AN ABSTRACT OF THE DISSERTATION OF

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Improving the understanding the relations of sustainability behaviors in manufacturing systems and actively engaging with manufacturers (especially SMEs) in sustainability efforts is key to the long-term success of U.S. industry and the natural environment. This study addresses this urgent need by establishing a systemic approach for the design of costing methods by linking the economic, environmental, and social domains of sustainable manufacturing with systems thinking principles, and by understanding the actual sustainability-related behaviors in a metal product manufacturing setting with the collaboration of a small manufacturer. The proposed system dynamics-based method identifies sustainability factors and behaviors of the manufacturing system and depicts their relations across three system levels:, the enterprise level, the shopfloor level, and the process/operation level. The creative method design approach from the domain of systems thinking, manages to integrate economic assessment, environmental assessment, and social assessment methodologies and to quantify the assessment results, which are embedded in a systems dynamics model. The model, consisting of identified

manufacturing behaviors related to product design modification, environmental impact control, and process safety improvement, is able to assist decision makers by demonstrating sustainability performance changes over a determined time period. Based on the results of this research, U.S. manufacturers will be able to develop systemic costing approaches towards improving worker well-being, energy efficiency, and cleaner production at lower cost.

A Framework for Integrating Systems Thinking into Sustainable Manufacturing

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In the end, thanks are given to the author’s parents, Yizhen Zhang and Shouhuan Chen.

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Chapter 1. Introduction

In this chapter, the background of this research will be introduced, followed by the problem statement, research questions, objectives, tasks, hypotheses, limitations, and research merits. As this dissertation is based on several manuscripts, this chapter will also explain how the four manuscripts formed the theme of this research and how each manuscript is related to others. The manuscripts are provided in Appendix and Chapter 5.

1.1 Background

The 21st century requires engineers to design production systems to bring concurrent benefits to various stakeholders including the manufacturer, society, and natural environment (Rusinko, 2007; Gunasekaran & Spalanzani, 2012). On the one hand, environmental policies and social protection policies have been enacted in different countries due to pollution and waste emitted from production (Barrett, 1994). On the other hand, manufacturers seek practices to sustain their business activities by conforming to those policies while still modifiable and competitive in the market. Increasing environmental and social concerns have led to a need to confront the challenges of balancing economic priorities against environmental and social responsibilities (Zhang et al., 2013). As a result, the sustainable manufacturing concept has emerged over the past 40 years, and can be defined as "the set of systems and activities for the creation and provision of manufactured products that balance benefits for ecological systems, social systems, and economic systems" (Zhang et al., 2014). This requires developing strategies to balance interests of all stakeholders, and presents new challenges to engineering management research and practice.

Current sustainability assessment methods are deficient in aiding proactive engineering management decision making and elucidating broader sustainability opportunities within a manufacturing enterprise, often resulting in *ad hoc*, reactive decisions to circumvent fines, energy/waste costs, or simply poor public perception. While these challenges are long-recognized, industrial and academic research has focused on increasing efficiencies with the goal of reducing costs and environmental burdens – individually and simultaneously – with cursory integration of social sustainability metrics. Thus, traditional methods remain insufficient and inadequate to embrace sustainability considerations. Understanding complex, non-linear and time depend system behaviors within a manufacturing system is vital to solve current sustainable manufacturing challenges.

Since the 1920s, there have been efforts to develop an applied holistic approach to solving problems – known as systems thinking – for better understanding an organizational system's behaviors (Mingers, 2014). Systems thinking as a science arose in 1950s as the result of the efforts of researchers from varied backgrounds such as biology, sociology, philosophy, and cybernetics to holistically explain the organizational systems they studied (Jackson, 2000). Systems thinking encourages practitioners, such as engineering managers, to adopt sociological awareness, human well-being, and emancipation philosophies (disadvantaged groups being assisted to get what they are entitled to), helps find ways to be profitable while adhering to economic, environmental, and social *weltanschauung* (the worldview of an individual or group), and aims to take technical, practical, and emancipatory interests into consideration to address different aspects of problem situations. With more knowledge gained, engineering managers will be able to make predictions of system behaviors, which is seen as the essence of management (Deming, 1993). In manufacturing, systems thinking offers a holistic approach that can help understanding the influences among manufacturing sustainability factors by looking at problems as the result of root causes (and not symptoms) and being composed of interconnected parts. Without question, manufacturers understand the importance of the sustainability of their operations, since it is being demanded by their leadership, customers, and broader society. This understanding, however, is often limited to efforts to conduct qualitative decision making, without an accounting of tangible and intangible costs and with inaccurate and incomplete data. Thus, manufacturers, especially small to medium sized enterprises (SMEs), struggle to systematically and quantitatively evaluate the full costs of their production activities, particularly in resolving and disaggregating system-level costs. The full cost in this research is defined as the summation of product-related costs, which include direct and indirect costs due to the transformation of materials and energy through the use of labor and equipment.

Developed upon systems thinking principles, the full cost model proposed in this dissertation looks into understanding the underlying behaviors associated with production activities and improving the environmental and social responsibility of manufacturing systems from cost perspective.

1.2 Problem Statement

As introduced above, research shall analyze economic, environmental, and social benefit conflicts within the manufacturing system in order to solve complex sustainable manufacturing problems in a practical way. System thinking allows researchers to identify not only relations of certain human behaviors, but also the dynamics of sustainability performance measures. With systems thinking, decision makers can address problems holistically, ensuring that economic, environmental, and social policies and goals are achieved. *The problem that remains to be solved in research*, is that current sustainable manufacturing assessment methodologies exist to tackle individual, ad hoc problems, and practitioners need a theoretical guide to solve complex problems with an understanding of the full costs of their decisions.

Manufacturers often hesitate to invest in environmental, safety, and health efforts with long lead-time outcomes and uncertain returns on investment. The reason lies in the challenge of relating environmental and social practices to potential economic benefits. Manufacturers want to measure sustainability behaviors on a cost basis, which is a key measure in business. Current costing methods are capable of evaluating system or product unit based costs at a certain time. Costs, however, usually associated with activities the performance of which change over time. Therefore, expressing such cost changes becomes necessary in making strategic decisions. Several key questions must be answered, for example, how much can be gained by employing an environmental safety and health (ESH) program? How much can be saved by changing a manufacturing process setting (e.g., energy consumption, material use) in manufacturing? And what is economic performance of these environmental, safety, and health efforts over time? In current sustainable manufacturing practices, a methodology relating environmental and safety impact with costs in order to evaluate system sustainability performance over time.

Therefore, this research is intended to solve two problems. First, sustainable manufacturing practitioners are not equipped with systems thinking methods that will assist holistic decision making. A theoretical foundation is required to guide researchers and practitioners. Second, a methodology is lacking to relate sustainability factors to each other and to assess manufacturing sustainability performance using a monetary value.

1.3 Research Purpose

The purpose of this dissertation is to solve the two aforementioned problems. This dissertation will develop a framework to integrate systems thinking methodologies into sustainable manufacturing behavior assessment – a framework that will assist researchers gain an in-depth understanding of manufacturing sustainability behaviors. This dissertation will also propose a holistic, full cost model as a tool to make decisions in support of sustainability goals.

Theoretical Purpose

The theoretical purpose of this research is to incorporate systems thinking philosophies into sustainable manufacturing practices, gain understanding (from a cost perspective) of underlying sustainability behaviors of a manufacturing system. In particular, this research aims to establish a theoretical framework for existing systems methodologies being adapted and integrated into manufacturing sustainability problems solving - a framework that guides researchers and practitioners in analyzing and understanding sustainability behaviors and making decision. The understanding gained through this framework will assist manufacturing practitioners in balancing economic, environmental, and social benefits and costs across the various levels within a manufacturing system.

Practical Purpose

By developing a full cost model under the proposed theoretical framework, practitioners will be able to predict system behavior performance, under both short-term and long-term perspectives. By analyzing costs related to sustainability behaviors, environmental impact and social impact will be expressed with monetary value. Hence, manufacturing practitioners can make sustainability-related decisions from the cost perspective based on the developed full cost model.

Examples of system behaviors that can be included in the model are listed below:

a. Material use reduction in product redesign can result in changes to manufacturing settings, manufacturing energy consumption, raw materials costs, and production time. Material reduction, however, may also result in reduced product quality and potential customer loss.

b. Installing a piece of new equipment will generate long term benefit. Production, however, can be affected during and after the time of installation period due to unfamiliarity of operation, training, and unexpected system failures.

c. Energy planning is intended to reduce energy consumption. Unexpected consequences could include delays, errors, or poor product quality.

Examples of decision making scenarios that can be made from a full cost model are listed below:

a. Establishing an environmental, safety, and health (ESH) program will reduce cost in the long run. The decision maker, however, will need to determine implementation costs, future investment needs, payback period, and the financial long term benefit of this program.

b. Injuries are a common issue for manufacturers. Injury prevention and reduction practices will help reduce injury-related costs. Engineers and managers will need to understand how their decisions will affect system costs in order to control the occurance of injuries.

c. An energy reduction plan implementation requires collaboration across the production system. During implemention, unexpected failures might be resulted. The decision maker will need to determine the adaptation period for this plan in order to improve production performance over time.

1.4 Research Objective

The objective of this research is to establish a systemic framework for the design of manufacturing costing methods by linking the economic, environmental, and social domains of sustainability with systems thinking principles. This will be facilitated by understanding the actual sustainability-related behaviors (e.g., injury behavior) of a product manufacturing system and integrating these behaviors within a full cost model.

1.5 Research Questions

Several research questions stem from the abvove stated objective.

Research Question 1: How do the underlying manufacturing system behaviors influence environmental and social impact and their related costs?

Under general Systems Theory, the behaviors of a system are correlated. The performance of one behavior will provide direct or indirect feedback to another with delay or without delay (Bertalanffy, 2003). Undoubtedly, the sustainability behaviors inside the manufacturing system have feedbacks. However, the relations between those behaviors can be close and loose. The close and loose relations can be used to guide decision making because. In order to understand the relations, we need to understand the important relations that shall be considered in decision making.

In manufacturing systems, production activities affect environmental impact and social impact. Conversely, social impact should also affect environmental impact and production activities. Prior research, however, has not investigated the factors that lead to the inter-relations of these activities.

Research Question 2: How can manufacturing cost change over time as a result of product design and internal and external policy decisions?

In order to avoid risks of not understanding system behaviors, a decision making method, based on full cost estimation that can provide an overview of sustainability outcomes over time is needed. With the method, manufacturers should be able to make strategic decisions by balancing time variant successes and failures (benefits and costs) related to product design and policy changes.

1.6 Research Tasks

To answer the research questions posed above, the following three reseach tasks are completed.

Task 1: Review systems thinking principles and methodologies to establish a theoretical foundation by building a conceptual model for assessing the full cost of manufacturing. This requires integration of sustainable manufacturing and systems thining principles and methods as well as defining key terms and operational definitions. This task aims to partially answer *Research Question 1* by setting up a theory basis for understanding sustainable manufacturing system behaviors.

Task 2: Identify and characterize the underlying behaviors among economic, environmental, and social behaviors. A full cost model approach will enable discovery of complex feedback relations within manufacturing systems, e.g., the effect of energy planning on product quality and flow of production. This task aims to answer *Research Question 1* by outlining system behaviors at three manufacturing system levels (i.e., enterprise level, shopfloor level, operation level).

Task 3: Identify the behaviors of environmental impact and social impact related to cost, and create and validate a full cost model to illustrate an operational framework for understanding manufacturing system behaviors. This task aims to answer Research 2 by building a system dynamics based model of an injury behavior in a manufacturing system.

1.7 Hypothesis

The model developed in Tasks 1-3 will be used to analyze the relations of sustainability factors in the system to test two general hypotheses and several sub-hypotheses.

General Hypothesis 1: Underlying manufacturing system behaviors influence environmental and social impacts and their related cost.

> Sub-Hypothesis 1: The variation of manufacturing activity variables (e.g., product material use, setup time, and machining time) independently affects environmental impact and social impact.
>
> Sub-Hypothesis 2: The simultaneous changes on manufacturing activity variables affect environmental impact and social impact

General Hypothesis 2: Manufacturing cost changes over time as a result of internal and external policy decisions.

> Sub-Hypothesis 1: Manufacturing cost changes over time as a result of internal policy decisions.
>
> Sub-Hypothesis 2: Manufacturing cost changes over time as a result of external policy decisions.

1.8 Limitations

The limitations of this research are:

a. The manufacturing system model is built based upon a medium manufacturer which may not be representative of all manufacturing systems.

b. This model is not an optimization model. Therefore, it cannot be used to find optimal parameters for a target system behavior.

c. Data that is not available from the case manufacturer is alternatively retrieved from US government agency.

e. The level of detail of the model depends on the accuracy researched and data availability

e. System behaviors modeled in this research are limited. More behaviors need to be modeled in order to create generalized manufacturing behavior performances.

f. Model validation is bounded by techniques provided by Barlas (1996). The model is partially validated due to the lack of comparable cases.

1.9 Research Outcomes and Outputs

Table 1.1 shows the outputs from this research. Four manuscripts will be generated, two have been published in peer-reviewed journals and one is published in peer-reviewed conference proceedings. Table 1.2 shows the research outcomes with associated research tasks and outputs.

Table 1.1 Output Manuscripts

#	Manuscript	Reference	
1	Manuscript 1: Assisting Sustainable Manufacturing Enterprise through System Dynamics: A Conceptual Model	Zhang H., Calvo-Amodio J., Haapala KR (2013) A conceptual model for assisting sustainable manufacturing through system dynamics. Journal of Manufacturing Systems, *http://dx.doi.org/10.1016/j.jmsy.2013.05.007*	Appendix A
2	Manuscript 2: A Systems Thinking Approach for Modeling Sustainable Manufacturing Problems in Enterprises	Zhang, H., Calvo-Amodio, J., Haapala, K.R., 2013. A Systems Thinking Approach for Modeling Sustainable Manufacturing Problems in Enterprises, in: Proceedings of American Society for Engineering Management International Annual Conference. Presented at the 2013 American Society for Engineering Management International Annual Conference, Minneapolis, MN.	Appendix B
3	Manuscript 3: Establishing Foundational Concepts for Sustainable Manufacturing Systems Assessment through Systems Thinking	Zhang H, Haapala K.R., Calvo-Amodio J. (2014) Establishing Foundation Concepts for Sustainable Manufacturing Systems Assessment. International Journal of Strategic Engineering Asset Management.	Appendix C
4	Manuscript 4: A Systemic Costing Method for Developing a Dynamic Cost Model of Sustainable Manufacturing Systems	Zhang H,. Calvo-Amodio J, Veltri A. (2014) A Full Cost Model for Sustainable Manufacturing Systems	Chapter 5

Table 1.2. Research Outcomes and Associated Tasks and Manuscripts

Outcome	Tasks	Manuscript
The theoretical framework shall integrate systems thinking principles and methodologies into sustainable manufacturing practices.	Task 1	A, B, C
Typical system behaviors shall be depicted in a conceptual model.	Task 2	A, B
The relations among productions behaviors, environmental impact, and social impact shall be captured.	Task 3	4
The system dynamics-based cost model shall generate performance of system activities over time.	Task 3	4

1.10 Research Scope

Figure 1.1 shows the scope of this dissertation and the future of this research. The research of integrating systems thinking and sustainable manufacturing assessment requires a theoretical foundation (Manuscript 1, 2, 3) to be established for guiding researchers and practitioners. Systems thinking methodologies aid in understanding system behavior relations and solving complex manufacturing problems. The full cost model (Manuscript 4), as a pilot study of this research is grounded on systems thinking principles. It illustrates how manufacturing practitioners can use systems thinking to better understand behaviors with two example cases. The full cost model, which shall include more dynamic system behaviors, will be developed in future research when more real world system behaviors are available.

