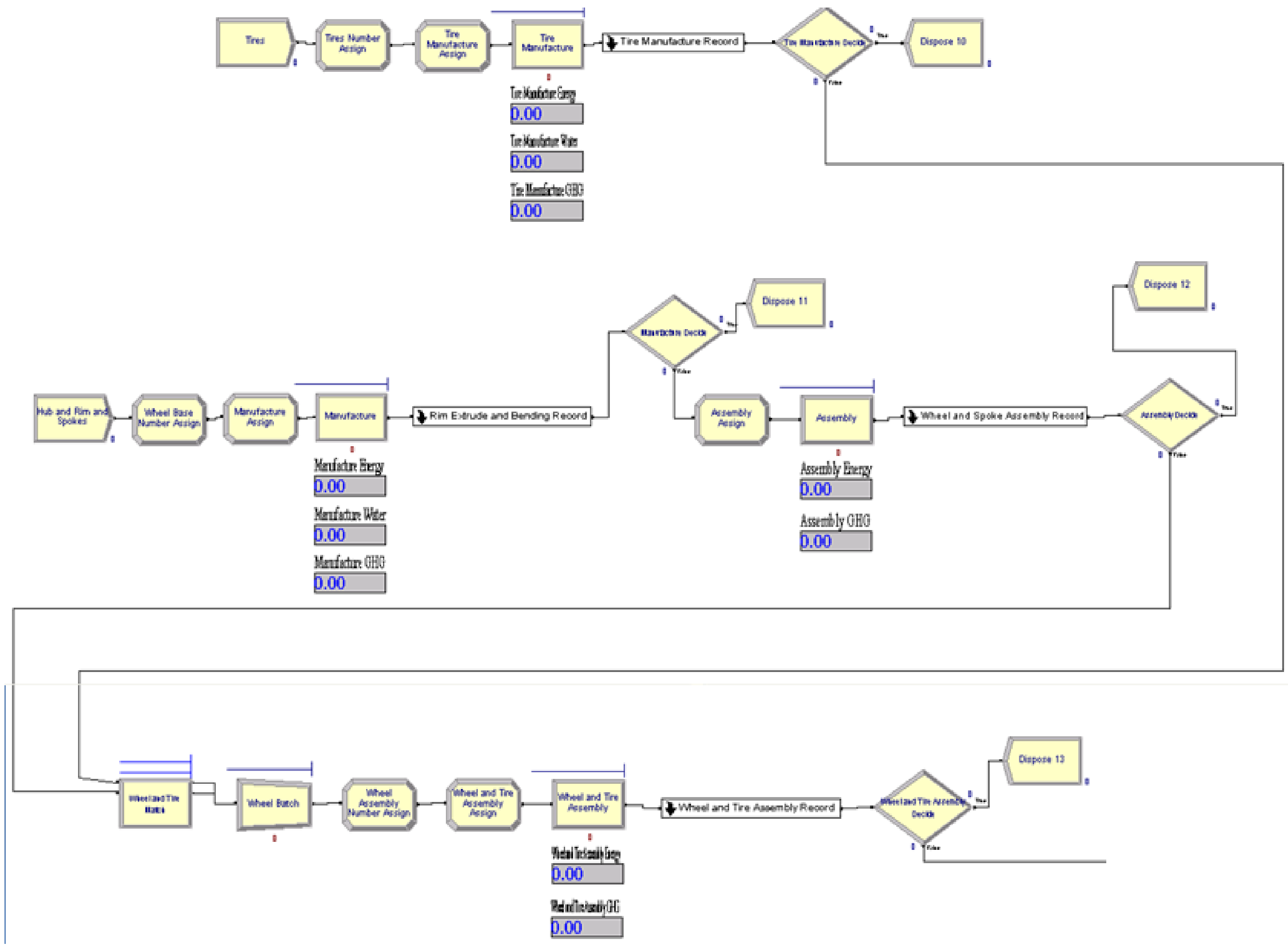

Figure 5.6: Wheel and Tire Feeder Plant Simulation Sub-Model

Due to the large number of processes, the simulation model for the OEM was divided into three sub-models as shown in the simple map in Figure 5.7. The first sub-model contains the processes for manufacturing the bicycle frame, followed by the sub-model where the frame and seat are assembled together. The final sub-model contains the drive train and wheel installation to finish the final bicycle assembly before leaving the OEM for shipment. In Figure 5.8, a screenshot of the simulation model for the OEM is presented, while Figures 5.9 - 5.11 detail the three sub-models within the OEM.

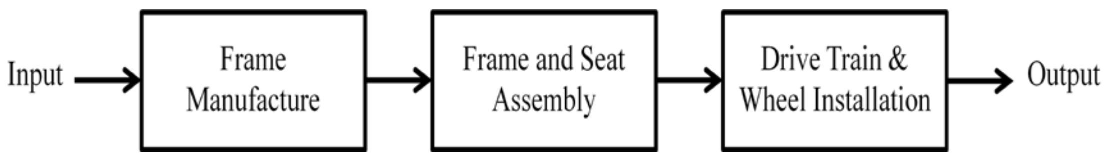

Figure 5.7: OEM Sub-model map

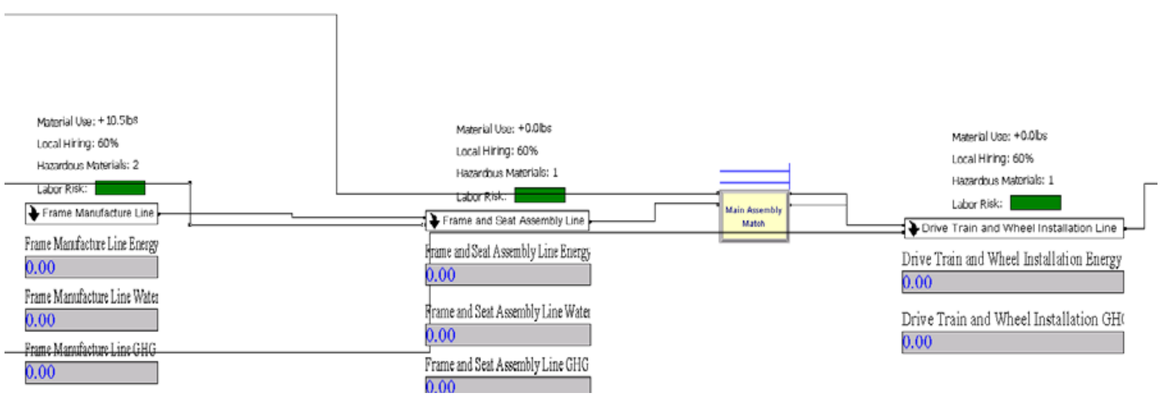

Figure 5.8: OEM Simulation Sub-Model

Figure 5.9 presents the frame manufacture sub-model within the OEM. The sub-model first creates the frame entity and assigns a number for matching during final assembly before continuing to the tube drawing process, after which defective tubes are disposed. The parts continue to the frame assembly process where the tubes are welded together to create the bicycle frame, after which defective frames are removed and the correct frames are sent to the painting process, where the frames are painted and then dried in an oven. Finally, frames with defective painting are discarded and the usable frames continue to the seat and frame assembly sub-model.