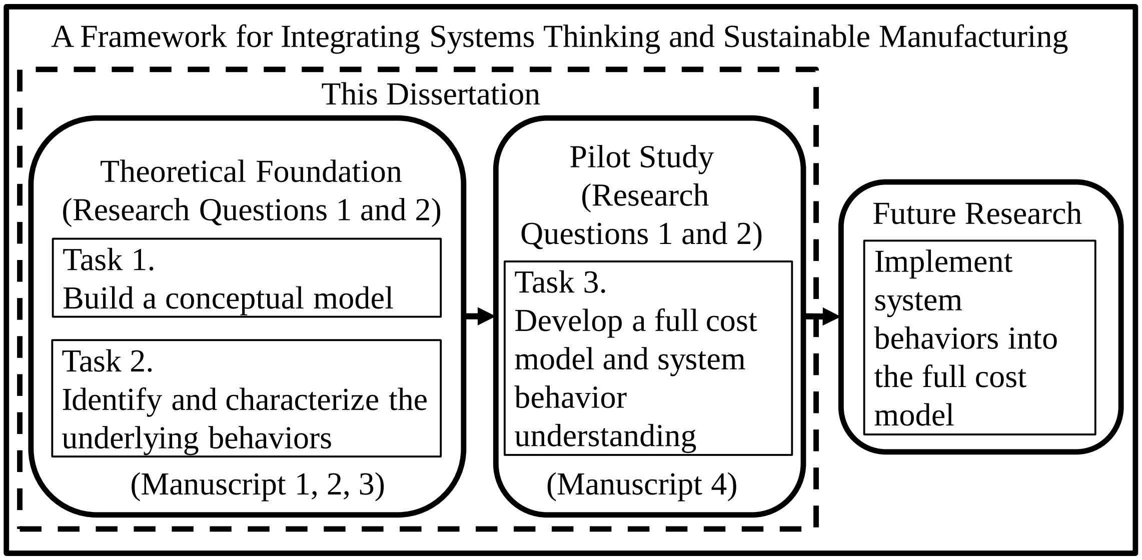


Figure 1.1. Research Scope

Chapter 2. Literature Review

This chapter introduces the existing literature on which this research is grounded and shows how the research in this dissertation will go beyond the existing knowledge base. First, the primary theory and historical background of sustainable manufacturing and systems thinking will be reviewed, followed by a rationale for integrating the two disciplines. This chapter draws from three peer-reviewed manuscripts produced as part of this dissertation research. The manuscripts can be found in Appendix A-C.

2.1 Primary Theory and Historical Background – Sustainable Manufacturing

Over 80 articles were collected from the 1980s to the present (2013) covering four areas of sustainable manufacturing research and selected about 40 representative articles were collected for content analysis. Several state of the art reviews by other researchers were also reviewed, including Westkämper et al. (2000), Ramani et al., (2010), Duflou et al., (2012), Umeda et al., (2012), and Haapala et al., (2013), which provided insights to structuring the problem situation.

2.1.1 Sustainable Manufacturing Methodologies

Fundamental methodologies around sustainable manufacturing are categorized into assessment methods and research concepts. The life cycle assessment (LCA) environmental impact assessment method has been widely used by practitioners to investigate environmental impacts associated with a product or system over the past twenty years. According to ISO 14040, the method comprises four stages: goal and scope definition, life cycle inventory, life cycle impact assessment, and interpretation (ISO, 2006, p. 14040). Besides LCA, three other approaches are commonly used, including process-based modeling methods, input and output (I/O) methods, and hybrid methods (Zhang & Haapala, 2011). Life cycle cost assessment (LCCA) or life cycle costing (LCC) concerns examining costs in monetary terms, taking into consideration all the cost factors related to an asset during the operation life (Woodward, 1997). It has been applied in cost assessment since 1970s (Woodward, 1997) and to sustainable manufacturing practices since the 1990s (Westkämper et al., 2000). Material flow cost accounting (MFCA), developed by Japanese manufacturers, is a tool to reduce environmental impact and cost over the product life cycle (Jasch, 2008). With increasing attention from consumers, social impact has become a critical concern for manufacturers. The social domain of sustainable manufacturing considers human safety and societal benefits. A framework for social life cycle assessment (Social LCA), which aligns with ISO14040 and ISO14044 standards, was developed by UNEP intending to provide enterprises a guideline of conducting social impact assessment (Benoît et al., 2010). Besides Social LCA, Hutchins and Sutherland (2008) studied the degree to which social impacts have been included in LCA and how social metrics could be incorporated into input-output analysis. Though research on social life cycle approaches and its relationship with LCA was recognized in the 1990s (O'Brien et al., 1997), little work was done in 2000s (Hunkeler, 2006).

Since the 1990s, several environmental life cycle impact assessment (LCIA) methods have been developed. For example, CML 2002 (Guinee, 2002) built upon the CML 1992 method (Heijungs, 1992), which operationalized the ISO 14040 LCA standards. It includes recommended normalization methods but no weighting methods (ILCD, 2010). Eco-indicator 99, besides serving the general purpose of LCIA, simplified the interpretation of results which can be calculated in single point eco-indicator scores (Goedkoop & Spriensma, 2001). ReCiPe 2008 was developed based on the CML 2002 and Eco-indicator 99 methods. It integrates midpoint and endpoint approaches in a single framework, and includes both normalization and weighting methods (Goedkoop et al., 2009). EDIP 97, developed in Denmark, supports the emission-related impact categories at a midpoint level as well as resources and working environment (Wenzel et al., 2000). EDIP 2003 is a follow up of EDIP 97 and includes exposure assessment based on regional information in the life cycle impact assessment of non-global emission-related impact categories at midpoint (Hauschild & Potting, 2005). EPS 2000 was first developed in 1990 and last updated in 2000. The method is designed to be used with Monte Carlo analysis and was the first endpoint based method, the first method that used monetization, and the first method that fully specified uncertainties (ILCD, 2010). The TRACI method developed by the U.S. EPA is a midpoint method representing the environmental conditions in the United States as a whole or per state (US EPA, 2003). The BEES method, developed by U.S. NIST measures the economic and environmental performance of building products (Gloria et al., 2007). The environmental performance measures are based on the ISO 14040 standards (ISO, 2006). IMPACT 2002+ proposes implementation of a combined midpoint/damage approach, linking all types of life cycle inventory (LCI) results through 14 midpoint categories to four damage categories (Crettaz et al., 2002). LUCAS was developed in 2005 based on the EDIP2003, IMPACT2002+, and TRACI methods to support efforts of Canadian LCA practitioners (Toffoletto et al., 2007). The LIME method, recently updated to LIME 2 (Itsubo and Inaba, 2012), was developed in Japan, building on various inputs from experts from around the world, and is used widely in Japan (Itsubo, Sakagami, Washida, Kokubu, & Inaba, 2004). Other methods have been developed, for example the Ecological Scarcity Method (Ecopoints 2006) developed in Switzerland (Brand et al., 1998) and MEEuP (Kemna et al., 2005) developed on behalf of the European Commission.

2.1.2 Sustainability Indicators

Over the past two decades, there has been a motivated effort to develop sustainability indicators for evaluation and improvement within the manufacturing industry at a number of levels (Feng, Joung, & Li, 2010). At the sector level, or even higher, material flow analysis (MFA) can be applied, which analyzes quantified flows and stocks of materials or substances (Brunner & Rechberger, 2004). Additionally, ecological footprinting (e.g., carbon, water, and nitrogen) has been undertaken, which measures human demand for natural capital that may be contrasted with the planet's ecological capacity to regenerate (Rees, 1992). Environmental pressure indicators developed for the European Union (EPI-EU) aim to give a comprehensive description of the most important human activities that have a negative impact on the environment (Kommission, 2000) (Feng et al., 2010). Similarly, the Intergovernmental Panel on Climate Change (IPCC) developed an approach to assesses the scientific, technical, and socio-economic information relevant to understanding the risk of human-induced climate change (IPCC, 2004). The Organization for Economic Co-operation and of Development (OECD) developed a core set of 50 environmental indicators, which covers a broad range of environmental issues and economic data to track the environment effects and responses by governments, industry, and households.

At the facility or corporation level, the Global Reporting Initiatives (GRI) provides guidelines for enterprises to assess sustainability performance and generate sustainability reports (GRI, 2006).

The General Motors Metrics for Sustainable Manufacturing (GM M4SM) includes over 30 metrics in six categories: environmental impact, energy consumption, personal health, occupational safety, waste management, and manufacturing costs (Dreher, Lawler, Stewart, Strasorier, & Thorne, 2009). The Wal-Mart Sustainability Product Index Questions (Wal-Mart Qs) look at the supply chain as a whole to develop measurement and reporting systems for product sustainability (Wal-mart, 2009). Instead of developing internal methods, the standard ISO 14031 Environmental Performance Evaluation guidelines can be employed, and contain two categories of indicators: environmental condition indicators (ECIs) and environmental performance indicators (EPIs). Similarly, the Eco-Management and Audit Scheme (EMAS), which was developed by European Commission, enables organizations to assess, manage and continuously improve their environmental performance (European Commission, 2006). The Dow Jones Sustainability Index (DJSI) is used to assess the sustainability performance of the top 10% of the companies in the Dow Jones Global Total Stock Market Index (DJSI, 2013).

At the product and process level, there are several LCIA methods to be employed, as described above. ReCiPe 2008 includes 18 impact categories at the midpoint level and three impact categories at the endpoint level: damage to human health, damage to ecosystem diversity, and damage to resource availability (Goedkoop et al., 2009). The Ford Product Sustainability Index (Ford's PSI), which is based on external assessment (e.g., life cycle assessment and life cycle costing), includes eight indicators in environmental and health, societal, and economics categories (Ford, 2007). The Sustainable Manufacturing Indicators developed by National Institute of Standards and Technology (NIST) contains five major categories: environmental stewardship, economic growth, social well-being, technological advancement, and performance management (US Department of Commerce, 2013).

Indicators presented above have been widely used by industry and government agencies. Practitioners, especially at small and medium enterprises (SMEs), however, in order to conduct sustainability assessment for decision making, often select their own indicators in an ***ad hoc*** manner. A top-down approach has been proposed that comprises four steps: determine the goal of the assessment, choose a metric type, determine the manufacturing scope of the assessment, and determine the geographic scope of the assessment (Reich-Weiser et al., 2008). In terms of the metric selection quality, (Feng et al., 2010) suggested that well-defined sustainability performance metrics for the manufacturing industry should be measureable, relevant and comprehensive, understandable and meaningful, manageable, reliable, cost-effective data accessible, and be timely in manner. Focusing on product and process metrics, a framework for selection has been proposed where the product metrics are grouped under a range of metrics clustered to make them more structured (Lu et al., 2010). The process metrics are identified based on the inputs/outputs of a machining process and are categorized into a hierarchy structure including line level, workstation level, and operation level. A method was proposed by Sutherland and co-workers for self-identified green business SMEs to develop their own indicators (Clarke-Sather, Hutchins, Zhang, Gershenson, & Sutherland, 2011). Detailed operations were described to guide practitioners in conducting the indicator development process and assign weightings to indicators.

There has been work specifically focused on addressing the social aspects of sustainability through social indicators. Lee et al. (2010) proposed a set of dimensions for human work to assist industrial sustainability assessment and work design. Based on the effect, dimensions were categorized into individual and societal levels. The dimensions identified include compensation, physical and mental safety, demand, variety of tasks and roles, social interaction, growth of skills and knowledge, opportunities for accomplishments and status, value of work, autonomy, and growth and personal development. Lee et al. (2012) presented an approach to quantify these metrics through identifiers for the dimensions, and established a method for measuring the fit between work that is ideal for a society and the work the company offers to the workers of the society. Several other researchers have focused on developing social metrics of sustainability, which can be found in Parris and Kates (2003), Brent and Labuschagne (2006), and (Hutchins, 2010). However, currently there is no agreed upon approach that would appropriately assess social impact on manufacturing from the product/process level through the enterprise level.

2.1.3 Sustainable Manufacturing Decision Making

Research for integrating sustainable manufacturing assessment into decision making has been performed since as early as late 1980s. Malakooti and Deviprasad (1987) developed an interactive multiple criteria approach and decision support system (DSS) for metal machining operations. They focused on minimizing machining cost and maximizing production without sacrificing workpiece quality. Over the past three decades, researchers have attempted different approaches to integrate environmental assessment into decision making, and many decision-making methods have been applied to assist manufacturing assessment, including the analytic hierarchy process (Avram et al., 2010), Markov processes (Milacic et al., 1997), and pairwise comparison analysis (Basu & Sutherland, 1999). (Hersh, 1999) pointed out that sustainability decision-making research is required in a number of different areas, including the development of improved models for decision making and problem classification, the development of improved user interfaces, and DSS based on different types of decision making models. Further understanding should be gained regarding the types of decision makers, organizations, and situations which make approaches from one end of the spectrum more appropriate than those from the other. Research on model classification should include the development of a taxonomy of the different types of problems that occur in sustainable decision making. Romaniw (2010) argued that detailed assessments are still lacking, as stakeholders need detailed impact assessments for their particular phase of product life. More detailed assessments give stakeholders information that can be used for better environmental management and more environmentally benign operations.

Olson et al. (1999) proposed a method utilizing input-output analysis coupled with Markov decision making to assist plant managers in determining and modifying the environmental impacts of their facility. Markov decision making is preferred in dealing with stochastic environments, though it does not fit all manufacturing processes. Basu and Sutherland (1999) integrated multi-objective programming into decision making involving several sets of objective functions in order to optimize a process. Pairwise comparison analysis (PCA) was undertaken to assign importance to each objective. This work provides a foundation for assigning weights to criteria of such assessments. Avram et al (2011) proposed a multi-criteria decision method for economic and environmental assessment of the use phase of machine tool system. AHP was used to structure the decision problem at both the process and system level. In order to assist sustainable decision makers in integrating assessment results from all three domains of sustainability. Clarke-Sather et al. (2011) utilized pairwise comparison for developing weights for economic, environmental, and social indicators. Zhang and Haapala (2012), took a further step and utilized AHP and pairwise comparison method to develop sustainability metric weightings, and then used a PROMETHEE method to rank decision making alternatives.