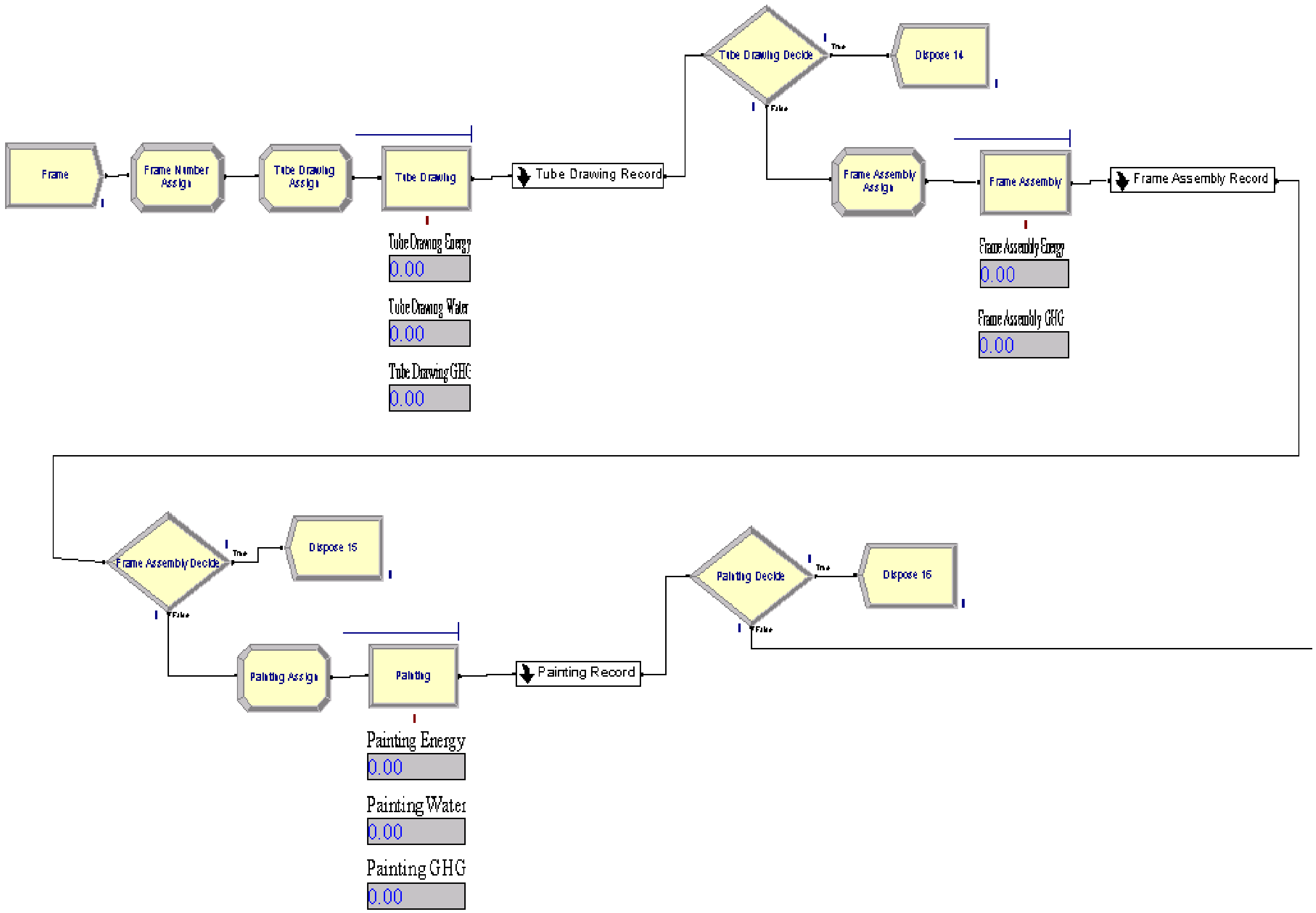

Figure 5.9: Frame Manufacture Sub-model in OEM

Figure 5.10 details the frame and seat assembly sub-model in the OEM, which starts by matching and batching frames from earlier in the OEM with seats that have been transported from the seat manufacturing plant. After being paired together, numbers are assigned for matching with drive trains and wheels later in the plant, and then sent through the frame and seat assembly process. This sub-model also contains the decal application process, where decals are applied to the frame of the bicycle, after which defective assemblies are discarded and proper assemblies continue to the drive train and wheel installation sub-model.

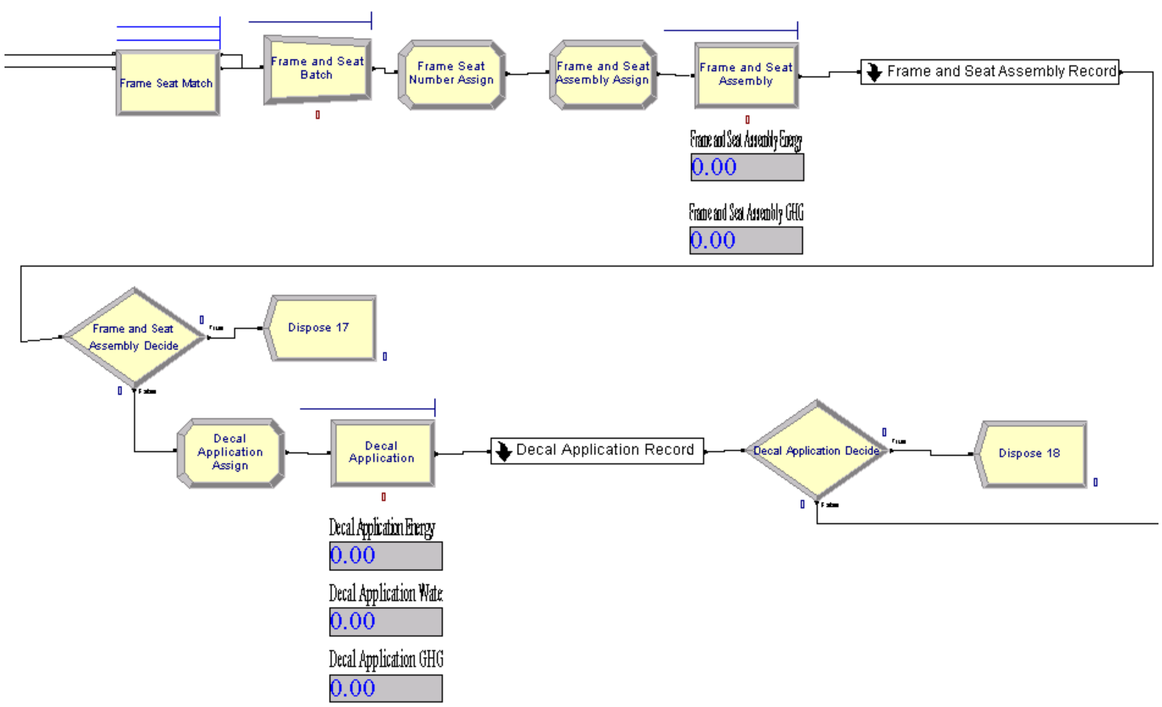

Figure 5.10: Frame and Seat Assembly Sub-model in OEM

The drive train and wheel installation sub-model is shown in Figure 5.11, starting with matching frames from earlier in the OEM with drive trains from the feeder plant.

The match process box is shown in Figure 5.8 in an effort to reduce confusion with process connector lines. After being matched and assigned a new number for later assembly, the parts continue through the drive train installation process and the defective assemblies are disposed. These assemblies are then matched and batched with wheel and tire assemblies from the feeder plant and sent through the wheel installation process, completing the bicycle assembly. Defective products are disposed, and usable bicycles are shipped to the customer.

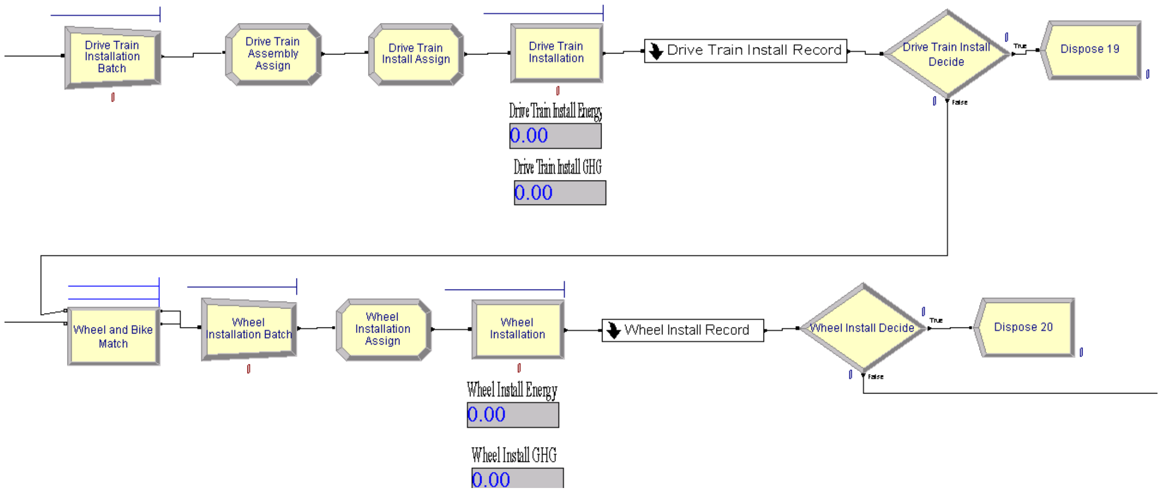

Figure 5.11: Drive Train and Wheel Installation Sub-model in OEM

Figure 5.12 details the Transport 1 sub-model which is identical to the other two transport sub-models. Parts from the feeder plants enter the sub-model and are batched together based on the capacity of the transport being used. The batches continue through the transport process box modeled as a seize-delay-release box, before being separated into individual units again. The individual units then continue to the OEM for final assembly.

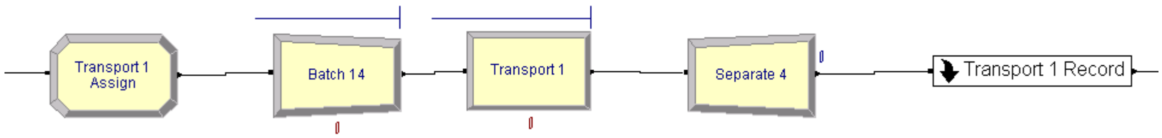

Figure 5.12: Example Transport Simulation Sub-Model

Figure 5.13 shows the punch press record sub-model as an example of how the metric values are recorded in the simulation. Each record box corresponds to a variable assigned to each entity for the process to capture the sustainability metrics. To capture the number of injuries and product defects, each entity is assigned a value of 0 or 1 based on whether an injury or defect occurs. The record boxes for these metrics count the total number of injuries and defects, which allows the injury rate and product defect ratio to be calculated.

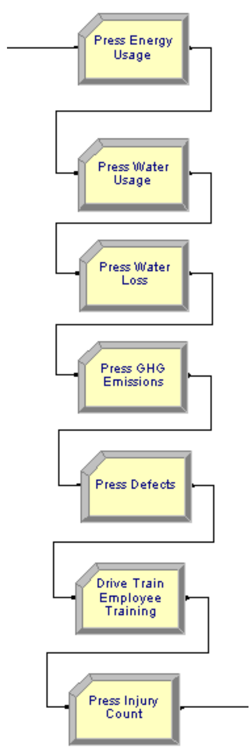

Figure 5.13: Sample Record Simulation Sub-Model from Case Study

Figures 5.3 - 5.13 illustrate the overall layout of the simulation model for the bicycle supply chain. In the model, defective products are disposed, but would likely undergo rework or recycling and enter the value stream again, but the simulation model does not capture this rework.

The simulation model was used to simulate the current state for the bicycle supply chain based on the parameters discussed in Section 5.1. Based on 8-hour work shifts 5 days a week, the simulation was run for 10 replications using a 6 month warm-up period and collecting data for a 12 month period. The reasoning for selecting the number of replications is provided later in this work. Using the current state SC Sus-VSM map developed in Section 5.2, three interventions to improve supply chain sustainability performance were identified, with each intervention focusing on a single aspect of sustainability. The economic intervention focused on reducing inventory levels at the drive train plant by reducing the chain assembly cycle time as shown in Table 5.1, as well implementing a truck with twice the capacity but reduced fuel-efficiency for Transport 1. The environmental intervention focused on reducing the painting process energy usage by 35% at the cost of increased cycle times as shown in Table 5.1. Finally, the societal intervention reduces the product defect ratio at the wheel and tire plant to 0.3% for all processes within the plant.

In addition to considering the interventions individually, the economic and environmental, economic and societal, and the environmental and societal intervention combinations were also considered to investigate possible interactions between interventions. Including the original current state scenario, a total of seven different scenarios were considered and simulated using the same run parameters (8-hr shifts, 5 days/wk, 6-month warm-up, 12- month run, and 10 replications).

To select the appropriate number of replications for the simulation model, an initial set of 8 replications was run for the current state simulation model and the total supply chain lead time as well as the half-width was noted. Using the initial number of replications (n_0), the total lead time half-width determined from the 8 replications (h_0), and the desired half-width for the total lead time (h), the required number of replication (n) can be determined using Equation 5.1 (Kelton et al., 2009).

$$n \cong n_0 \frac{{h_0}^2}{h^2} = 8 \times \frac{8.936^2}{8^2} = 9.98\, replications \qquad (5.1)$$

The half-width calculated from the Arena software is based on a 95% confidence interval, therefore, to achieve a half-width of 8 days for the total lead time based on a 95% confidence interval, a total of 10 replications are required.

CHAPTER VI

Case Study Analysis and Results

6.1 SC Sus-VSM Results

The first part of the case study dealt with the application of the SC Sus-VSM methodology to the simulated current state supply chain. The SC Sus-VSM for the case study was shown in Figure 4.6. The main goal of developing the SC Sus-VSM is to assess the supply chain and identify improvement opportunities for its sustainability performance. The SC Sus-VSM successfully accomplished this goal and was used to identify the three interventions used for the remainder of the case study. When data is available, the SC Sus-VSM can be easily developed using the visuals selected for the metrics. The metric visuals resulted in an understandable and uncluttered SC Sus-VSM where the product flow was easily traced through the supply chain. Because of the high-level supply chain view captured in SC Sus-VSM, the amount of detailed information that can be captured is limited. However, the SC Sus-VSM was useful in identifying problem locations which would most benefit from further investigation into the source of the problem.

6.2 Case Study Data Analysis

Based on the results of the SC Sus-VSM, economic, environmental, and societal interventions were determined and simulated using the DES model to build the case study. The analysis for the case study was performed using the methodology described in Phase 4 of Chapter IV. While the data for most metrics could be extracted from the simulation, the WIP needed to be calculated using the queue data and cycle times for each process in the supply chain. The data for all the metrics (14) in each of the seven scenarios is compiled in Table 6.1, which also contains the normalized metric values as described in the methodology. The changes made for each intervention are described at the end of Chapter V.

Using the results from Table 6.1 and the methodology from Chapter IV, the normalized metrics were then weighted and aggregated together to determine the sub-index scores. Once this was completed, the sub-index scores were weighted and aggregated together to calculate the overall sustainability index for the supply chain. For this case study, equal weighting was used for both steps to provide transparency to what was occurring. The results from these steps can be seen in Table 6.2.

Table 6.1: Measured and Normalized Metric Values from Case Study

			Measured Value						
	Individual Metrics	Unit	Current State	Economic Intervention	Environmental Intervention	Societal Intervention	Economic-Environmenal	Economic-Societal	Environmental-Societal
Environmental	Material Usage	lbs	20.8	20.8	20.8	20.8	20.8	20.8	20.8
	Water Usage	gal	84.5	84.9	89.1	84.3	89.2	84.4	89.6
	Energy Usage	kWh	257.2	265.0	253.3	257.6	262.6	266.7	251.8
	GHG Emissions	lbs	514.6	529.8	499.2	502.6	521.4	530.9	501.8
Economic	Supply Chain Lead Time	days	437.4	287.8	467.3	438.5	316.9	286.3	467.0
	Value-added/Lead Time Ratio	%	0.060%	0.089%	0.057%	0.062%	0.082%	0.090%	0.059%
	Transport Time/Distance	min/mi	160 min/125mi	160 min/125mi	160 min/125mi	160 min/125mi	160 min/125mi	160 min/125mi	160 min/125mi
	WIP	days	436.8	287.2	466.7	437.9	316.3	285.7	466.4
Societal	Product Defect Ratio	#/wk	28.8	28.8	27.9	26.2	28.6	26.3	25.2
	Recordable Injury/Sickness Rate	#/wk	7.0	6.8	6.8	6.9	6.8	7.3	6.7
	Employee Training Intensity	hr/wk	115	115	115	115	115	115	115
	Hazardous Chemicals/Materials	-	2.5	2.5	2.5	2.5	2.5	2.5	2.5
	Local Community Hiring Ratio	%	60%	60%	60%	60%	60%	60%	60%
	Diversity Ratio	%	52.50%	52.50%	52.50%	52.50%	52.50%	52.50%	52.50%

			Normalized Values						
	Individual Metrics	Unit	Current State	Economic Intervention	Environmental Intervention	Societal Intervention	Economic-Environmenal	Economic-Societal	Environmental-Societal
Environmental	Material Usage	lbs	5.00	5.00	5.00	5.00	5.00	5.00	5.00
	Water Usage	gal	5.00	4.98	4.73	5.01	4.72	5.00	4.70
	Energy Usage	kWh	5.00	4.85	5.08	4.99	4.90	4.82	5.11
	GHG Emissions	lbs	5.00	4.85	5.15	5.12	4.93	4.84	5.12
Economic	Supply Chain Lead Time	days	5.00	6.71	4.66	4.99	6.38	6.73	4.66
	Value-added/Lead Time Ratio	%	5.00	7.41	4.74	5.13	6.82	7.45	4.87
	Transport Time/Distance	min/mi	5.00	5.00	5.00	5.00	5.00	5.00	5.00
	WIP	days	5.00	6.71	4.66	4.99	6.38	6.73	4.66
Societal	Product Defect Ratio	#/wk	5.00	4.99	5.14	5.45	5.04	5.43	5.61
	Recordable Injury/Sickness Rate	#/wk	5.00	5.16	5.11	5.05	5.15	4.77	5.19
	Employee Training Intensity	hr/wk	5.00	5.00	5.00	5.00	5.00	5.00	5.00
	Hazardous Chemicals/Materials	-	5.00	5.00	5.00	5.00	5.00	5.00	5.00
	Local Community Hiring Ratio	%	5.00	5.00	5.00	5.00	5.00	5.00	5.00
	Diversity Ratio	%	5.00	5.00	5.00	5.00	5.00	5.00	5.00