2.1.4 Sustainability Assessment of Manufacturing Processes

Sustainability assessment has been conducted for various manufacturing processes since the 1990s. In the early stage of process analysis, researchers developed methods to conduct assessment. Munoz and Sheng (1995) developed a model to predict the environmental impact of machining processes. The model identified quantifiable dimensions including energy utilization, process rate, workpiece primary mass flow, and secondary flow of process catalysts. Jawahir and Jayal (2011) conducted sustainability evaluation for dry, near-dry, and cryogenic machining. Choi et al. (1997) developed an assessment method based on the material balance of a process and the relationship among the different processes. Later, with LCA methods gaining acceptance and wider use, literature tends to have two directions.

First, specific models and approaches have been developed to analyze certain manufacturing or machining processes with LCA techniques. For example, Dahmus and Gutowski (2004) presented a system-level environmental analysis of machining, which includes not only material removal process, but also material preparation and cutting fluid preparation. Rajemi et al. (2010)

developed a model for optimizing the energy footprint of a turning process, identifying critical parameters in minimizing energy use and reducing energy cost and environmental footprint. Yuan and Dornfeld (2010) conducted sustainability analysis on atomic layer deposition processes through material and energy flow analysis, and suggested strategies and methods for sustainability performance improvement. Haapala et al. (2012) analyzed steel product manufacturing processes and developed models for improving environmental performance of steel making and casting processes.

Second direction is case study exporation using LCA methodologies. There are many case studies in this direction. Example studies include Gamage and Boyle (2006) who conducted an LCA on manufacturing of an office chair. Serres et al. (2011) conducted using LCA on the MESO-CLAD (Direct additive laser manufacturing, Construction Laser Additive Directe in French) process and conventional machining, among others.

2.1.5 Sustainable Manufacturing Research Limitations and Challenges

The review of prior work above reveals that the community has been conducting research within the four areas identified for at least the past two decades. Although several have been developed, sustainability assessment methodologies still need a precise and well-accepted method to standardize practice. Social impact assessment, due to its complex nature, for example, remains a challenge to researchers, and associated normalization and weighting methods must be developed to properly assess social impact. Sustainability indicators have been well developed in literature, however, the method of how practitioners select or develop proper indicators and utilize those indicators must be a focus of researchers. Decision making research for sustainable manufacturing is primarily limited to a single sustainability domain (economic, environmental, or social). Multi-criteria decision making methods, including weighting of criteria and social assessment results, must be developed to better assist practitioners. Other decision making approaches (e.g., fuzzy logic) also need to be better applied to sustainable manufacturing problems. Sustainability assessment of manufacturing processes will continue to be a major component of manufacturing research – it is enabling processes that have led to technology advancements (Jawahir & Jayal, 2011).

Unfortunately, it can be seen that few efforts have been undertaken to assist practitioners in systemically utilizing research results in solving real-world sustainable manufacturing problems, which are often quite complex and rife with uncertainties in prediction. Past research has largely focused on a single sustainability domain or one manufacturing process. Designing a sustainable manufacturing system requires understanding not only individual processes, but also understanding the underlying relations among humans, processes, and environmental consequences. Nevertheless, economic evaluation of sustainability as an interest of industry remains a challenge to academia. Therefore, in order to make wise decisons it is critical for SMEs to understand their systems from micro (operation) through macro (enterprise) levels and, using this understanding, diagnose the causes of certain behaviors for the design of more sustainable engineering and policy solutions. Sustainable manufacturing decision making requires integration of knowledge from within the domains of economic, environmental, and social impact analysis to enable the establishment of full cost modeling of manufactured products and manufacturing systems.

A full cost model. Manufacturers often hesitate to invest in environmental, safety, and health efforts with long lead-time outcomes and uncertain returns on investment. The reason lies in the lack of relating environmental and social practices to potential economic benefits. As the most important measure of success in business, manufacturers tend to measure sustainability behaviors with cost. For example, how much can we gain from employing an environmental safety and health (ESH) program? How much can we save from changing the process setting (i.e., feed, speed, depth of cut) in manufacturing? Therefore, a full cost model relating all sustainability practices needs to be designed so as to have US manufacturers, especially SMEs, understand the potential monetary benefit from sustainability practices.

Fundamental system behaviors. Understanding the relations of sustainability behaviors in manufacturing systems and actively engaging with manufacturers (especially SMEs) in sustainability efforts is key to the long-term success of U.S. industry and the natural environment. It is critical for SMEs to understand their systems from micro (operation) through macro (enterprise) levels; and through this understanding, diagnose the causes of certain behaviors for the design of more sustainable engineering and policy solutions. In existing literature, this understanding is limited.

Several researchers have addressed this urgent need to have a systemic approach in sustainability research. According to Gutowski (2011): *to connect manufacturing to the new Science of Sustainability, much larger boundaries of analysis need to be considered. While an evaluation at the level of the firm is a desirable goal, without a credible framework that connects the firm to the planet, the local evaluation may be meaningless*. Fiksel (2013) posited: *Sustainability* *challenges cannot be addressed in isolation, because problems are highly interdependent and most solutions have hidden consequences*, and he went on to say *that the emerging field of sustainability science and engineering argues that a "systems approach" is needed to understand the intricate linkages among environmental media, human health, ecology, and economic activities, and to support wise decision making*. Efforts on integrating systems thinking into sustainable manufacturing and connecting the three sustainability domains together either remain calling for research (Kibira et al., 2009) or focus on world level eco-system sustainability (Fiksel et al., 2013).

A decision making method. In order to avoid risks of not understanding system behaviors, a decision making method, *based on full cost estimation* that can provide an overview of sustainability outcomes over time is needed. With the method, manufacturers should be able to make strategic decisions by balancing successes and failures (benefits and costs) over time. Existing work includes a proposed system dynamics framework (Kibira et al., 2009). The framework, however, focused on facilitating collaboration on research instead of understanding system behaviors and being a decision making method.

2.2 Primary Theory and Historical Background – Systems Thinking

Systems thinking science offers a holistic approach to understand the interactions between factors within a system; it also provides an approach to understand complex problems as a system of interconnected problems. Systems thinking science provides a framework to holistically analyze and understand system behaviors. Approaches to systems thinking include hard systems thinking, system dynamics, soft systems methodology, and total system intervention, among others.

2.2.1 Hard Systems Thinking

The term ***hard systems thinking*** was given by Checkland (1985) to label various systems approaches including operations research (OR), systems analysis (SA), and systems engineering (SE). Such approaches aim to build models, primarily mathematical, to capture the working of real world problems as accurately as possible. In hard systems thinking, systems are defined to be goal seeking. Hard systems thinkers believe the world is a set of systems and that these can be systematically engineered to achieve objectives. Hard systems thinking is criticized, however, in that the modeling is about simplification following a logical positivistic or reductionist approach. It also demands the goal of the system of concern to be clearly defined before analysis and minimizes the effect of human behavior on the system.

2.2.2 Soft Systems Methodology (SSM)

Soft Systems Methodology (SSM) is "a methodology, setting out principles for the use of methods, that enables intervention in ill-structured problem situations where relationship-maintaining is at least as important as goal-seeking and answering questions about 'what' we should do as significant as determining 'how' to do it" (Jackson, 2003). SSM mainly focuses on the learning that occurs when ideal systems are confronted with reality. Compared with hard systems thinking, which is goal-seeking oriented and assumes the world contains systems which can be "engineered," soft systems thinking is system learning oriented and assumes that the world is problematic but can be explored by using systems models (Checkland, 1985). Approaches include soft operational research (Soft OR), which is concentrated on defining the situation, resolving conflicting viewpoints, and coming to a consensus about future action.

Jackson (2003) classified applied systems thinking approaches within four sociological paradigms according to their problem context nature (Figure 2.1). The horizontal axis in the figure shows the nature of relationships among those concerned with the problem context – participants. Participants in a unitary relationship share similar values, beliefs, and interests. Those in a pluralist relationship do not share the same values and beliefs. Participants in coercive relationships have few interests in common and hold conflicting values and beliefs. The vertical axis shows the complexity of problems to be studied. Complexity continuously changes from simple to complex. The two system types are conceptualized at two extremes (Flood & Jackson, 1991; Jackson & Keys, 1984; Jackson, 1990).

<table>
<tr><th></th><th></th><th colspan="3">Relationship Between Participants</th></tr>
<tr><th></th><th></th><th>Unitary</th><th>Pluralist</th><th>Coercive</th></tr>
<tr><td rowspan="2">System Complexity</td><td>Simple</td><td>Statistical Quality Control, System Dynamics Economic Sustainability</td><td rowspan="2">General Systems Theory, Interactive Planning,
Soft Systems Methodology, System Dynamics, Social Sustainability</td><td>Creative Problem Solving, Critical Systems Heuristics</td></tr>
<tr><td>Complex</td><td>System Dynamics, Viable System Model, Environmental Sustainability</td><td>Not Defined</td></tr>
</table>

Figure 2.1. Grid of problem contexts (Adapted from Flood & Jackson (1991))

2.2.3 System Dynamics

System dynamics was developed in the middle of the twentieth century by Forrester to understand the time variant behavior of systems, and is based on feedback control theory (Brown & Donald Campbell, 1948; MacMillan, 1951; Porter, 1950). System dynamics not only assists understanding of system structures and dynamics of complex systems, but also provides a rigorous modeling method to build simulations of complex systems. Such simulation models can be used to design more effective policies and organizations (Sterman, 2000). System dynamics has been applied to issues as diverse as corporate strategy, the dynamics of diabetes, the cold war arms race between the US and USSR, and even the combat between HIV and the human immune system (Sterman, 2000).

System dynamics models use positive and negative feedback loops to identify the dynamics that arise from these interactions. In system dynamics, a causal loop diagram (Figure 2.2) reveals the structure of a system. By understanding the structure of a system, it becomes possible to ascertain the system's behavior over a period of time (Meadows, 2008). System dynamics also adopts mental models, which are relative, enduring, and accessible internal conceptual representations of an external system whose structure maintains the perceived structure of that system, to build and understand the structure of the complex system (Doyle & Ford, 1998). Another characteristic is that system dynamics describes complex systems using quantitative and qualitative modeling methods(Forrester, 1961). This approach can facilitate the modeling of a manufacturing system's sustainability policy and management decisions.

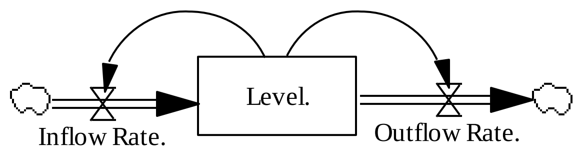


Figure 2.2 Causal loop diagram (Calvo-Amodio, 2014)

An effective model relies on a wide range of information about the system (Forrester, 1980). Information can be classified into three categories: mental, written, and numerical data (Figure 2.3). Carried information decreases from mental databases to numerical databases (Forrester, 1991). A mental model contains information for decision making points and behaviors, e.g., reasons for certain responses (Forrester, 1991). The written database contains information from published literature that has been processed. The numerical database is only available for certain parameter values and contains less information than the mental model database and written database.

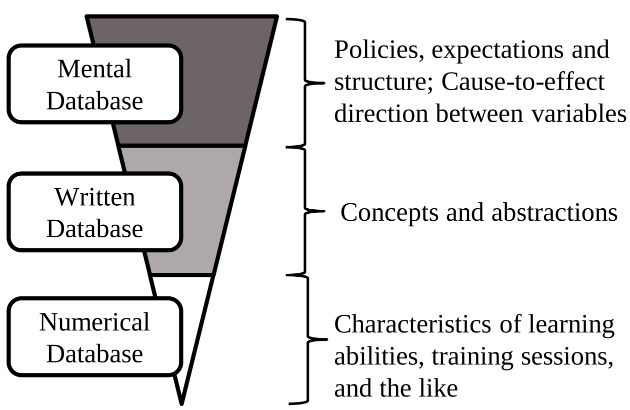


Figure 2.3. Decreasing information content in moving from mental to written to numerical databases (Calvo-Amodio, 2014)

System dynamics modeling can satisfy the goal of manufacturing enterprise decision making based on sustainability assessment. Variables captured in a model to support this goal would include both hard variables (relates to attributes that are quantifiable and quantification can be validated) and soft variables (relates to the attributes of human behavior). Wastes, energy consumption, material use, and related factors are primary concerns for environmental impact assessment; labor cost, material cost, transportation cost, and related factors are major concerns for economic impact assessment; and injury rate, noise level, wage level, and related factors are concerns for social impact assessment.

The actual decision making process is another system modeling domain, which involves considering human behavior and values from the operational level through the enterprise level of the system. The decision making process within each level specifically serves the purpose of satisfying the goals of each substructure of the system model. These substructure representations can accept the complexity, nonlinearity, and feedback loop structures that are inherent in social and physical systems.

2.2.4 A System of Profound Knowledge

Deming (1993) introduced the concept of the system of profound knowledge to provide an outside view to understand the system, which he believed cannot be understood by itself. The layout of profound knowledge includes four parts – appreciation for a system; knowledge about variation, which admits that system performance has variation; theory of knowledge, namely prediction is based on the understanding of the system; and psychology, which is to understand people's behavior within a system. As the theory can be applied to the various aspects of sustainable manufacturing system behaviors, it can be a link to connect sustainable manufacturing research and systems thinking research. The connection is described within the conceptual model presented in Chapter 3.

2.2.5 Total Systems Intervention

Total systems intervention (TSI) was developed by Robert Flood and Michael C. Jackson in the late 1980s and early 1990s based on the philosophy and theory formulated as critical systems thinking (Flood, 1990). TSI can be used in a coherent manner to promote successful intervention in a complex organizational and societal problem situation. Sociological awareness, human well-being, and emancipation comprise the philosophical base for TSI, which aims to take technical, practical, and emancipatory interests into consideration to address different aspects of problem situations. There are three phases in TSI (Jackson, 2003), i.e., creativity, choice, and implementation, taken in order to understand the problem context, choose the appropriate system approach, and solve the problem. Because the problem context changes over time, TSI is a dynamic meta-methodology.

2.2.6 Creative Design of Methods

Creative design of methods (CDM), sometimes called TSI2, was developed by Gerald Midgley (1997), who posited that the drawing of boundaries is crucial for determining how improvement is to be defined and what action can be contemplated. At the beginning of a system intervention, it is necessary to gather the people involved in the system from different perspectives. He also argued that justifying systems intervention requires continually redrawing the boundaries to "sweep in" stakeholders previously excluded from consideration. The proposed creative design of methods (changed to creative design methodology in 1997) looks at a problem as a series of systematically interrelated research questions. Each question is addressed using different methods or part of a method. Then, synthesis is completed to allow individual questions to be addressed as a part of a whole system of questions.