Table 6.2: Sustainability Index with Sub-indices

Sub-index	Current State	Econ Intervention	Environ Intervention	Societal Intervention	Econ-Environ	Econ-Societal	Environ-Societal
Economic	5.00	6.46	4.76	5.02	6.14	6.48	4.80
Environ	5.00	4.92	4.99	5.03	4.89	4.92	4.98
Societal	5.00	5.02	5.04	5.08	5.03	5.03	5.13
Sustainability Index	**5.00**	**5.47**	**4.93**	**5.05**	**5.35**	**5.48**	**4.97**

Examining the sustainability index results in Table 6.2 shows the effect of the interventions on supply chain sustainability performance. For the intervention combinations, the sub-index scores seem to be an equal combination of the individual intervention scores in most cases, although one intervention appears to have a greater effect than the other in some cases.

Examining the data collected in Table 6.1 for each metric provides more information on the intervention effect on the sustainability index. In the economic intervention, which showed the second highest sustainability index score, the WIP for the supply chain was reduced by approximately 35%, resulting in an improved lead time and value added to lead time ratio. With three of four economic metrics being improved, the increased score in the economic sub-index is expected. However, the reduced fuel mileage caused by the increased truck capacity results in an increase in energy consumption and GHG emissions, causing a small decrease in the environmental sub-index.

For the environmental intervention, which resulted in the lowest score, there is a noticeable reduction in the energy consumption and GHG emissions, resulting in an improvement in the environmental sub-index. However, there is approximately a 6.5% increase in supply chain WIP, causing negative effects to both the lead time and the value added/lead time ratio, resulting in a significant decrease in the economic sub-index.

The societal intervention resulted in only small improvements to the sustainability index, but seemingly had no negative effects. Closer examination shows an approximate improvement of 9% to the product defect ratio metric, as well as a small improvement to the supply chain WIP, with corresponding positive effects to the lead time and value added/lead time ratio. These changes result in small improvements in all three sustainability aspects, with no drawback being indicated. Given that the financial cost of implementing interventions is not considered in SC Sus-VSM or the simulation, this improvement without any drawback is likely unrealistic.

The economic and environmental intervention combination shows a significant improvement in the sustainability index, and the economic sub-index score is improved over the current state, but it appears to be affected more by the economic portion of the intervention compared to the environmental portion. The causes for this are not readily identifiable. The environmental sub-index is worse than in either individual intervention, although this is possibly due to variability in the simulation.

The economic and societal intervention combination produced the greatest benefit to the sustainability index score. For the economic and societal intervention, the sub-index scores appear to be a straightforward combination of the two interventions, with neither having a larger effect. However, the environmental sub-index score is again lower than either individual intervention. While a more neutral score would be expected, this score could still be caused by variability within the simulation.

The environmental and societal intervention combination resulted in a slightly negative effect on the sustainability index score. The environmental and societal intervention also appears to be a more straightforward combination of the two individual interventions, but as with the other two intervention-pairs, the environmental sub-index score is lower than either of the individual interventions. In fact, while the environmental and societal intervention both have a positive effect on the environmental sub-index score, the intervention pair has a small negative impact. Examining Figure 6.7 from the DOE analysis discussed in section 6.3 indicates that there is a negative interaction between the environmental and societal interventions which could be causing unexpected behavior.

6.3 Design of Experiments-based Analysis

Once the sustainability index has been determined for all interventions and intervention pairs, a DOE style analysis was performed as described in the methodology to examine the sensitivity of the supply chain sustainability to the interventions that were considered. A 95% confidence interval was used for this case study. The seven treatments considered were entered into the test matrix shown in Table 6.3. For each treatment, a '+' indicates that an intervention is present, while a '-' indicates the intervention is not present. For interactions, the sign is the product of the signs for the individual interventions; so for AB in the current state, the product of two '-' is a '+'.

Using the absolute effects and the decision limit from Table 6.3, a Pareto chart was built in Figure 6.1, with horizontal axis labeled according to the letters assigned to each intervention in the test matrix.

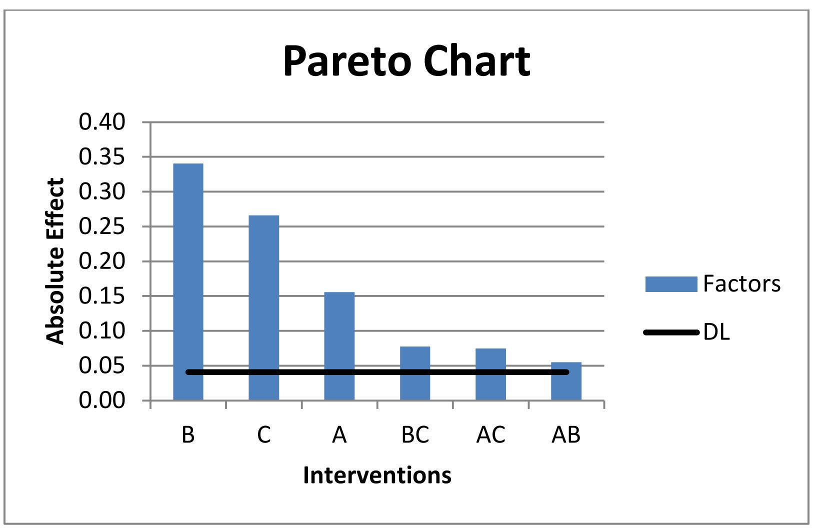

Figure 6.1: Pareto Chart for Case Study Interventions and Intervention Pairs

Table 6.3: Test Matrix for Case Study Sustainability Index

Intervention	Econ	Environ	Societal	Econ-Environ	Econ-Societal	Environ-Societal	**Sustainability Index**											
Treatment	**A**	**B**	**C**	**AB**	**AC**	**BC**	**y_1**	**y_2**	**y_3**	**y_4**	**y_5**	**y_6**	**y_7**	**y_8**	**y_9**	**y_{10}**	**y_bar**	**S^2**
Current	-	-	-	+	+	+	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	0.00000
Economic	+	-	-	-	-	+	5.52	5.44	5.52	5.44	5.41	5.45	5.51	5.44	5.46	5.48	5.47	0.01341
Environ	-	+	-	-	+	-	4.92	4.96	4.92	4.96	4.89	4.91	4.95	4.91	4.96	4.92	4.93	0.00580
Societal	-	-	+	+	-	-	5.05	5.06	5.05	5.06	5.01	5.07	4.98	5.04	5.08	5.07	5.05	0.00841
Econ-Environ	+	+	-	+	-	-	5.37	5.33	5.37	5.33	5.35	5.32	5.36	5.35	5.39	5.36	5.35	0.00421
Econ-Soc	+	-	+	-	+	-	5.48	5.50	5.48	5.50	5.44	5.50	5.43	5.44	5.52	5.46	5.48	0.00865
Environ-Soc	-	+	+	-	-	+	4.99	4.97	4.99	4.97	4.93	4.94	4.97	4.94	5.05	4.97	4.97	0.01056
Σy+	158.00	149.49	159.89	154.39	154.05	154.00											**S_e =**	0.0854
Σy-	204.44	212.95	202.55	208.05	208.39	208.44											**σ_{eff} =**	0.0204
y+_bar	5.27	4.98	5.33	5.15	5.14	5.13											**df =**	63
y-_bar	5.11	5.32	5.06	5.20	5.21	5.21											**t =**	1.998
E	0.16	-0.34	0.27	-0.05	-0.07	-0.08												
|E|	0.16	0.34	0.27	0.05	0.07	0.08											**DL =**	0.0408

According to the Pareto chart, the environmental intervention is the most significant, followed by the societal and economic interventions. The intervention combination pairs are statistically significant, but less significant than the individual interventions, which would be expected. To further analyze the sensitivity of the sustainability index to the interventions, response plots were created following the methodology described in Chapter IV. Table 6.4 shows the response values and the effective standard deviation used for each plot, while Figures 6.2-6.4 contain the response plots for the interventions and Figures 6.5-6.7 contain the response plots for the interaction pairs.

Table 6.4: Response Plot Values and Effective Standard Deviation for Case Study

Factor	Response/ Average	Interaction	Response/ Average	Interaction	Response/ Average	Interaction	Response/ Average
A+	5.43	A+B+	5.35	A+C+	5.48	B+C+	4.97
A-	4.99	A+B-	5.47	A+C-	5.41	B+C-	5.14
B+	5.09	A-B+	4.95	A-C+	5.01	B-C+	5.26
B-	5.25	A-B-	5.02	A-C-	4.97	B-C-	5.23
C+	5.16	-	-	-	-	-	-
C-	5.19	-	-	-	-	-	-
Factor	Response/ Std. Dev	Interaction	Response/ Std. Dev	Interaction	Response/ Std. Dev	Interaction	Response/ Std. Dev
Se =	0.0854	A+B Se =	0.09	A+C Se =	0.09	B+C Se =	0.08
σeff =	0.0204	A+B σeff =	0.03	A+C σeff =	0.03	B+C σeff =	0.03
-	-	A-B Se =	0.08	A-C Se =	0.08	B-C Se =	0.09
-	-	A-B σeff =	0.02	A-C σeff =	0.02	B-C σeff =	0.03

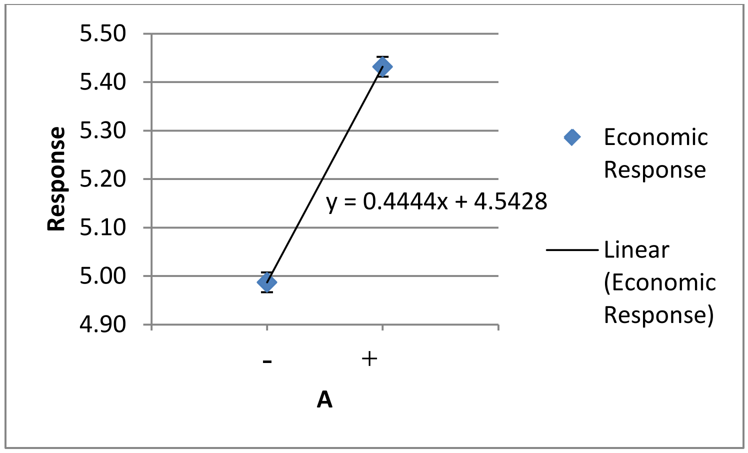

Figure 6.2: Economic Intervention (A) Response Plot

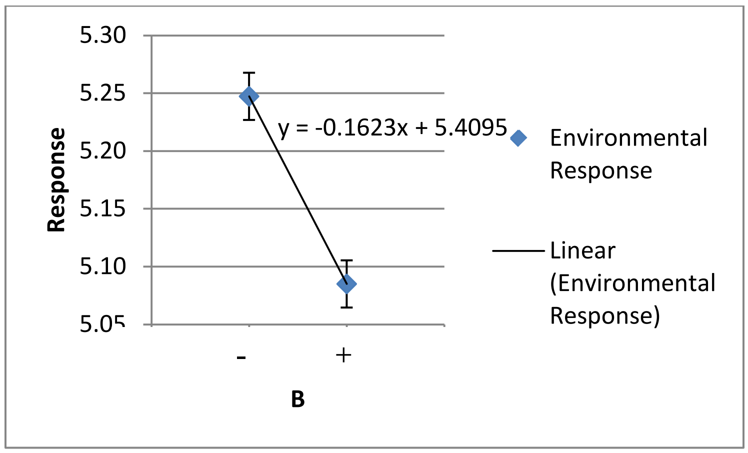

Figure 6.3: Environmental Intervention (B) Response Plot

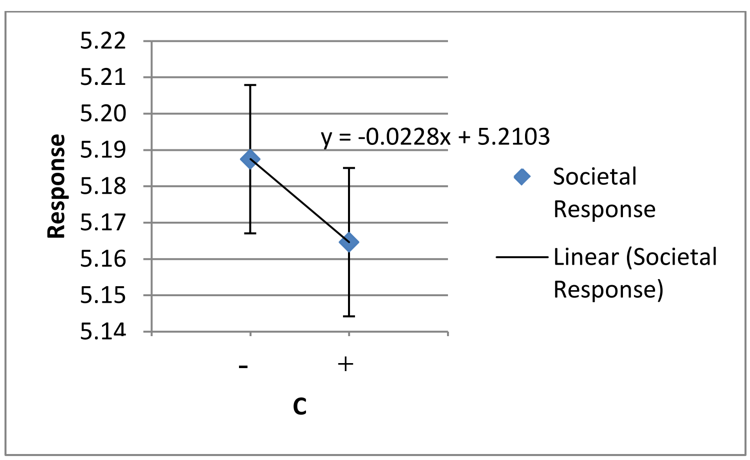

Figure 6.4: Societal Intervention (C) Response Plot

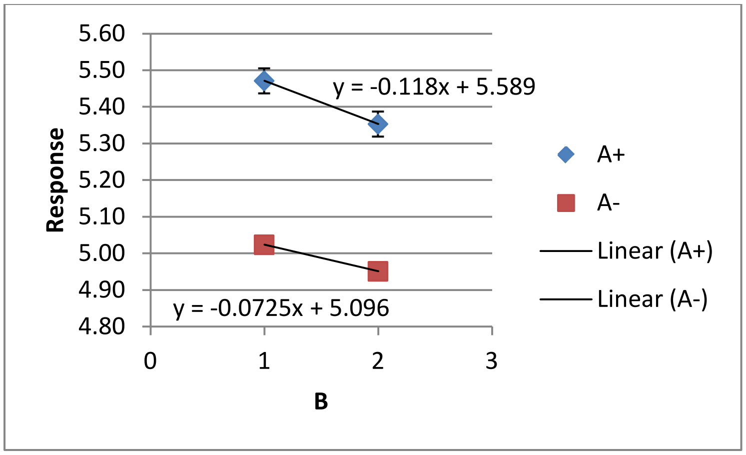

Figure 6.5: Economic and Environmental (AB) Intervention Response Plot

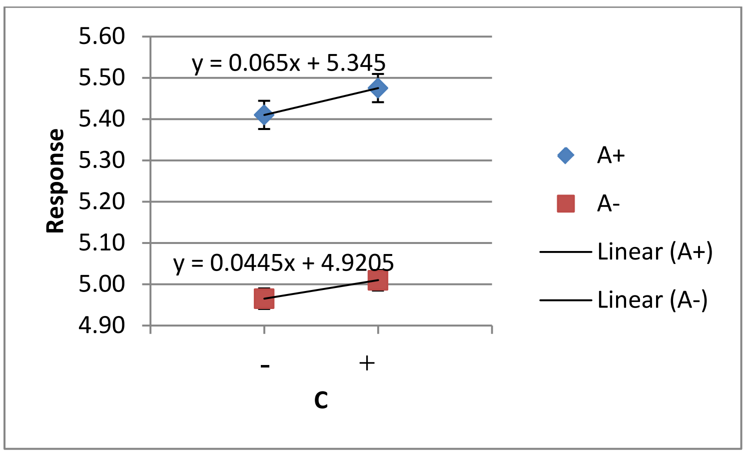

Figure 6.6: Economic and Societal (AC) Intervention Response Plot

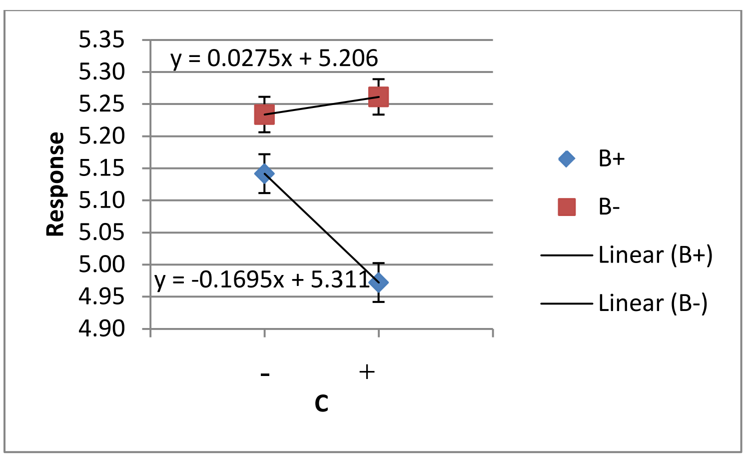

Figure 6.7: Environmental and Societal (BC) Intervention Response Plot

The error bars for a few of the response plots are not visible due to the small deviation. The slope of the trend line is the main indicator of how sensitive the sustainability index is to the intervention being plotted. For this case study, the plots show that the sustainability index is most sensitive to the environmental and the economic interventions. However, while the economic intervention results in a positive effect on the sustainability index, the environmental intervention results in a negative effect. The sustainability index is least sensitive to the societal intervention, showing a small negative or net-zero effect within reasonable error. In Figure 5.18, the plot indicates that there is an interaction between the environmental and societal interventions, as the societal intervention has five times the effect with the environmental intervention in place as it does with no other intervention involved.