2.3 Systems Thinking and Sustainable Manufacturing

A sustainable manufacturing system is a complex system with various factors that influence each other not only through various systemic levels (i.e., the enterprise, facilities, and operations), but also across sustainability domains (i.e., economic, environmental, and social). A study by Zhang and Haapala (2012) demonstrated that a machining process setting change can increase production rate and lead to cost savings. On the other hand, however, that setting change may cause additional environmental and social impacts, including energy consumption, material use, and operator health effects. In addition, although a process setting change may have promising sustainability performance at the operation level, the decision may conflict with a facility manager's strategy; a decision made at the shopfloor level may have greater sustainability benefits than at a lower operational performance level. This utilitarianism philosophy is a common engineering ethic in solving such problems in management level decision making. A criticism is that the distribution of goods and harms may not be fair (Manion, 2002). Therefore, research shall analyze those conflicts within the system in order to solve problems in a practical way. Systems thinking allows researchers to identify not only relations of certain human behaviors, but also the dynamics of assessment that results from each sustainability domain.

With this ability, decision makers can address problems holistically, and ensure economic, environmental, and social policies and goals are achieved.

Researchers have applied system dynamics to solve sustainability-related problems for several decades (Wolstenholme, 1983), but studies are limited in modeling sustainable systems. Since the 1980s, efforts have investigated modeling sustainable development (Wolstenholme, 1983; Bockermann, Meyer, Omann, & Spangenberg, 2005) and industry environmental impact (Rehnan, Nehdi, & Simonovic, 2005 ;Anand, Vrat, & Dahiya, 2006). In addition, others (Kantardgi, 2003; Oyarbide, Baines, Kay, & Ladbrook, 2003; Seidel et al., 2008; Tesfamariam & Lindberg, 2005) have adopted system dynamics in modeling of manufacturing systems, yet few environmental impact and social considerations have been involved in the analysis.

In recent years, Kalninsh & Ozolinsh (2006), Kondoh & Mishima (2011), and Kibira et al. (2009) have proposed frameworks for using system dynamics in sustainable manufacturing to improve collaboration, sharing and reusing of systems dynamics models through a defined vocabulary and structured data. These have not led to operational methods and tools, however. Unless sustainable manufacturing practitioners adopt systems thinking principles, system dynamics will not be properly utilized in modeling sustainable manufacturing. Therefore, work needs to be done to educate researchers in systems thinking and then to advance the use of system dynamics models to analyze the dynamics of manufacturing systems and improve their sustainability performance.

Chapter 3. A Conceptual Model for Assisting Sustainable Manufacturing Decision Making with System Dynamics

In this chapter, a general conceptual model for assisting sustainable manufacturing enterprise decision making is proposed. Operational definitions for this research are first presented, followed by a conceptual model which includes three structures: enterprise level structure, shopfloor level structure, and operation level structure. Variable definition, model development, and model validation within each structure will also be discussed.

3.1 Root (Operational) Definitions for Sustainable Manufacturing Systems Thinking

In this section, several operational definitions are proposed (Table 1) in the context of sustainable manufacturing system thinking. The terms were selected based on the frequency of occurrence in existing sustainable manufacturing research. The definitions were developed after reviewing a set of prior definitions in the context of sustainable manufacturing. In order to clarifty the meaning of terms used in this research, the proposed definitions below were composed with the CATWOE method developed by (Checkland, 1981) to establish root definitions, as described below.

With the CATWOE method (Checkland, 1981), terms are evaluated according to the letters of the acronym for the method. “C” represents customers of the system, who are beneficiaries or victims affected by the system activities. “A” represents actors, which are the agents who carry out or cause to be carried out the main activities of the system. “T” represents transformation which is the main process for inputs being transformed into outputs. “W” represents

Weltanschauung, a word for world view, which makes this operational definition meaningful. "O" represents ownership of the system, which has a prime concern for the system and the power to cause the system to cease to exist. "E" represents environmental constraints on the system which are the features of the system's environment. Ideally, an operational definition should encompass all six elements.

Table 3.1 Root Definitions for Foundational Concepts in Sustainable Manufacturing Systems Thinking

Terms	Definition	Description	References
Sustainable Manufacturing	The set of systems and activities for the creation and provision of manufactured products that balance benefits for ecological systems, social systems, and economic systems.	"Creation" includes the design of products and manufacturing systems, and the manufacture of physical products. "Provision" includes delivery and recovery of products, through remanufacturing, recycling, and other activities. "Balanced benefits" shows that the benefits cannot be optimized for each subsystem, but a balance point can be reached to bring positive benefits to society and economy. This assumes there is a cost born by ecological system (the benefit usually is negative).	(US Department of Commerce, National Institute of Standards and Technology, 2013)
Economic Weltanschauung*	An approach for analyzing and implementing organizational activities towards maximizing the financial benefits for internal and external stakeholders.	Internal stakeholders include employees, shareholders, and anyone who has interests in the organization. External stakeholders include suppliers, distributors, and other participants throughout the product value chain.	**** Weltanschauung***, a German word for "world view", refers to the framework of ideas and beliefs through which individuals interpret the world.
Environmental Weltanschauung	An approach for analyzing and implementing organizational activities towards minimizing the consequences of energy and natural resource consumption and waste releases.	The stakeholders shall take environmental ethics in their organizational activities, especially economic activities. The "consequence" is commonly known as "impact".	
Social Weltanschauung	An approach for analyzing and implementing organizational activities towards maximizing the human well-being of internal and external stakeholders.	Human well-being includes multiple aspects of social life (see definition). The term here refers to the consideration of human well-being in activities and decisions throughout the product life cycle.	(Benoît et al., 2010)

Product Life Cycle	A set of consecutive and interlinked stages where participants generate value with the product in the ecosystem and human society, and usually includes design, raw material extraction, material processing, manufacturing, use, post-use activities, and disposal of residuals produced in each stage.	A product's life cycle does not necessarily have all of these stages. In some literature, four stages are described, pre-manufacturing, manufacturing, use, and post-use (Lu et al., 2010). Past definitions usually define the product life cycle based on its physical flow. Here, "design" describes the information flow of the product information. Design includes design of products, design of a manufacturing systems, design of post-use strategies, etc.	(EPA, 2013a); (Lu et al., 2010); Sheng et al., 1998; (ISO, 2006, p. 1) Campanelli et al., 2011
Life Cycle Assessment	A technique for decision makers to evaluate the potential environmental impact of a defined product system for a given geospatial region and temporal period.	Life cycle assessment includes four stages: goal and scope definition, life cycle inventory, life cycle impact assessment, and interpretation. Product life cycle impact assessment evaluates the environmental impact throughout the product life cycle.	(EPA, 2013a); (Goedkoop et al., 2009); (Curran, 2006); (Campanelli et al., 2011); (Benoît et al., 2010)
Environmental Impact Assessment	The process of identifying the consequences of the defined system activities on the environment, and measures that may help mitigate adverse effects.	Different from life cycle impact assessment, environmental impact assessment can evaluate a smaller scope or one stage of the product life cycle. In another words, environmental impact assessment is an evaluation technique for ***environmental weltanschauung***.	(EPA, 2013a); (ISO, 2006); (Curran, 2006)
Manufacturing System	A network of activities/processes that utilizes human resources and natural resources to produce products for targeted consumers regulated by laws, market forces, and internal policies.	This term is defined in the sustainable manufacturing system assessment context. The network shows there are underlying structures behind the manufacturing physical components. All the activities in this network meanwhile, are restricted by environmental constraints including laws, market forces, and internal (organizational) policies.	(Lu et al., 2010); (ISO, 2006, p. 1); (Campanelli et al., 2011)

Decision Making	The process of selecting from among several alternatives which are generated to accomplish a specific goal with certain constraints.	Decision making involves alternatives, constraints, and a goal.	(Avram et al., 2011)
Stakeholder	Entities or individuals that affect or are affected by an organization's activities or products so as to gain interest with implementing their strategies.	"Stakeholders" here refers to the participants over the product life cycle, e.g., shareholders of manufacturers, distributors, product users, or employees. The ecosystem is also a stakeholder which affects manufacturing and is affected by manufacturing.	*GRI*, 2006; (ISO, 2009)
Indicator	A parameter defined to provide a decision maker with quantitative or qualitative information about or describe the state of a target phenomenon.	Indicators, depending on the problem context, shall be defined by decision makers according to the goal and scope of the analysis. As reviewed in this paper, many indicators have been developed to assist decision makers.	(EPA, 2013a); (Sheng et al., 1998); *GRI*, 2006; (Curran, 2006) ; (Benoît et al., 2010); (ISO, 2013)
Life Cycle Costing	A compilation and assessment of all the costs associated with the product in its operational life cycle to optimize value during ownership for its stakeholders.	Life cycle costing evaluates the costs in two dimensions: costs associated with the product in its life cycle stages and the costs' monetary value that is changed over time.	(EPA, 2013a); (US Department of Commerce, National Institute of Standards and Technology, 2013); (Benoît et al., 2010); Mearig et al., 1999
Social Impact Assessment	The process of practitioners identifying the social impacts that are likely to follow specific policy actions or defined system activities, to assess the significance of these impacts, and to identify measures that may help avoid or minimize adverse effects.	Social impact assessment, like environmental impact assessment for life cycle assessment, or ***environmental weltanschauung***, is a technique for the broader concept of ***social weltanschauung***.	(Benoît et al., 2010)
System Boundary	A set of criteria defined by practitioners specifying which unit processes and/or materials are included in the studied system.	Defining a system boundary requires a goal and scope for the study. In the boundary, not only are components included, but so are the relations of those components.	(ISO, 2006, p. 14040)

Energy Use	Different forms of the conversion and application of energy to support human activities.	Five areas of energy use can be defined: direct energy, indirect energy, intermediate energy, primary source, and renewable energy.	GRI, 2006
Human Well-Being	A concept that reflects a human individual's life situation, including knowledge, friendship, self-expression, affiliation, bodily integrity, health, economic security, freedom, affection, wealth and leisure in a defined societal situation.	In the context of sustainable manufacturing, human well-being usually refers to both human physical/mental safety, and the fulfillment of needs. Specifically, it involves ergonomic considerations in manufacturing, and psychological considerations in other organizational activities.	(Benoît et al., 2010)
Process	A set of interrelated or interacting activities that are organized to accomplish the transformation of inputs to outputs under existing constraints.	A process can occur at more than one level. A sub-process, if it is the smallest element, can be called a unit process.	(ISO, 2006, p. 14040)
Unit Process	The smallest element considered to accomplish an activity in a manufacturing system.	An activity, if it is the smallest element of a process, can be called a unit process.	(ISO, 2006, p. 14040)
Waste	The substances or time which the manufacturer intends or is required to dispose of.	In addition to material waste, this definition refers to the concept of time waste from lean manufacturing, which is well-established.	(ISO, 2006, p. 14040)
Product	Any good or service offered to serve the needs of other members of society.	Service can be a co-product associated with a product, for example, maintenance and recycling activities. It can also be the main product with goods as co-products to support the service.	(ISO, 2013)
Materials	Physical components that are extracted from the ecosystem and will be processed into matter or a product component used to assist manufacturing processes, during which value will be added.	Materials can include raw materials, associated process materials, semi-manufactured goods or parts, and materials for packing purposes.	GRI, 2006
Recycling	The process of converting waste into a reusable material in order to add value.	Recycling is one form of product recovery. It changes waste into useful materials for producing new products.	(ISO, 2006, p. 14040)

Remanufacturing	A recovery process to rebuild, repair, and/or restore parts or an instrument to match the consumer expectations for a new product.	Remanufacturing is one form of product recovery. Usable parts of the product will be processed to be like-new parts in inventory, and later used to produce products equivalent or superior to new ones (Lund, 1984).	(ISO, 2006, p. 14040)
Enterprise Level System	A set of interrelated activities, materials, energy, and information that are organized to support the management of production.		
Operational Level System	A set of activities, materials, energy, and information that are organized to conduct one process of manufacturing.		
Shopfloor Level	A set of activities, materials, energy, facility, and information that are organized to support manufacturing processes.		

3.2 Variable Definition

Within system dynamics (SD) modeling, a system is represented by a number of variables (factors) and their interactions (behaviors) that establish and inform the goal and scope definition of the proposed model. Identifying these factors and their behaviors thus becomes the first step for model developers. A well-represented system serves reliable model development and performance analysis, therefore, variables must be identified with respect to system functionality and decision maker's considerations. In sustainability assessment, three metric sets (economic, environmental, and social) are quantified, as reviewed briefly below (Brent & Labuschagne, 2006; Dreher et al., 2009; Feng et al., 2010; Graedel & Allenby, 2002; Hutchins & Sutherland, 2008; Jawahir et al., 2006; Jawahir & Dillon, 2007; Lu et al., 2010; Parris & Kates, 2003a; UNDSD, 2001).

Economic Metrics. The capital and operating expenditures required to create a product have a direct effect on a manufacturer's economic performance, but also affect the economics of operations, facilities, and the enterprise as a whole. Product and process-related economic performance metrics should reflect the impact on the company, as well as on the broader economy. Economic metrics can be quantified in terms of monetary value, and may include operating cost, retained earnings, and locally-based spending. Financial performance is a familiar topic to engineers and other decision makers, being necessary to ensure competitiveness. Moreover, monetary data is straightforward to analyze and communicate to a diverse audience.

Environmental Metrics. At the enterprise level, environmental indicators are based on the external (e.g., emissions limits) and internal (e.g., waste reduction goals) policies. The scope is broadened from the facility to the supply chain and, ultimately, to the whole life cycle to include indicators about recycling and logistics processes (e.g., transportation CO_2 emissions). At the operation (micro) level, environmental indicators relate to the materials and energy use, byproducts, emissions, and wastes. These indicators aggregate with non-process related metrics (e.g., water for potable uses, heating energy, and lighting energy) at the shopfloor level.

Social Metrics. The social domain of sustainable manufacturing considers human safety and societal benefits. Manufacturers are responsible for creating a safe and healthy environment – considering worker safety and workplace illumination and noise levels, for example. Meanwhile, companies have responsibilities to the local community, such as creating job opportunities, purchasing insurance, providing worker compensation, and complying with laws and regulations. It is important to note that research on analyzing the social impacts of manufacturing is limited. Lee et al. (2010) proposed a set of dimensions for human work to assist industrial sustainability assessment. Based on the effect variation, different aspects were categorized into individual and societal levels. The dimensions identified include compensation, physical and mental safety, demand, variety of tasks and roles, social interaction, growth of skills and knowledge, opportunities for accomplishments and status, value of work, autonomy, and growth and personal development. These dimensions form the basis of social metric definition in this work.

3.3 System Dynamics Model Development

A manufacturing system can be defined to include three behavioral levels: 1. The enterprise level, which deals with strategic decisions of management and production (e.g., sustainability policy making and employee recruitment); 2. The shopfloor level, which deals with production organizing decisions (e.g., manufacturing process flow and scheduling); and 3. The operation level, which deals with single unit process decisions (e.g., energy, waste, and workload). Zhang et al. (2013) proposed a sustainability assessment-system dynamics (SD) model structure (see Figure 1) that encompasses these three levels of a manufacturing system. At each level, sustainability assessments are integrated into the appropriate SD model substructure by identifying the types of human (e.g., knowledge and skills), natural (e.g., materials and energy), and physical (e.g., facilities and equipment) capital inputs. Environmental, economic, and social assessment methods are then used to quantify the variables and identify the relations between and among the variables. Assessment results are output from the SD model in a manner to facilitate system design and decision making at three analogous levels: corporate policy making, manufacturing system design, and manufacturing process design. As such, environmental impacts, economic costs, and social responsibility measures will holistically inform decision making within and across organizational levels. The refined model will be comprised of three substructures to respond to manufacturing decision paradigms (see Figure 3.1).