In trying to establish an approach towards improving supply chain sustainability, it is necessary to determine which interventions should be pursued first, so as to achieve the greatest benefit. For the case study presented in this paper, performing the economic intervention clearly provided the greatest improvement to the sustainability index. Given that the main concern for most companies is improving profits and reducing costs and waste, performing economic interventions first is a reasonable approach. Following the same reasoning, the societal intervention should be performed next, as it provided small improvements in all sub-indices of the sustainability index. Due to the overall decrease in the sustainability index for the environmental intervention, it might be questioned whether the intervention should be performed at all. With environmental legislation requiring reductions in GHG emissions, however, the implementation of environmental interventions will likely still be required. Also, given the downstream location of the environmental intervention in this case study, the negative effects of the increased painting oven cycle time are likely more prominent than they might be at a different location in the supply chain. From the intervention pair response plots, the only plot that indicates an interaction between interventions is the economic-societal plot, and that is a positive interaction. This information indicates that companies should not be greatly concerned with detrimental effects caused by implementing multiple interventions. Given the complex nature of these interactions, however, they should be monitored in future case studies to verify this tendency.

From this case study, pursuing economic interventions should be the first priority, followed by societal interventions, and finally environmental interventions. However, due to environmental legislation, it may be necessary to pursue environmental interventions before societal. Further case studies should be performed to verify that this general approach provides the greatest benefit towards sustainability, as the location of the interventions and the type of supply chain being considered could greatly affect how the supply chain reacts to those interventions.

CHAPTER VII

Conclusions and Future Work

7.1 Conclusions

The first research question raised in this work considered how Sus-VSM could be adapted and applied at the supply chain level to identify potential sustainability improvements. Identifying relevant and measureable metrics that adequately captured the sustainability of the supply chain while retaining metrics from standard Sus-VSM when feasible was the first challenge faced. After reviewing relevant literature, a total of 14 metrics were decided upon. The economic and environmental metrics from standard Sus-VSM were used with little modification, although a metric to capture GHG emissions was added. Only one societal metric was retained from Sus-VSM, as the other metrics were not relevant at the supply chain level. Five additional societal metrics were selected that were more easily measured and took different stakeholders into account, including employees, customers, the local community, and the company itself. Visuals for these metrics were adapted from Sus-VSM when possible, although new visuals were created for GHG emissions and the societal metrics. These visuals allowed for a clear and uncluttered SC Sus-VSM.

Another aspect of the question is how SC Sus-VSM can be applied to more complex supply chains. For a relatively small number of branches, SC Sus-VSM is easily applied, but an increased number of branches results in an excessively cluttered map. While further verification is necessary, the SC Sus-VSM application could be focused to important locations in the supply chain to simplify the map, similar to the method used by Brown et al. (2014). With the simplified SC Sus-VSM, locations for potential sustainability improvements could still be identified, making SC Sus-VSM a useful tool at the supply chain level.

One difficulty faced in applying SC Sus-VSM is the availability of data for completing the map. In a supply chain where multiple companies are involved, there will be an unwillingness to share information and data due to confidentiality concerns. For large companies with significant influence over other companies in the supply chain, this difficulty may be less problematic. In order to alleviate this difficulty in obtaining data, SC Sus-VSM can be applied to a hypothetical supply chain to convince companies to share information by highlight the potential benefits. Additionally, a simulation model might also provide methods of alleviating this difficulty, as discussed later in this section.

The second research question considers which types of interventions should be implemented first to achieve the maximum possible benefit to supply chain sustainability performance. From the case study, the economic-societal intervention provides the most benefit, followed closely by the economic intervention. The environmental intervention resulted in a negative impact on the sustainability index due to increased amounts of WIP. Implementing the intervention at a different location with less potential to create a bottleneck may have resulted in a substantially changed outcome. The societal intervention produced modest improvements in all aspects of sustainability. From the case study, a general approach of implementing economic interventions first, followed by societal and finally environmental interventions was developed. This approach needs further verification through future case studies with different supply chain configurations and different interventions being implemented, but provides a starting point for companies to improve supply chain sustainability performance. In this case study, equal weighting was used when aggregating the metrics in the sustainability index; if a user wishes to emphasize certain aspects sustainability performance through weighting, this approach may require appropriate adaptation.

In addition to only considering a simple supply chain for one product, the case study also does not consider the cost of implementing the intervention considered. This could cause some results to be unrealistic and is particularly noticeable for the societal intervention, which provides supply chain sustainability performance benefits for all three aspects of sustainability with no apparent drawbacks. Incorporating the implementation cost for the interventions into the study would provide more accurate results that can be used to improve the general approach toward sustainability improvements.

The third research question deals with what advantages are gained from using DES in conjunction with SC Sus-VSM to assess the sustainability performance of a supply chain. One of the main problems with assessing supply chain sustainability performance is the ability to collect data. Unless a company that closely manages its supply chain is being considered, collecting information necessary to build the SC Sus-VSM is difficult, as feeder companies will be unwilling to share data due to confidentiality issues. However, the DES model can be used to help deal with this problem in a number of ways. First, if only a portion of the needed data is missing, the simulation can be used along with a reasonable estimate of the data to simulate and assess the supply chain. Also, simulating the supply chain allows a clearer illustration of how implementing sustainability interventions can benefit the entire supply chain, including the feeder plant companies. With a clearer picture of the potential benefits, the feeder companies might be willing to cooperate and supply the needed data themselves, removing the need for estimation.

The DES model also greatly aids the creation of future state maps for the supply chain, as it allows changes caused by interventions to properly be taken into account. Without the simulation model, the future state map would require estimations of what might occur with each intervention, and due to the complex nature of the supply chain, this would be almost impossible. Also, by aiding future state map creation, the simulation allows many different interventions to be considered quickly and efficiently. Each intervention can be entered into the DES model and simulated to assess the sustainability performance for that intervention. This allows a company to weigh various options and implement the improvements that provide the greatest benefit to the supply chain sustainability performance. Overall, the simulation integrates well with SC Sus-VSM, allowing quicker and more accurate assessment of supply chain sustainability, despite issues caused by supply chain complexity and lack of data.

One of the major limitations to the DES model was the difficulty encountered in modeling the metrics to assess the societal aspect of sustainability. Metrics such as the product defect ratio and injury ratio can be related to the process cycle times, but there is a difficulty in connecting these metrics to the other aspects of sustainability, so variations will not cause the appropriate changes in other aspects. For the product defect ratio this is partially overcome by removing defective products from the value stream, which affects the amount and location of WIP that occurs in the supply chain. However, the injury ratio lacks this type of connection, and the other societal metrics are difficult to model in the simulation in any form. Finding methods of modeling all the societal metrics such that variations have the appropriate effect in all sustainability aspects would greatly improve the usefulness of the DES model.

The fourth and final research question considered in this work deals with what advantages can be gained by using a DOE style analysis together with SC Sus-VSM. The main advantage of a DOE analysis is the ability to determine the sensitivity to interventions on the supply chain sustainability performance. Using the data from the sustainability index, the DOE analysis showed which intervention and intervention pairs had significant effects. The individual interventions in the case study were more significant than the intervention combinations. This tendency is present in the real world, although an intervention pair may be more significant than a individual intervention on occasion.

For the significant interventions, the response plots show further detail and indicate the sensitivity of the sustainability performance to the intervention based on the slope of the trend line. Furthermore, the response plots for the intervention pairs also indicate whether there is an interaction between the two interventions. Failure to identify these interactions can lead to unexpected results when interventions are implemented. By determining the sensitivity of the supply chain sustainability performance to various interventions, companies can allocate resources towards interventions with the highest sensitivity. Also, using information from the economic, environmental, and societal sub-indices in the sustainability index, a more detailed DOE analysis can be performed for each of those sub-indices, allowing focus on a particular area of sustainability performance. Overall, while some results from the DOE analysis can be seen directly in the sustainability index, other results such as interactions between interventions can only be clearly seen using the DOE analysis.

As discussed in the methodology, a limitation of the DOE style analysis is the randomness present in factors that would be held constant in a typical DOE analysis. To eliminate this problem, a simulation model could be used and the factors held constant in the simulation, but the ability of the model to present the real world scenario being considered would be reduced. For this reason, it was decided to use the average values for cycle times, water usage, etc., to reduce but not eliminate the randomness in the factors. While this allows the DES model to more accurately represent the supply chain, it does increase the amount of experimental noise present in the results of the DOE style analysis.

Overall, there is significant work left to be performed to finish validating the usefulness of the SC Sus-VSM tool and accompanying DES model, but there are some general observations that can be made. First, SC Sus-VSM greatly benefits from the DES model, as the model provides a level of detail that is not typically captured in the SC Sus-VSM, but provides further insight into how the supply chain sustainability performance can be improved. However, a less detailed examination of the supply chain can still be performed quickly using the SC Sus-VSM, so the assessment speed is not greatly inhibited. This indicates that mapping applications can greatly benefit from implementing simulation. Additionally, the societal metrics used in SC Sus-VSM were useful in assessing the overall sustainability of the supply chain, and while the metrics were difficult to include in the DES model, they functioned well in the SC Sus-VSM itself. These societal metrics can provide a starting point for other attempts to assess the sustainability of supply chains.

7.2 Future Work

Performing additional case studies with supply chains of varying complexity and product types is the most important work moving forward. This would verify not only the application of SC Sus-VSM, but the benefits from implementing DES and a DOE style analysis with SC Sus-VSM, as well as further establish a general approach to implementing interventions. Additionally, a literature study regarding the weighting of sustainability metrics would allow a weighting baseline to be established for the metrics used in SC Sus-VSM, improving the value of the tool to companies lacking knowledge to decide metric weightings. Research into integrating an optimization model with the data collected in the sustainability index would also be useful for applying SC Sus-VSM. After simulating and collecting data for several potential interventions to the supply chain, an optimization model could include intervention costs and project budget to determine the optimal intervention for the supply chain sustainability performance. Incorporating the implementation cost of interventions into the methodology would also improve the value of SC Sus-VSM. Finally, since not every societal metric was capable of being modeled in the simulation, research into alternate metrics or methods of altering the current metrics could allow a greater number of metrics to be simulated in the DES model.

REFERENCES

Abdulmalek, F., Rajgopal, J., (2007), "Analyzing the benefits of lean manufacturing and value stream mapping via simulation: A process sector case study", International Journal of Production Economics, Vol. 107, Iss. 1, May 2007, pp. 223–236, http://dx.doi.org/10.1016/j.ijpe.2006.09.009.

Arbulu, R., Tommelein, I., (2002), "Value Stream Analysis of Construction Supply Chains: Case Study on Pipe Supports Used in Power Plants", Proceedings of 10th IGLC Conference, Aug. 2002, Gramado, Brazil.

Barbosa-Póvoa, A., (2009), "Sustainable Supply Chains: Key Challenges", Computer Aided Chemical Engineering, Vol. 27, pp. 127-132.

Bourlakis, M., Maglaras, G., Gallear, D., Fotopoulos, C., (2013), "Examining sustainability performance in the supply chain: The case of the Greek dairy sector", Industrial Marketing Management, Vol. 43, Iss. 1, 2013, http://dx.doi.org/10.1016/j.indmarman.2013.08.002.

Braglia, M., Carmignani, G., Zammori, F., (2006), "A new value stream mapping approach for complex production systems", International Journal of Production Research, Vol. 44, Iss. 18-19, pp. 3929-3952.

Brown, A., Amundson, J., Badurdeen, F., (2014), "Sustainable Value Stream Mapping (Sus-VSM) in Different Manufacturing System Configurations: Application Case Studies", Journal of Cleaner Production: Special Issue on Lean and Green Initiatives, In Press, Corrected Proof, Available online 17 June 2014, ISSN 0959-6526, http://dx.doi.org/10.1016/j.jclepro.2014.05.101.

Chen, M., Johnson, O., (2011), Quantifying and Managing Supply Chain Greenhouse Gas Emissions, Stanford Global Supply Chain Management Forum, Stanford University, Palo Alto, California, January, 2011.

Dinesh Seth, Nitin Seth, Deepak Goel, (2008) "Application of value stream mapping (VSM) for minimization of wastes in the processing side of supply chain of cottonseed oil industry in Indian context", Journal of Manufacturing Technology Management, Vol. 19 Iss: 4, pp.529 - 550.

Dolcemascolo, Darren., (2006), "Improving the Extended Value Stream: Lean for the Entire Supply Chain." New York: Productivity, 2006. Print.

EPA, (2007), “The Lean and Energy Toolkit: Achieving Process Excellence Using Less Energy,” United States Environmental Protection Agency, Available via http://www.epa.gov/innovation/lean/toolkit/LeanEnergyToolkit.pdf, Accessed 1/18/2014.

EPA, (2007), “The Lean and Environment Toolkit,” United States Environmental Protection Agency, Available via http://www.epa.gov/lean/environment/toolkits/energy/index.htm, Accessed 1/18/2014.

Faulkner, W. and Badurdeen, F., (2014), "Sustainable Value Stream Mapping (Sus-VSM): Methodology to Visualize and Assess Manufacturing Sustainability Performance", Journal of Cleaner Production, In Press, Corrected Proof, Available online 1 June 2014, ISSN 0959-6526, http://dx.doi.org/10.1016/j.jclepro.2014.05.042.

Faulkner, W., Templeton, W., Gullett, D., Badurdeen, F., (2012), "Visualizing Sustainability Performance of Manufacturing Systems Using Sustainable Value Stream Mapping (Sus-VSM)." Proceedings of the 2012 International Conference on Industrial Engineering and Operations Management Istanbul, Turkey, July 3-6, 2012.

Fearne, A., and A. Norton., (2009), “Sustainable Value Stream Mapping in the Food Industry,” In: Waldron , K., ed. Handbook of Waste Management and Co-Product Recovery in Food Processing, Woodhead Publishing, Cambridge.

Feng, S., Joung, C., Li, G., (2010), "Development Overview of Sustainable Manufacturing Metrics", Proceedings of the 17th CIRP International Conference on Life Cycle Engineering, Hefei, P.R. China, 19-21 May 2010.

Fleisch, E., Tellkamp, C., (2005), "Inventory Inaccuracy and Supply Chain Performance: A Simulation Study of a Retail Supply Chain", International Journal of Production Economics, Vol. 95, Iss. 3, pp. 373-385.

Folinas, D., Aidonis, D., Triantafillou, D., Malindretos, G., (2013), "Exploring the Greening of the Food Supply Chain with Lean Thinking Techniques", Procedia Technology, Vol. 8, pp. 416-424.

Forrester, J.W., (1961), "Industrial Dynamics", Massachusetts Institute of Technology Press.

Fowler, J., Rose, O., (2004) "Grand Challenges in Modeling and Simulation of Complex Manufacturing Systems", SIMULATION, Vol. 80, Iss. 9, pp. 469-476.

Global Reporting Initiative, (2011), "G3.1 and G3 Guidelines." N.p., Web. 18 Jan. 2014. Available via https://www.globalreporting.org/reporting/G3andG3-1/Pages/default.aspx.

Guinee, J, (2002), “Handbook on Life Cycle Assessment: Operational Guide to the ISO Standards,” Dordrecht, The Netherlands, Kluwer Academic Publishers.

Herrmann, J., Lin, E., Ram, B., Sarin, S., (2000), "Adaptable Simulation Models for Manufacturing", Proceedings of the 10th International Conference on Flexible Automation and Intelligent Manufacturing, Vol. 2, pp. 989-995, College Park, Maryland, June 26-28, 2000.

Higuchi, T., Troutt, M., (2004), "Dynamic Simulation of the Supply Chain for a Short Life Cycle Product- Lessons from the Tamagotchi Case", Computers & Operations Research, Vol. 31, Iss.7, pp. 1097-1114.

Hollman, S., Klimmer, F., Schmidt, K., Kylian, H., (1999), “Validation of a questionnaire for assessing physical work load”, Scandinavian Journal of Work, Environment & Health, Vol. 25, Iss. 2, pp. 105-114.

Irani, S., Zhou, J., (2003), "Value Network Mapping (VNM): Visualization and Analysis of Multiple Interacting Value Streams in Jobshops, LAI Conference, Boston, MA.

Jahangirian, M., Eldabi, T., Naseer, A., Stergioulas, L., Young, T., (2010), "Simulation in Manufacturing and Business: A Review", European Journal of Operational Research, Vol. 203, Iss. 1, pp. 1-13.