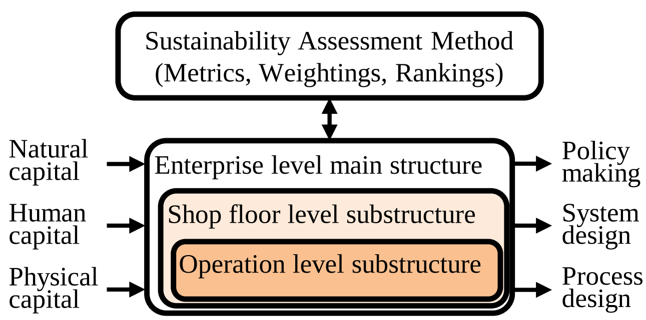


Figure 3.1. Sustainability Assessment–System Dynamics Model Structure (Zhang et al., 2013c).

This systemic methodology allows sustainability assessment methodologies to be integrated into the appropriate SD model substructure by identifying the appropriate types of human (e.g., knowledge and skills), natural (e.g., materials and energy), and physical (e.g., facilities and equipment) capital inputs. Environmental, economic, and social assessment methods will be used to quantify the variables and identify the feedback loops between variables, as described below. Assessment results will facilitate system design and assist decision making at three levels. As such, environmental impacts, economic costs, and social responsibility measures will more holistically inform decision making within and across organizational levels.

Each model solves a different problem. Three model substructures, represented with causal loop diagrams following standard notation by Sterman (2000), are presented with each solving a different sustainable manufacturing problem. The problem, however, may cause cascading effects across different levels of the manufacturing system. Therefore, a comprehensive solution for a manufacturing system requires an integrated model of the system with these substructures. Nevertheless, as defined by Deming (1993), “a system is a network of interdependent components that work together to try to accomplish the aim of the system.” The model substructure should have an aim, a boundary, components, and relations among components. To illustrate the model, this section, accordingly, describes the conceptual model from each substructure level standpoint by considering its system definition, variable identification and system behavior, and model verification and validation. Meanwhile, Deming’s theory of profound knowledge is integrated as a link to connect sustainable manufacturing and systems thinking.

3.3.1 Enterprise Level Substructure

The enterprise level system includes management activities, the goals of which are to lead to strategic decisions for balancing enterprise economic benefits and environmental impacts from production, along with social responsibilities. The decision makers at the enterprise level usually include the chief executive officer (CEO), chief financial officer (CFO), facility manager, and others who are involved in strategic decision making.

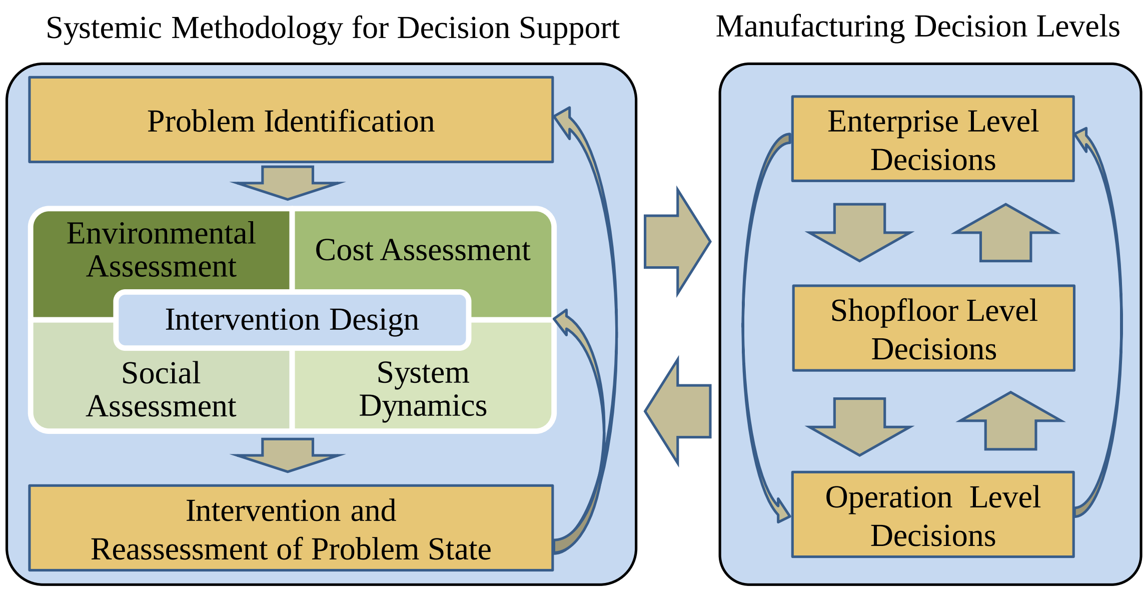


Figure 3.2. The Systems Thinking Approach for Sustainability Decision Making in Manufacturing Enterprises

Variable Identification and Behaviors: The system includes various components, which in this model are identified as variables, and whose performance can be stable or unstable. The prediction of system performance is based on the amount of knowledge known about the system (Deming, 1993). Therefore, variable identification becomes crucial. Governmental agencies (e.g., NIST), non-governmental organizations (e.g., GRI), and individual enterprises (e.g., Wal-Mart) have developed sustainability metrics and indicators, which cover economic, environmental, and social aspects. The variables in the conceptual model herein are identified based on these developed indicators, as well as the sustainability behaviors of the manufacturing system. For example, environmental performance variables are selected from GRI indicators (Global Reporting Initiative, 2014). When building the model, however, practitioners may select variables respective to the sustainability behaviors of the investigated system. The example enterprise level substructure model (see Figure 3.3), which uses standard system dynamics modeling standard notation (Sterman, 2000), describes basic behaviors related to sustainability practices in an enterprise. For instance, at this level, the production volume is not only affected by the internal situation, including installed capacity, production investment, environmental impact from production, and human well-being, but also affected by the external situation, such as enterprise market share. A reinforcing loop (noted as an R in the figure) which feeds on itself to produce growth or decline, is formed by production volume, material use, production cost, and production investment, but this loop is limited by enterprise funding capabilities. Environmental impact results from material and energy use of the enterprise system. The enterprise will undertake environmental impact reduction activities when the performance is lower than the environmental impact regulation standard or enterprise's satisfaction level.

From social impact standpoint, Deming (1993) noted that people are born with a need for relationships with other people, and need for love and esteem by others. The management of people thus affects a worker's physical and psychological health. In Figure 3.3, human well-being, which may include many aspects (e.g., esteem, need, interaction, and health), is affected by production because of the workload that has been caused by production requirements. Thus, the balancing loop (noted as a B in the figure), which attempts to move some current state to a desired or reference state though some action, including production volume, workload, human well-being, and pressure to reduce production rate, is limited by the human well-being standards of the production environment. It should be noted that these behaviors change over time and delays may occur from one to another.

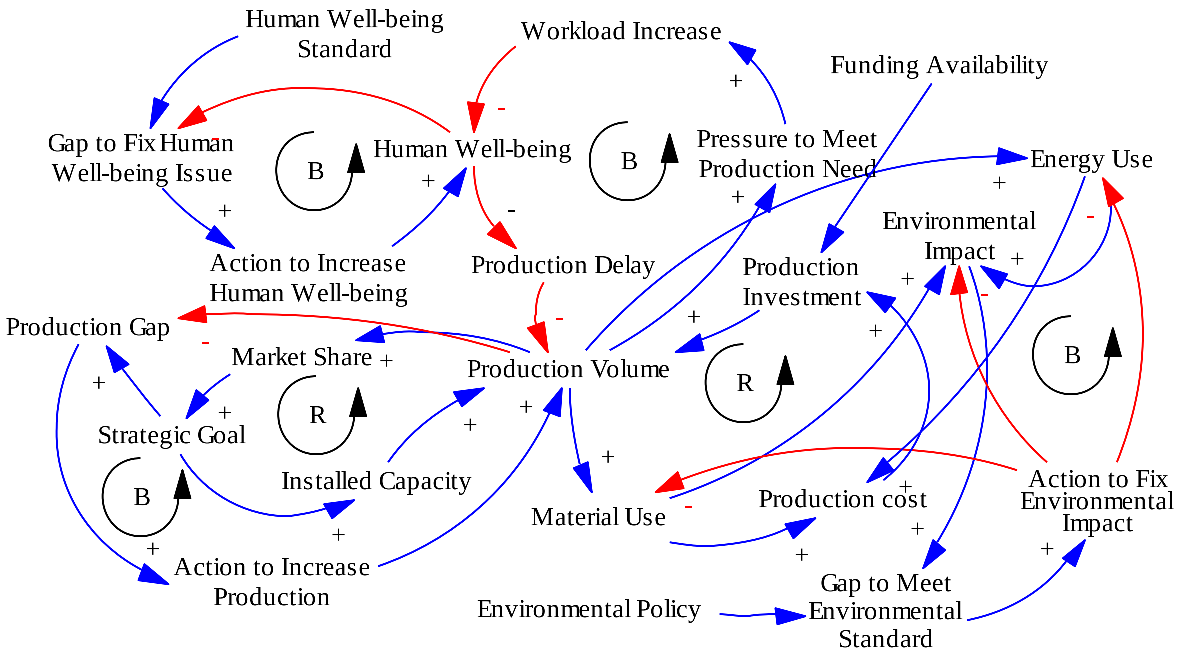


Figure 3.3. Example Enterprise Level System Dynamics Model

Model Verification and Validation**:** The aim of modeling a system is to predict, and prediction depends largely on knowledge of the system (Deming, 1993). To have the model provide high quality sustainability performance prediction results (especially over time), the conceptual model must be further verified and validated through a model validation procedure, such as proposed by Barlas (1989), which includes a structure confirmation test, sensitivity test, and behavior pattern test. Verification can be carried out by comparing the equations and their form to existing relationships in the system modeled and to system information reported in the literature (Forrester & Senge, 1980; Barlas, 1996). In this study, tests will be conducted by examining the structure of equations to *in situ* systems studies, as well as by reviewing relevant prior research. Thus, real industrial systems will be utilized in model development, and literature will provide supplementary sources to validate the model structure.

3.3.2 Shopfloor Level Substructure

The shopfloor level system includes shopfloor production activities, the goal of which is to utilize less material to fulfill the needs of production and, meanwhile, to generate the lowest environmental and social impacts. Behaviors include production scheduling, material use and handling, production rate, and actions to control production. The decision makers at this level usually include industrial engineers, schedulers, and production managers, as well as those who are involved in production decision making in other capacities (see Figure 3.4).

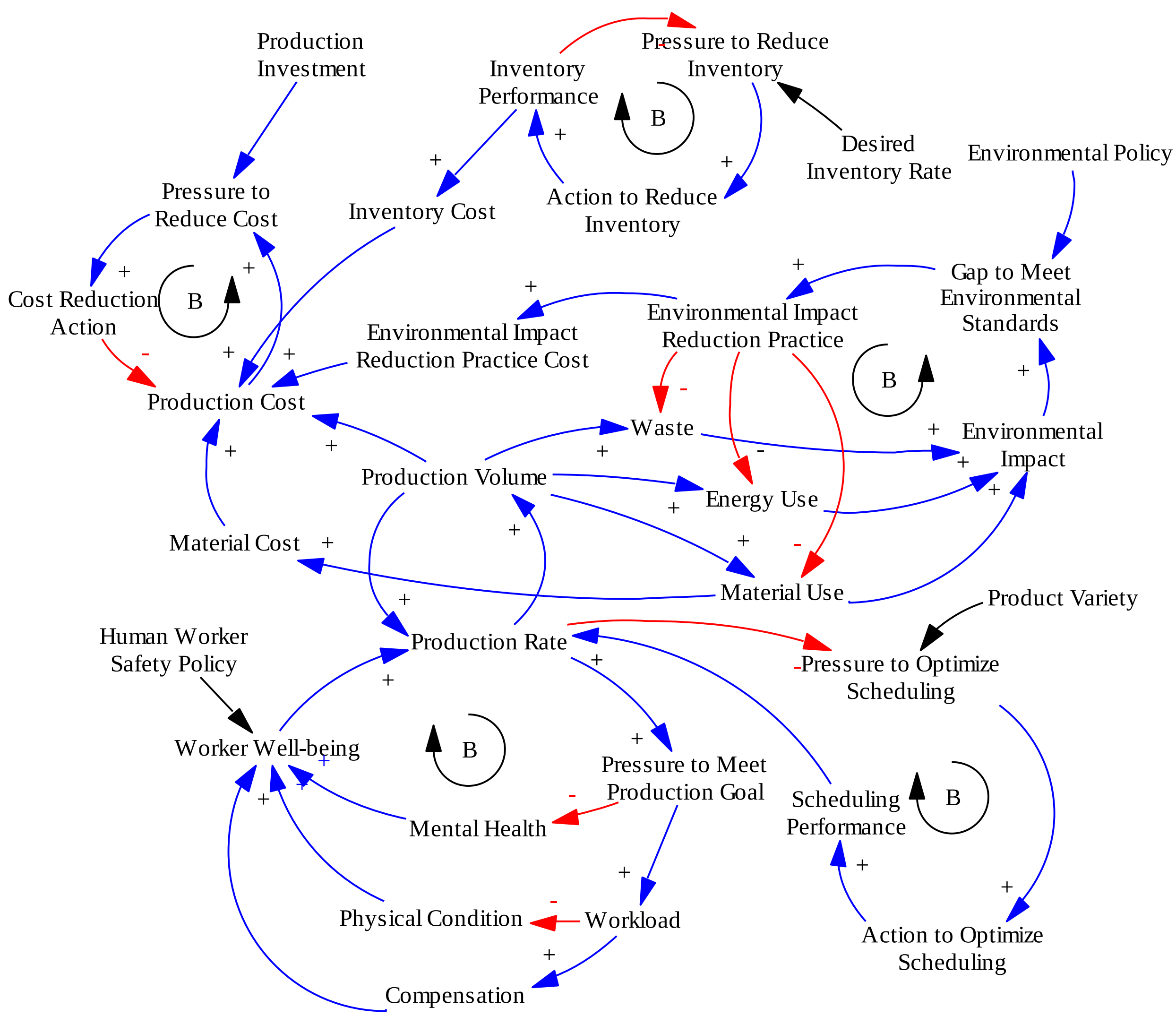


Figure 3.4. Example Shopfloor Level SD Model

Variable Identification and Behaviors**:** The knowledge required for the system at the shopfloor level includes all the production related behaviors, based on which variables are identified. The sustainability performance of the system can be assessed based on the production data collected and interpreted. The more comprehensive data collected, the better the understanding that will be gained about the system (Deming, 1993). An example conceptual model substructure of the shopfloor level is shown in Figure 3.4 with some identified production behaviors.

To meet the needs of production, production volume and production rate is scheduled accordingly. Consequently, material, energy, and labor can be defined. Material use and energy use contribute to the environmental impact of production, as well as economic cost. The overburdened production will, in return, be limited by production capacity and market share. Meanwhile, environmental policies will also limit the production through fines and incentivized environmental impact reduction practices, the cost of which will contribute to the production cost (Global Reporting Initiative, 2013). In addition, product variety is another factor that affects production rate (Zhang & Haapala, 2012). A higher production rate shortens break time and puts workers under higher workload and pressure. Although compensation may increase, the overall workload and pressure may result in body injury and affect mental health (Lee et al., 2010). Therefore, the behavior of increasing production rate is also limited by worker safety policy.

Model Verification and Validation**:** To move from a conceptual model to a dynamic decision support tool, the causal loop diagram model will be converted to a stock and flow diagram, and the variables will be both qualitatively and quantitatively measured. The model should replicate the actual production performance, and variables and behaviors shall be adequately justified with respect to the investigated system. The verification and validation procedure is similar to that described above.

3.3.3 Operation Level Substructure

The operation level system considers the mechanistic operating activities of each unit process (e.g., a machining operation). The goal of this substructure is to complete the required unit operations with compliance to product design, production specifications, and environmental and safety regulations. Due to the nature of this level, the decisions of engineers and operators usually have less of an impact on the shopfloor and enterprise level decisions; however, bottom-up feedback may affect product design and other strategic decisions (e.g., safety and welfare). An example conceptual model substructure of this level is shown in Figure 3.5.

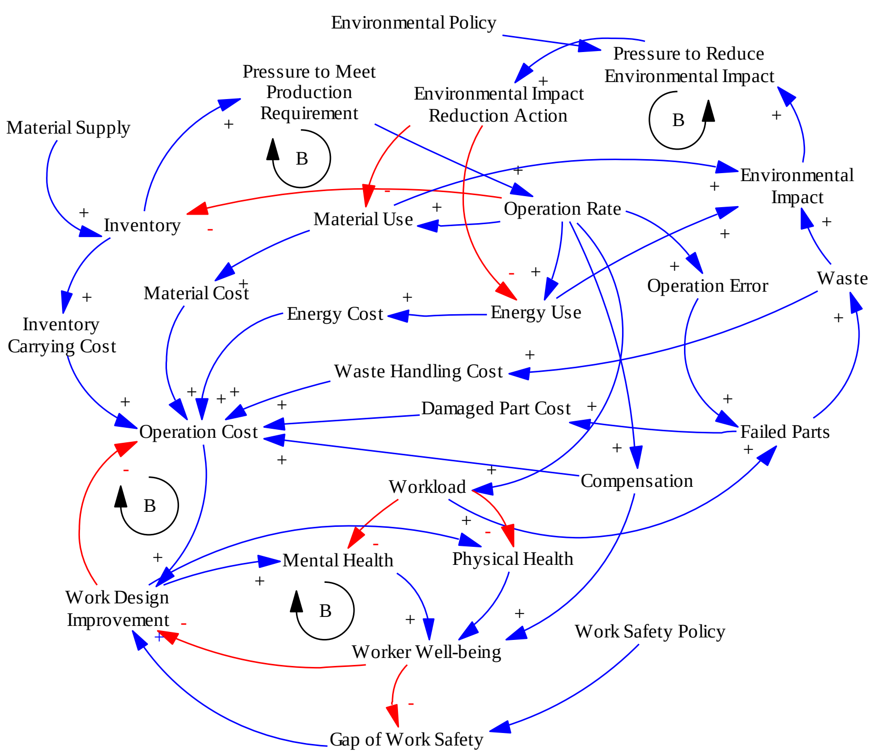


Figure 3.5. Example Operation Level System Dynamics Model

Variable Identification and Behaviors**:** At the operation level, the economic and environmental variables are identified based on the unit process life cycle inventory (UPLCI) method (Overcash, Twomey, & Kalla, 2009). Economic behaviors around production are related to material cost, energy cost, labor compensation, and waste handling cost. The overuse of materials, energy, and labor cost will conversely increase the pressure of production investment, and motivate engineers to redesign the operations to reduce cost. As for environmental impact behaviors, production environmental impact is directly related to process material use and energy consumption. Since physical and mental health are affected by production rate (Zhang & Haapala, 2012), work design is another factor that affects worker well-being. Well-designed work will address ergonomic issues in the work area and avoid injuries. The complexity of work fills operator's need of skill learning (Lee et al., 2012), but, on the contrary, overcomplexity will result in frequent human errors and psychological effects, as noted by Deming (1993). People have both sources of extrinsic motivation and intrinsic motivation, and overcomplexity may reduce the enjoyment of their work. Thus, a loop in the model has been formed for through worker well-being and work design.

Model Verification and Validation**:** When modeling a single operation, process-based modeling provides a guideline for developing economic and environmental impact behaviors. A dynamic model, however, means more than a hard system simulation. At this level, interactions between operators and the way in which operators make certain decisions, will affect other processes, quality of the product, and so forth. Therefore, actual operation data must be applied to the conceptual model, which should be modified accordingly.

3.4 Summary

Sustainable manufacturing decision makers are required to employ systems thinking when approaching operation level, shopfloor level, and enterprise level issues. These complex problems involve the interaction of human behaviors with manufacturing system elements. System dynamics provides an appropriate framework for modeling manufacturing systems for sustainability assessment. The main advantages of system dynamics include a means to understand the system by identifying relationships among factors, the use of a structured model that allows decision makers to simulate current functioning of the system and to explore opportunities for improvement, and assistance for decision makers in predicting system sustainability performance metrics for various system alternatives. Most importantly, it offers engineers and managers an approach to adopt systems thinking to solve sustainable manufacturing problems holistically.

The conceptual model approach presented for sustainable manufacturing enterprise assessment, can be used to investigate the sustainability behavior relations and their association with costs at enterprise, shopfloor, and operational levels. Next, this conceptual approach is developed and applied to examine the manufacturing system of an actual SME that produces metal products.

Chapter 4. Research Methodology

In this section, a full cost model is proposed to address research questions and tasks presented in Chapter 1. The static model integrates cost assessment, environmental impact assessment, and social impact assessment into a systems dynamics model and acts as a database support for the dynamic model. The dynamic model, targeted at addressing Research Questions 1 and 2, is meant to provide researchers a way of understanding sustainable manufacturing system behavior, and to provide manufacturing practitioners a tool to make decisions towards improving sustainability performancebased on system behavior over time performance.

4.1 The Full Cost Model Structure

The intervention method is developed upon creative design of method theory which allows system practitioners to apply methods from various domains involved in solving a specific problem. As the purpose of developing a full cost model is to inform management and engineering decision making, the intervention method shall be a decision making model that could integrate all aspects of a manufacturing system including production behaviors, economic behaviors, environmental behaviors, and social behaviors. Meanwhile, the model shall be able to separate and connect factors from all three manufacturing system levels so that cross-level impacts could be evaluated. With all the requirements above, system dynamics (SD) proved to be an effective modeling method as the basis of this intervention method (Zhang et al., 2013). In addition to the merits above, SD also provides the systems factor performance over time from a decision impact, which allows decision makers to evaluate the impact in both short term and long term.

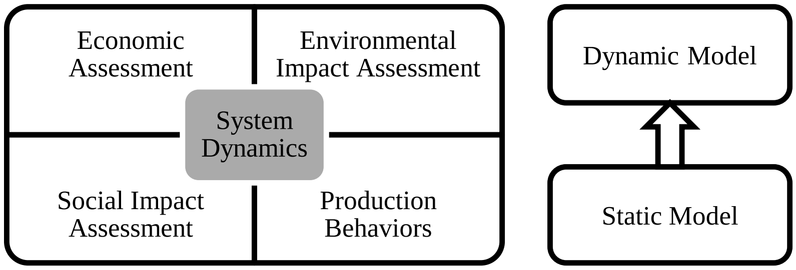


Figure 4.1. The Intervention Method of the Full Cost Model

The proposed model (Figure 4.1) includes two sub-models: a static model and dynamic model. The dynamic model is developed from the static model and includes system decision making behaviors, as described below.

The static model: The static behaviors are expected to serve as the fundamental structure for the dynamic model. Production processes, energy usage, material use, labor time, safety cost, environmental impact, among other behaviors. are all included in the static model. When developing this model, cost assessment, environmental impact assessment, and social impact assessment were embedded since their relations are usually direct and well defined. An example operation level static model is shown in Appendix A.

The dynamic model: Built upon the static model, the dynamic model serves as the decision support method for decision makers to simulate the consequences of certain behaviors over an effective decision period (predetermined time length). Decision makers are able to see to what extent manufacturing system behaviors would affect specified outcomes (e.g., production cost, energy use, or wages) during the effective decision period. Manufacturing system behaviors may include production behaviors (e.g., adjusting machining settings or production rate) or environmental and safety behaviors (e.g., implementing an ESH policy or program). The behaviors should follow the system archetypes elaborated by systems thinkers, e.g. (Senge, 1990), and represented with stock flow diagrams. The eleven archetypes that have been identified are accidental adversaries, balancing loop, drifting goals, escalation, fixes that fail, growth and underinvestment, limits to success, reinforcing loop, shifting the burden, success to the successful, and tragedy of the commons. All decision making behaviors can be described with these archetypes, individually or combined.

4.2 The Full Cost Model

In this section, a full cost model structure is proposed, including model terminology and variable definition. The static model consists of the sustainability assessment domains, and the dynamic model describes manufacturing system behaviors.

4.2.1 Terminology and Variable Definitions

All the variables and their units that will be used in this model are defined and listed in the tables below (Table 4.1). These variables are categorized into the base information variables which controls the whole system at all three levels.

Base information variables (Table 4.1) are those influencing at least two levels of factors. These variables include monthly throughput (N_{month}) which is a key variable used in allocation of many cost items in this model. Electricity cost rate (r_{elec}), natural gas cost rate (r_{gas}), working hours per day ($T_{working}$) are also variables influencing factors in two or three levels of the manufacturing system.

Table 4.1. Base Information Variables

Variables	Definitions	Units
N_{month}	Monthly production volume	NA
$T_{working}$	Working hours per day	Hour
$r_{operator\_rate}$	Operation level labor cost rate	dollars/hour
$r_{shopfloor\_rate}$	Shopfloor level labor cost rate	dollars/hour
r_{adm_rate}	Enterprise level labor cost rate	dollars/hour
T_{break}	Break time per working day	Hours
r_{fringe}	Fringe rate of labor cost	NA
$d_{working}$	Monthly working days	NA
r_{elec}	Electricity cost rate	Dollars/kWh
r_{gas}	Natural gas cost rate	dollars/thousand cubic feet
EI_{factor}	Electricity Reduction CO2 emission factor	metric ton CO2/kWh

The operation level model structure deals with problems within a unit process, e.g., milling, welding, and painting. Operation level variables (Table 4.2) include factors that are involved in a single operation. Cost items at this level typically include labor cost, energy cost, material cost, and machine depreciation. Lighting for these processes is included in shopfloor level, and is allocated based on the throughput of the month (N_{month}). Environmental impact at this level is caused by energy use and material use. Therefore, Global Warm Potential (GWP) carbon dioxide equivalent (kg CO_2e) and material related environmental impact indicator are used at this level. Social impact at this level, due to the scope of the impact fact and this study, is limited to wage and injury.

Table 4.2. Operation Level Variables

Variables	Definitions	Units
i	Process i, i=1,2,3, …	
$T_{operation\_i}$	Operation time of process *i* for producing a functional unit	minutes
$P_{operation\_i}$	Operation machine power of process *i* for producing a functional unit	kW
T_{setup_i}	Setup time of process *i* for producing a functional unit	min
P_{setup_i}	Machine setup power of process *i* for producing a functional unit	kW
E_{elec_i}	Electricity use of process *i* for producing a functional unit	kWh
C_{elec_i}	Electricity cost of process *i* for producing a functional unit	Dollars
E_{gas_i}	Gas use of process *i* for producing a functional unit	Cubic feet
C_{gas_i}	Gas cost of process *i* for producing a functional unit	Dollars
C_{energy_i}	Energy cost of process *i* for producing a functional unit	Dollars
C_{labor_i}	Labor cost of process i for producing a functional unit	Dollars
$E_{labor\_efficiency}$	Labor efficiency at work	
$C_{machine\_i}$	Machine depreciation of process i for producing a functional unit	Dollars
$T_{machine\_i}$	Process i machine total service time during its use life	Hours
$I_{machine\_i}$	Initial cost of the machine used at process i	Dollars
$S_{machine\_i}$	Salvage value of the machine used at process i	Dollars
$U_{machine\_i}$	Machine usage of process i for producing a functional unit	%
U_{tool_i}	Tool usage of process i for producing a functional unit	%
T_{tool_i}	Total tool life of process i for producing a functional unit	%
$C_{tool\_unit\_i}$	Unit tool cost of process i	Dollars
C_{tool_i}	Tool cost of process i for producing a functional unit	Dollars
$M_{material\_i}$	Material use of process i for producing a functional unit	Pounds
$C_{material\_unit\_i}$	Unit material cost of process i	Dollars
$C_{material\_i}$	Material cost of process i for producing a functional unit	Dollars
$N_{operator\_i}$	Number of operators at process i	
T_{risk_i}	Effective risk exposure time at process i	Hours
IR_i	Injury rate at process i	Injuries per month
$T_{risk\_prioryear\_i}$	Prior year's effective risk exposure time for producing a functional unit at process i	Hours
$T_{prioryear\_risk\_i}$	Prior year's total effective risk exposure time at process i	Hours
EI_{co2e_i}	Carbon dioxide equivalent emission for producing a functional unit at process i	kilograms
C_{injury_i}	Injury cost of process i	Dollars
$C_{injury\_i\_single}$	Single case cost of process i injury	Dollars
IR_{i_prior}	Prior period process i injury rate	Injuries per month

The shopfloor level model structure deals with problems of organizing the production at shopfloor, for example, production scheduling, building maintenance, production support activities (parts management), and inventory control. Shopfloor level variables (Table 4.3) include factors that are usually overhead cost items (e.g., lighting, heating, building maintenance). They also include variables the values of which are aggregated from operation level. For example, the total process electricity use ($E_{process\_shopfloor}$) is aggregated by single operation electricity use of all processes at operation level. Environmental impact at this level includes impact values from single processes from operation level and production support energy use (e.g., lighting, heating, air) and raw materials which will go through multiple processes on the shopfloor.