Jarkko, E., Lu, W., Lars, S., Thomas, O., (2013), "Discrete Event Simulation Enhanced Value Stream Mapping: An Industrialized Construction Case Study", Lean Construction Journal 2013, pp. 47-65.

Jawahir, I.S.; K.E. Rouch; O.W. Dillon; Jr., K.J.; Joshi, A. Venkatachalam and I.H. Jaafar. (2006). Total Life-cycle Considerations in Product Design for Manufacture: A Framework for Comprehensive Evaluation, (Keynote Paper), Proc. TMT 2006, LloretdeMar, Barcelona, Spain, September 2006, 1-10.

Keil, S., Schneider, G., Eberts, D., Wilhelm, K., Gestring, I., Lasch, R., Deutschlander, A., (2011), "Establishing Continuous Flow Manufacturing in a Wafertest-Environment Via Value Stream Design", Advanced Semiconductor Manufacturing Conference (ASMC) 2011 22nd Annual IEEE/SEMI, p 1-7.

Kelton, W., Sadowski, R., Zupick, N., (2009), "Simulation with Arena.", Boston: McGraw-Hill, 2009. Print.

Kenney, J., Keeping, E., (1962), "The Standard Deviation" and "Calculation of the Standard Deviation." §6.5-6.6 in Mathematics of Statistics, Pt. 1, 3rd ed., Princeton, NJ: Van Nostrand, pp. 77-80, 1962.

Laínez, J., Bojarski, A., Espuña, A., Puigjaner, L., (2008), "Mapping Environmental Issues within Supply Chains: a LCA based Approach", Computer Aided Chemical Engineering, Vol.25, pp. 1131-1136.

Lee, Y., Cho, M., Kim, S., Kim, Y., (2002), "Supply Chain Simulation with discrete-continuous Combined Modeling", Computers & Industrial Engineering, Vol. 43, Iss.s 1-2, pp. 375-392.

Lian, Y., Landeghem, H., (2002), "An Application of Simulation and Value Stream Mapping in Lean Manufacturing", Proceedings 14th European Simulation Symposium. Dresden, Germany.

Montevechi, J., Miranda, R., Friend, J., (2012). "Sensitivity Analysis in Discrete Event Simulation Using Design of Experiments", Discrete Event Simulations - Development and Applications, Dr. Eldin Wee Chuan Lim (Ed.), ISBN: 978-953-51-0741-5.

Montgomery, D., (2005), "Design and Analysis of Experiments", 6th ed., Hoboken, NJ: John Wiley & Sons, Inc., 2005. Print.

NACFAM (National Council for Advanced Manufacturing), 2014. Sustainable Manufacturing, http://www.nacfam.org/PolicyInitiatives/SustainableManufacturing/tabid/64/Default.aspx Accessed 5/5/2014.

National Institute of Standards and Technology, (2010), "Sustainable Manufacturing Indicators Repository." N.p., 11 May 2010. Web. 18 Jan. 2014. Available via http://www.mel.nist.gov/msid/SMIR/Indicator_Repository.html.

Negahban, A., Smith, J, (2014), "Simulation for Manufacturing System Design and Operation: Literature Review and Analysis", Journal of Manufacturing Systems, Vol. 33, Iss. 2, pp. 241-261.

Norton, A., (2007), “Sustainable Value Stream Mapping as a Technique for Analysing and Reducing Waste in the UK Chilled Food Sector,” PhD Thesis, University of London, Imperial College, Centre for Environmental Policy.

Paju, M., Heilala, J., Hentual, M., Heikkila, A., Johansson, B., Leong, S., Lyons, S., (2010), "Framework and Indicators for a Sustainable Manufacturing Mapping Methodology", Proc. of the 2010 Winter Simulation Conference, December 5-8, Baltimore, Maryland, pp. 3411-3422.

Persson, J., (2002), "The Impact of Different Levels of Detail in Manufacturing Systems Simulation Models", Robotics and Computer Integrated Manufacturing, Vol. 18, pp. 319-325.

Ramanathan, U., (2014), "Performance of Supply Chain Collaboration - A Simulation Study", Expert Systems with Applications, Vol. 41, Iss. 1, pp. 210-220.

Rother, M., Shook, J., (1999), “Learning to See: value stream mapping to add and eliminate muda,” The Lean Enterprise Institute, Massachusetts.

Seleim, A., Azab, A., AlGeddawy, T., (2012), "Simulation Methods for Changeable Manufacturing", Procedia CIRP, Vol. 3, pp. 179-184.

Sarimveis, H., Patrinos, P., Tarantilis, C., Kiranoudis, C., (2008), "Dynamic Modeling and Control of Supply Chain Systems: A Review", Computers and Operations Research, Vol. 35, Iss. 11, pp. 3530-3561.

Seth, D., Seth, N., Goel, D., (2007), "Application of value stream mapping (VSM) for minimization of wastes in the processing side of supply chain of cottonseed oil industry in Indian context", Journal of Manufacturing Technology Management, Vol. 19 Iss: 4, pp.529-550.

Shuaib, M., Badurdeen, F., Rouch, K.E., Feng, S.C., Jawahir, I.S., (2014), "Product Sustainability Index (ProdSI) - A Metrics-based Framework to Evaluate the Total Life-cycle Sustainability of Manufactured Products", Journal of Industrial Ecology, Manuscript Accepted for Publication.

Shutterstock, (2014), "Bicycles. Isolated vector bike accessories set", Available via http://www.shutterstock.com/pic-148916186/stock-vector-bicycles-isolated-vector-bike-accessories-set.html?src=fszYp731DDJFTR92pSQt4A-1-11, Accessed 4/15/2014.

Simons, D. and Mason, R., (2002), “Environmental and transport supply chain evaluation with sustainable value stream mapping,” 7th Logistics Research Network Conference. Birmingham, UK.

Singh, B, Garg, S, Sharma, S, (2011), "Value Stream Mapping: literature review and implications for Indian industry," The International Journal of Advanced Manufacturing Technology, Vol. 53, Iss. 5-8, pp 799-809.

Solding, P., Gullander, P., (2009), "Concepts for simulation based Value Stream Mapping", Proc. of the 2009 Winter Simulation Conference, December 13-16, Austin, Texas, pp. 2231-2237.

Standridge, C., Marvel, J., (2006), "Why Lean Needs Simulation.", Proc. of the 2006 Winter Simulation Conference, December 3-6, Monterey, California, pp. 1907-1913.

StatTrek, (2014), "Important Statistics Formulas." Statistics Formulas. N.p., n.d. Web. 01 July 2014. Available via http://stattrek.com/statistics/formulas.aspx.

Tako, A., Robinson, S., "The Application of Discrete Event Simulation and System Dynamics in the Logistics and Supply Chain Context", Decision Support Systems, Vol. 52, Iss. 4, pp. 802-815.

Terzi, S., Cavalieri, S., (2004), "Simulation in the supply chain context: a survey", Computers in Industry, Vol. 53, Iss. 1, pp. 3–16, http://dx.doi.org/10.1016/S0166-3615(03)00104-0.

Torres, A., Gati, A., (2009), “Environmental Value Stream Mapping EVSM as Sustainability Management Tool,” Proc. of Portland International Center for

Management of Engineering and Technology Conference 2009, August 2-6, Portland, Oregon, 1689-1698.

U.S. Department of Commerce website. 2009. http://trade.gov/competitiveness/sustainablemanufacturing/how_doc_defines_SM.asp Accessed 5/8/2014.

Wan, X., Orçun, S., Pekny, J., Reklaitis, G., (2003), "A Simulation Based Optimization Framework to Analyze and Investigate Complex Supply Chains", Computer Aided Chemical Engineering, Vol. 15, pp. 630-635.

Wang, P., Halim, I., Adhitya, A., Srinivasan, R., (2011), "Integrating Economic, Environmental and Social Indicators for Sustainable Supply Chains", Computer Aided Chemical Engineering, Vol. 29, 2011, pp. 1220–1224, http://dx.doi.org/10.1016/B978-0-444-54298-4.50023-4.

Zhang, H., Calvo-Amodio, J., Haapala, K., (2013), "A Conceptual Model for Assisting Sustainable Manufacturing through System Dynamics", Journal of Manufacturing Systems, Vol. 32, Iss. 4, pp. 543-549.

Zhang, X., Lu, T., Shuaib, M., Rotella, G., Huang, A., Feng, S.C., Rouch, K., Badurdeen, F., Jawahir, I.S., (2012), “A metrics-based methodology for establishing product sustainability index (ProdSI) for manufactured products” 19th CIRP International Conference on Life Cycle Engineering, Berkeley, pp. 435-441.

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