Table 4.3. Shopfloor Level Variables

Variables	Definitions	Units
$E_{light\_shopfloor}$	Lighting electricity consumption per day on shopfloor	kWh/day
N_{month_target}	Monthly target throughput	Units/month
$n_{light\_shopfloor}$	Number of light bulbs in the shop	
$P_{light\_shopfloor}$	Light power of the shopfloor lights	Watts/bulb
$t_{light\_shopfloor}$	Time length during a working day when shopfloor light is on	Hours
$C_{light\_shopfloor}$	Shopfloor lighting cost	Dollars
$E_{naturalgas\_shopfloor}$	Natural gas use at shopfloor for a working day	therm
$E_{electricity\_shopfloor}$	Electricity use at shopfloor for a working day	kWh
$C_{naturalgas\_shopfloor}$	Natural gas cost at shopfloor for a working day	Dollars
$C_{energy\_shopfloor}$	Total energy cost at shopfloor for producing a functional unit	Dollars
$C_{safety\_devices}$	Monthly cost spent on safety devices, e.g., glasses, gloves	Dollars
$C_{ancillary}$	Monthly ancillary equipment or material cost to support production, e.g., computer, paper, paper towels, software	Dollars
$C_{building\_maintenance}$	Monthly building maintenance cost	Dolllar
j	Different raw material component, e.g., j = steel, plastic, …	

$m_{raw\_material\_j}$	Raw material j use for producing a functional unit	Pounds
$C_{raw\_material\_j}$	Raw material j cost for producing a functional unit	Dollars
$C_{raw\_material}$	Raw material cost for producing a functional unit	Dollars
$C_{material}$	Total material cost for producing a functional unit	Dollars
T_{cycle}	Production cycle time	Hours
T_{WIP}	Work in process time when producing a functional unit	Hours
$n_{labor\_shopfloor}$	Number of general shopfloor labers including supervisors, material handlers, and others who do not belong to a unit process	
$T_{labor\_shopfloor}$	Shopfloor labor working time per working day	Hours
$C_{labor\_shopfloor}$	Shopfloor labor monthly cost	Dollars
$E_{process\_shopfloor}$	Total process electricity use for producing one functional unit	kWh
$W_{pollution\_i}$	Environmental impact pollution i	Pounds
$C_{taxrate\_i}$	Tax rate of a pollution i	Dollar/Metric Ton
C_{fine_i}	Fine of a pollution	Dollars
P_i	Probability of violations cited by government regulatory agencies	NA

The enterprise level model structure deals with problems of administration (e.g., office, sales, marketing, and finance) and strategic product decisions (e.g., product design, and pricing). Enterprise level variables (Table 4.4) include energy use, administration, equipment use, labor expense, and research and developemtn as business support activities. There are also variables with values are aggregated from operation level variables and shopfloor variables, for example, manufacturing cost ($C_{manufacturing}$), enterprise monthly electricity use ($E_{enterprise}$).

Table 4.4. Enterprise Level

Variables	Definitions	Units
$C_{manufacturing}$	Total cost for manufacturing a functional unit at shopfloor	Dollars
$C_{month\_manufacturing}$	Total monthly manufacturing cost	Dollars
C_{market}	Monthly marketing cost	Dollars
n_{adm}	Number of administrative labers	
T_{labor_adm}	Monthly working hours	Hours
E_{light_office}	Lighting electricity consumption per day in office area	kWh/day
n_{light_office}	Number of light bulbs	
P_{light_office}	Light power of the office lights	Watt/bulb
t_{light_office}	Length of time during a work day when office lights are on	Hours
C_{light_office}	Office lighting cost	Dollars
$E_{equipment}$	Monthly electricity use for supporting equipment, e.g., computers, printers, …	kWh/month
$C_{equipment}$	Monthly equipment (depreciation) and supporting material use	Dollars/month
$C_{R\&D}$	Monthly R&D investment	Dollars
$C_{labor\_enterprise}$	Enterprise labor cost for producing a functional unit	Dollars
$C_{production}$	Total production cost for producing a functional unit	Dollars
$C_{selling}$	Monthly selling cost, e.g., shipping, tax	Dollars
$E_{enterprise}$	Monthly electricity use of the whole enterprise.	kWh
$C_{energy\_enterprise}$	Monthly energy cost of the whole enterprise	Dollars
$C_{social\_activity\_i}$	A social activity cost for enhancing work safety or work environment	Dollars

The variables listed above at the three levels are commonly used factors in a manufacturing system. These variables are interrelated and influence each other. Meanwhile, some of these can be key indicators for operational, engineering, and strategic decision making. Therefore, analyzing the dynamics of these factors become important for manufacturing management, especially when dealing with sustainability behaviors which are usually complex problems.

4.2.2 Economic Assessment

Economic assessment methods that can be used in analyzing manufacturing cost include life cycle costing, activity based costing, and process based costing. In this full cost model, however, these three methods are integrated based on the merits of addressing different cost items which will be explained in the following text. Before analyzing the costs, however, the first task is to define the goal, scope, and functional unit of this assessment.

Goal and scope: The model shall serve the decision maker's objective. Therefore, three levels of the manufacturing systems provide unique perspective for decision maker at operation, shopfloor, and enterprise levels. The operation level decision makers are usually operators and process engineers who determine process settings. The objective of these decision makers is to optimize the process performance including time reduction, quality control, material and energy use, and human health. Cost items include labor cost, energy cost, material cost, and equipment depreciation. The functional unit of the cost analysis, based on process, material and geometric characteristics, can be defined as a single unit of the manufactured product, 1 m of cut, and others (Kellens et al., 2012). In this study and application section, we use one unit product as functional unit.

Labor cost: Labor cost can comprise a large portion of manufacturing cost in labor intensive industry. For metal product manufacturing industry, labor cost is usually the most expense item other than raw material cost. Direct labor costs such as setup times and operation time can be easily traced by a time study or a digital production audit system. For example, at the operation level for a metal cutting process, the setup time and machining time are accounted for in the labor cost. Besides labor cost rate, a fringe benefit cost covers medical insurance and other non-wage compensation expenses. An operation level labor cost can be calculated with Equation 4.1 (variables are defined in Tabel 4.2).

$$C_{labor\_i} = T_{operation\_i} * r_{labor\_rate}*(1+ r_{fringe})* E_{labor\_efficiency} \qquad (4.1)$$

At the shopfloor level, since the functional unit is set to be a unit product, the labor cost would need to be allocated based on the monthly throughput (N_{month}). In this case, however, an inaccurate of assessment would result, As monthly throughput (N_{month}) varies each month, the labor cost can can vary over time. The difference which shall be accounted as a WIP (Work in Process) cost, is allocated in shopfloor labor cost. The WIP cost considered in this way can be difficult to trace. Additionally, there is an efficiency of labor cost; operator activities that are not directly related to production need to be addressed. For example, using the restroom, chatting with neighbors, and delays before and after a break are paid by the company but these activities do not add value to the product even though they are often necessary in production. These costs can be addressed in the cost model in the form of labor efficiency ($E_{labor\_efficiency}$).

WIP cost: WIP cost is an inventory cost. WIP is a somewhat relative value based on a comparison with a standard (or baseline) manufacturing cost. That is, if a company can produce 100 units a month and the total cost for manufacturing is $2000, then the unit cost is $20. The next month, due to the delay, it may only produce 70 units, while the total manufacturing cost for 100 units remains the same and the unit cost will increase to $28.6. The equation (Equation 4.2) is show below.

$$C_{wip}= C_{month\_manufacturing} / N_{month} * (N_{month\_target} - N_{month}) \qquad (4.2)$$

Material cost: Material cost at the operation level includes production assisting materials (e.g., machining coolant, or argon) and other cosumables (e.g., operation tols). Production assisting materials cost is process dependent. For example, the paint use for a painting process can be estimated based on the process time, speed of the paint gun use, and the unit paint cost. In general, material cost can be calculated with Equation 4.4.

$$C_{material\_i} = C_{material\_unit\_i} * m_{material\_i} \tag{4.3}$$

Raw material cost, can be calculated at the shopfloor level because the raw materials travel through most of the manufacturing processes. Counting raw materials as a whole cost item would simplify the cost model and avoid allocation inaccuracies. Equation 4.4 shows the calculation of raw material cost.

$$C_{raw\_material} = \sum_{j=0}^{n} C_{raw\_material\_j} \tag{4.4}$$

Tool cost: Tools used in manufacturing operation usually have a useful life. Allocating tool cost to a unit product can be based on production time and common average tool life. For example, if a die for a forming process will last for 6 months and during the six months the total production is 600 units, then, the die cost for this process is $0.01 per unit product produced (as shown in Eqation 4.5).

$$C_{tool\_i} = u_{tool\_i} / t_{tool\_i} * C_{tool\_unit\_i} \tag{4.5}$$

Equipment cost: Depreciation of the equipment (e.g., a CNC milling machine or a punch press) is a form of cos. The depreciation method can be used in this assessment include unit production depreciation and declining balance depreciation (Newnan et al., 2009). Meanwhile, life cycle costing can also be applied to equipment cost as equipment usually has longer useful life (e.g. 10

years). Here, the unit of production method (Equations 4.6 and 4.7) is shown below as this is a commonly used method in industry to represent equipment cost.

$$U_{machine\_i} = T_{operation\_i} / T_{machine\_i} \tag{4.6}$$

$$C_{machine\_i} = (I_{machine\_i} - S_{machine\_i}) * T_{operation\_i} / T_{machine\_i} \tag{4.7}$$

Energy cost: Energy includes electricity use and natural gas use. Lighting, process equipment electricity use, and air compressor electricity use are accounted in electricity use. Process energy assessment considers both setup time when the machine is idle (T_{setup_i}) and operation time ($T_{operation\_i}$) when the machine is doing actual work.

$$Eelec\_i = Tsetup\_i * Psetup\_i + Toperation\_i * Poperation\_i \tag{4.8}$$

The cost for process electricity use can be calculated with Equation 4.9.

$$C_{elec\_i} = E_{elec\_i} * r_{elec} \tag{4.9}$$

The gas use includes both natural gas and special gas (e.g., argon and N2). Natural gas is mainly used for heating and production environment maintenance. Special gas is used for production processes. Therefore allocation of natural gas use (Equation 4.10) depends on the monthly throughput (N_{month}) while special gas use is process depend (Equation 4.11).

$$C_{naturalgas\_shopfloor} = E_{naturalgas\_shopfloor} * r_{gas} / N_{month} \tag{4.10}$$

$$C_{gas\_i} = E_{gas\_i} * r_{gas} \tag{4.11}$$

Enterprise level energy cost (Equation 4.12) is the aggregation of operation level energy cost, shopfloor energy cost, as well as office area energy cost.

$$C_{energy\_enterprise} = C_{energy\_shopfloor} + (E_{light\_office} + E_{equipment}) * r_{elec} / N_{month} \quad (4.12)$$

Production support cost: This category consists of items that are to support the production, for example building maintenance (Cbuilding_maintenance), safety devices ($C_{safety\_devices}$), and ancillary materials ($C_{ancillary}$). These costs are mostly shopfloor level costs. They can be allocated to a single unit of product with monthly throughput. Ancillary materials may include convey carts, computers, paper, chairs, paper towels, toilet papers, and laundry detergent. At the enterprise level, R&D ($C_{R\&D}$), marketing (C_{market}), office equipment ($C_{equipment}$), selling ($C_{selling}$), and administration labor ($C_{labor\_enterprise}$) can be counted as production support costs. They can also be allocated with monthly throughput in order to get a per unit cost.

Manufacturing cost: The total cost for producing a single unit of product is aggregated from all the costs associated with manufacturing, including energy, labor, tool, material, administrative, equipment, and production support costs. The monthly manufacturing cost can be estimated by multiplying single unit manufacturing cost by monthly throughput.

4.2.3 Environmental Impact Assessment

A common method employed in environmental impact assessment is life cycle assessment (LCA). The ISO 14040 provided the definition of LCA and a framework for conducting LCA studies includes four phases of activities, goal and scope definition, life cycle inventory, impact assessment, and interpretation (ISO, 2006). This method is a systematic set of procedures for compiling and examining the inputs and outputs of materials and energy and the associated environmental impacts directly attributable to the functioning of a product or service system throughout its life cycle (US EPA, 2010). Practitioners and researchers from many domains come together using LCA to calculate indicators of potential environmental impacts that are linked to manufactured products, such as climate change, stratospheric ozone depletion, tropospheric ozone (smog) creation, eutrophication, acidification, toxicological stress on human health and ecosystems, the depletion of resources, water use, land use, and noise (Rebitzer, 2004). On the manufacturing shopfloor, LCA can be conducted by analyzing environmental impact of production processes usually upstream electricity and material production.

The major impact categories in SME manufacturers are energy, airborne emissions, water consumption and wastewater, solid waste and resource recovery (Haapala et al., 2013). For energy consumption, carbon dioxide equivalent is a measure that quantitatively describes global warming potential (GWP) from greenhouse gas emissions (GHG) including carbon dioxide, methane, nitrous oxide, fluorinated gases (US EPA, 2014). Manufacturing shopfloor energy consumption is mainly from electricity use and natural gas use. The GWP value (EI co_{2e}) can be calculated with Equation 4.13.

$$EIco_{2e\_elec} = EFco_{2e\_elec} * E_{electricity\_shopfloor} \tag{4.13}$$

The electrical grid emission factor (EF_{co2e} = 6.89551 × 10-4 metric tons CO2 / kWh) is based on the U.S. annual non-baseload CO_2 output rate (EPA, 2014). The natural gas emission factor (EF_{co2e_gas}) is 0.005302 metric tons CO_2/therm (EPA, 2013; IPCC, 2006). The GWP related to natural gas consumption can be calculated using Equation 4.14.

Table 4.5. Commonly Used Environmental Impact Indicators and Measures (Widder et al., 2011)

Indicators	Abbr.	Explanation	Emissions	Measurement
Global Warming Potential	GWP	Impact of anthropogenic emissions which enhance the radiative forcing of the atmosphere	CO_2, CH_4, N_2O, halocarbons	kg CO2-eq
Ozone Depletion Potential	ODP	Impact on stratospheric ozone layer due to anthropogenic emissions, which causes a greater level of UV-B radiation to reach the earth's surface	CFCs, HCFCs, halons, methyl bromide	kg CFC11-eq
Acidification Potential	AP	Impact of acidifying pollutants on soil, groundwater, surface waters, and ecosystems	SO_x, NO_x, HCl, HF, NH_3	kg SO_2-eq
Eutrophication Potential	EP	Impact of excessive macronutrients in terrestrial and marine ecosystems	PO_4, NOx, nitrates, NH_3	kg PO_4^{-3} -eq
Photo-oxidant Formation Potential	POFP	Propensity to produce certain air pollutants which react with sunlight to form reactive chemical compounds, such as ozone, which negatively impact on the terrestrial ecosystem	Non-methane-hydrocarbons	kg C_2H_4- eq
Ecotoxicity Potential	ETP	Impacts of toxic substances on aquatic and terrestrial ecosystems	Mercury, chromium, cadmium, dioxins, arsenic, other toxic compounds	kg DCB-eq DCB: dichlorobenzene
Human Toxicity Potential	HTP	Impacts of toxic substances on human health	PM10, PM2.5, soot, XO_2, NO_x, CH_4,	kg DCB-eq
Abiotic Resource Depletion Potential	ADP	Depletion of natural resources (including energy resources)	Mineral use, fossil-fuel use, etc.	kg Sb-eq
Water Consumption	WC	Water consumed in the production of power, primarily cooling tower losses	Water	H_2O (Liters)

$$EI_{co2e\_gas} = EF_{co2e} * E_{naturalgas\_shopfloor} \quad (4.14)$$

For material consumption, environmental impact is associated with material, which can be mixed in air emissions and waste fluid. Table 4.5 shows some commonly used metrics for assessing environmental impact related to production material use. Practitioners can select these or other metrics that fit their assessment needs.

4.2.4 Social Impact Assessment

The purpose of social impact assessment is to help manufacturers take responsibility in designing good work for employees, bring benefit to the local community, and help product users achieve their needs. Over the past 20 years, the concept of product life cycle has encouraged companies take responsibility for their products across the life cycle from raw material extraction to disposal of the products.

Corporate social impact assessment methods include various sociology methodologies, e.g., surveys, focus groups, interviews, content analysis, and participant observation. Social assessment largely depends on the scope of the study and the stakeholder in focus. Managers can design good work for operators by considering human psychological and physical needs. Recent findings reveal that psychological factors (e.g., motivation, psychological fatigue, physical fatigue) have direct relations with production cost, quality, and time. Lee et al. (2010) has defined twelve dimensions in designing a good work. These include compensation, safety, social interaction, variety, aesthetics, feedback, accomplishment and status, demand, autonomy, value, technical growth, and personal growth. These can be guidelines for decision making. With regard to metrics of social impact assessment, workload, injury rate, and wage have been used in prior work (Zhang and Haapala, 2014) to assess production impact on shopfloor workers. Practitioners need to select appropriate metrics for assessment and then assigned to a specific stakeholder category and impact subcategory. The method of quantifying each metric developed by Zhang and Haapala (2014) is to evaluate the difference between the local performance standard (P_{local}), e.g., average operator wage, and the work cell performance (P_j), e.g., wage for the operator position under study. Social impact measures are then normalized into relative values which sum to 1 for all scenarios analyzed. The normalized value (a_{ij}) is calculated using Equation 4.15.

$$a_{ij}=\frac{P_{ij}-P_{local,ij}}{\sum_{j=1}^{m} P_j-P_{local,ij}} \tag{4.15}$$

Equation (4.15), $\boldsymbol{a}_{ij}$ is the normalized value of i^{th} metric and j^{th} alternative. There are n metrics and $\boldsymbol{m}$ alternatives. The total social impact, I_{3_j}, of each alternative (j) can then be calculated as (Equation 4.16):

$$I_{3\_j} = \sum_{i=1}^{n} a_{ij} \tag{4.16}$$

Social capital which “refers to the collective value of all ‘social networks’ and the inclinations that arise from these networks to do things for each other”(Putnam, 2001), can be an indicator for corporate social responsibility performance, as sociologists (Bourdieu, 1977; Ferragina, 2010; Hanifan, 1916; Jacobs, 1992; Putnam, 2001) in the last century have studied how social networks affect performance of a corporate system and beyond. It is accepted that social capital eventually leads to the creation of human capital (Coleman, 1988), therefore the direct impact of social capital on productivity cannot be overlooked in a manufacturing system. Factors that contribute to social capital include but are not limited to confidence (Knack & Keefer, 1997), associativity (Narayan & Pritchett, 1997), cohesion (Perkins & Long, 2002), and how a group relates to the rest of the society.

The Global Reporting Initiatives (GRI) provides guidelines to report sustainability performance of corporations (GRI, 2013). Under social category, labor practices and decent work, human rights, society, and product responsibility have been identified as indicators. Similarly, social LCA guidelines developed by UNEP following the structure of LCA (Benoît et al., 2010) also provide a framework for analyzing the social impact of a system. For social impact assessment, stakeholders are divided into five categories: workers, consumers, the local community, society, and value chain actors (Benoît et al., 2010). Within each category, subcategories have been identified. For example, for worker stakeholder category, freedom of association and collective bargaining, child labor, fair salary, working hours, forced labor, equal opportunity/discrimination, health and safety, and social benefits/social security are identified. Depending on manufacturing system scenarios, practitioners can develop their own set of indicators by referring to such indicators established from guidelines and standards.

The challenge of social impact assessment lies in quantitative measurement of social impact. Existing methods are deficient in quantitatively evaluating social impact of a manufacturing system. This complex problem reveals the complicated dynamics of the social system (e.g. company, society). Thereby, defining the goal and scope, which are the basis of selecting indicators and metrics, is critical to social assessment.

4.2.5 Collection and Treatment of Data

The purpose of the data collection is to build the systems dynamics model and validate the model. In this study, the source of data is a local medium sized manufacturer producing laboratory equipment. This study will utilize both historical data from this manufacturer and a manufacturer historical injury data set from OSHA for another manufacturer.

Quantitative data (Table 4.6) are collected from various means, including an onsite data tracking system, personal communication, existing company documents, and historical data.

Table 4.6. Data Content

Data Type	Data
Material	Material cost, material weight, recycled steel sheet mass, inventory material mass
Energy	energy consumption at each machine, lighting energy consumption, heating energy consumption, office energy consumption
Cost	material cost, labor cost, energy cost
Time	process time at each station, production rate, waiting time, working hours per day
Labor	number of workers
Injury	number of injuries incidents, time gap between two injuries, injury cost

Model will be calibrated to replicate the expected behavior over time. Once the parameters are calibrated to represent a historical behavior, a sensitivity analysis of the variables will be conducted through the built in sensitivity function in the simulation (Vensim Professional). Decision makers will be able to see the behavior results change according to the variable value changes. During the model calibration, data will be adjusted to avoid special circumstances interruption and errors in actual collection.

4.2.6 Model Validation

The developed full cost model must be verified and validated to ensure repeatable and reliable results. The validity of a model is closely related with its purpose, and so the validity of the purpose of the model must be substantiated (Barlas, 1996). Therefore, a sustainable manufacturing system dynamics model should support system design with the goals of energy efficiency, pollution prevention, employee friendliness, social responsibility, and market competitiveness among other factors. The developed model will be tested according to the process shown in Figure 4.2, based on the validation framework summarized by Barlas, which includes direct structure testing, structure-oriented behavior testing, and behavior pattern testing. The structure confirmation test, a direct structure test method, assesses the validity of a model's structure. It can be carried out by comparing the equations and their form to existing relationships in the system modeled and to system information reported in the literature (Barlas, 1996; Forrester and Senge, 1980). In future work, tests will be conducted by examining the structure of equations to ***in situ*** systems studies, as well as by reviewing relevant prior research. Thus, real industrial systems will be utilized in model development, and literature will provide supplementary sources to validate the model structure.

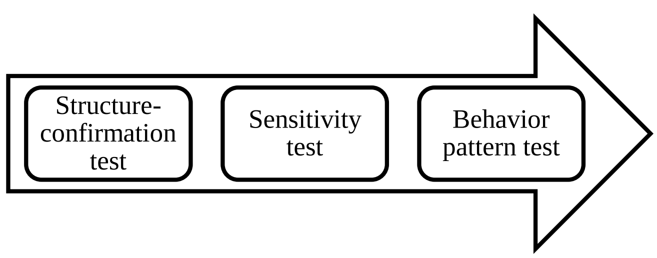


Figure 4.2. Model validation process (Barlas, 1996).

The sensitivity test, a structure-oriented behavior testing method, indirectly assesses model structure validity (Barlas, 1989; Forrester and Senge, 1980). Highly sensitive parameters in the system model are determined and investigated to ascertain whether the real system would exhibit similar sensitivity. For example, an environmental policy modification may cause a change in operation-level behaviors and, consequently, impact waste treatment methods and energy use. Such a policy change can be simulated within an SD model, and then historical data applied to compare results for the simulated and real systems. The behavior pattern test is preceded by the prior two tests, and designed to measure the differences the model can reproduce in the behavior pattern exhibited by the real system (Barlas, 1989). It should be noted that model construction and revision should be conducted in concert with the validation process. Figure 4.3 summarizes the logical sequence of steps (discussed above) for the model validation process, based on the research by Barlas (1996).

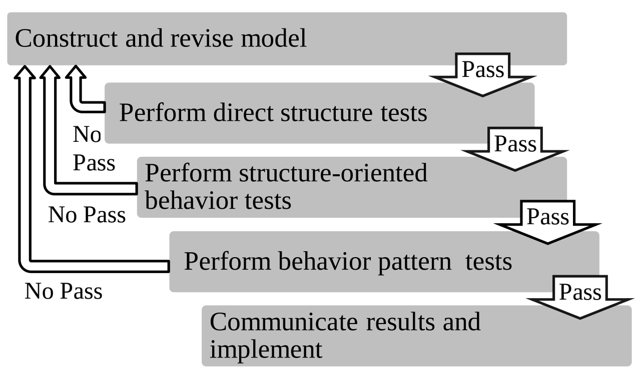


Figure 4.3. Model validation procedure (Barlas, 1996).

4.3 Summary

In this chapter, the research methodology was presented with structure of the model, sustainability assessment of the system, and model validation methods. In order to illustrate the application of the proposed full cost model, Chapter 5 presents a manuscript consisting of a recap of the methodology and an application case based on an actual manufacturing system.

Chapter 5. A Full Cost Model for Sustainable Manufacturing Systems

Abstract

This paper addresses the important need of understanding the relations of sustainability behaviors in manufacturing systems by linking economic, environmental, and social domains of sustainable manufacturing with systems thinking principles, and by understanding the actual sustainability-related behaviors for a real metal product manufacturer. The proposed full cost model identifies sustainability factors and behaviors of the manufacturing system and depicts their relations across three system levels, the enterprise level, the shopfloor level, and the process/operation level. The creative method design approach from the domain of systems thinking principles, integrates economic assessment, environmental assessment, and social assessment methodologies and quantifies the assessment results, which are embedded into a systems dynamics model. The full cost model serves as a decision making tool for manufacturing practitioners to balance economic, environmental, and social benefits.

5.1. Introduction

Organizations have typically focused on cost, yield, and operating logistics as the primary performance drivers for competitive decision-making. However, environment, safety, and health (ESH) issues are becoming important business performance drivers. Historically, ESH costs have not been adequately assessed in the up-front engineering of operating processes, resulting in only a partial understanding of the overall cost of manufacturing. Early assessment (i.e., preferably at the product design stage) of cost allows financial impact to be uniformly compared with other competitive performance factors, provides a more comprehensive and objective data set to apply to design and manufacturing decisions, and minimizes downstream risk and cost. There is a deficiency in relating environmental and social practices to potential economic benefits and a belief that a long time horizon is needed to capture benefits, such as reduced liability and recurring waste, and chemical and material costs.

With this problem being recognized, systems thinking approaches, which tackle complex problems by analyzing underlying system component relations, have been identified as crucial to sustainability research. According to Fiksel et al. (2013), a systems approach is desired to understand the linkages among economic, environmental, and social activities and to solve complex problem by considering hidden consequences of solutions. Efforts integrating systems thinking with manufacturing and the three sustainability domains (i.e., economic, environmental, and social) either continue the call for research (Kibira et al. 2009) or focus on global-level eco-system sustainability (Fiksel et al., 2013). Therefore, a practical tool for understanding manufacturing cost related behaviors is desired to support management, engineering, safety and environmental decision making.

The purpose of this work is to develop a full cost model that will assist small and medium enterprises (SMEs) in metal product manufacturing industry to evaluate economic, environmental, and social performance, and to provide a decision making method to assess sustainability tradeoffs over time. This research is significantly *in enhancing manufacturing decision making.* The economic bottom line is critical to SMEs, often, however, new practices have to be adopted even when they have negative or uncertain impacts on financial benefit (Hahn, Figge, Pinkse, & Preuss, 2010; Hahn et al., 2010; Pagell, Wu, & Wasserman, 2010; Pinkse & Kolk, 2009; Winn, Pinkse, & Illge, 2012). The model developed in this study will relate environmental and social performance measures to manufacturing cost, which represents the decision makers' economic bottom line. Full cost, in this research, is defined as the summation of product-related manufacturing costs, which include direct and indirect costs due to the transformation of materials and energy through the use of labor and equipment. The full cost model should not only assist manufacturing decision makers at all levels, but also provide researchers a way of understanding manufacturing costs associated with underlying system behaviors.

5.2. Background

This research is grounded on both sustainable manufacturing research and systems thinking science. In this section, related literature on each domain will be reviewed, followed by a discussion of research limitations and how this research will go beyond current knowledge.

5.2.1 Systems Thinking and Sustainable Manufacturing

Increasing demands for eco-friendly products from customers and environmental and social responsibility concerns have motivated sustainable manufacturing practices (Dornfeld, 2013; Duflou et al., 2012; Karl R. Haapala et al., 2011; Hutchins & Sutherland, 2008; Jawahir & Dillon, 2007; Overcash et al., 2009; Rickli & Camelio, 2010). Research over the past two decades falls into four categories (Zhang et al., 2014): sustainable manufacturing assessment methodologies (Benoît et al., 2010; ISO, 2006, p. 14040; Jasch, 2008; O'Brien et al., 1997; Woodward, 1997), sustainability indicators (Brunner & Rechberger, 2004; DJSI, 2013; Dreher et al., 2009; Feng et al., 2010; Goedkoop et al., 2009; Lu et al., 2010), sustainable manufacturing decision making (Avram et al., 2011; Basu & Sutherland, 1999; Hersh, 1999; Malakooti & Deviprasad, 1987; Milacic et al., 1997; Zhang & Haapala, 2014), and sustainability assessment of manufacturing processes (Choi et al., 1997; Dahmus & Gutowski, 2004; Haapala et al., 2012; Jawahir & Jayal, 2011; Kellens et al., 2012; Munoz & Sheng, 1995; Yuan & Dornfeld, 2010b). The literature, however, has invested little effort into investigating the tradeoffs among economic, environmental, and social benefits of product, process, and system design changes. It is posited that the underlying interactions between sustainability behaviors are somewhat overlooked due to the lack of system perspectives on sustainable manufacturing processes and systems

.

Systems thinking encourages practitioners to understand underlying behaviors behind a problem and keep learning about the system (Senge, 1990). To establish the foundation of integrating systems thinking into sustainable manufacturing, Zhang et al. (2014) developed several fundamental concepts for sustainable manufacturing systems thinking, including an operational definition of sustainable manufacturing, economic weltanschauung, environmental weltanschauung, social weltanschauung, and definitions for commonly used terms in manufacturing from systems perspective. This prior work utilizes elements from a systems-based methodology for tackling unstructured problems developed by Checkland (1981) named Soft Systems Methodology (SSM). Following the operational definitions, a structured problem is presented to show a vision for this research, which involves extending environmental impact focused research to a broader scope (synergizing economic, environmental, and social dimensions), facilitating multidisciplinary collaboration, and developing a better understanding of the manufacturing system dynamics (Zhang et al., 2013). A system dynamics based conceptual model was later proposed to illustrate the system methodologies in understanding system behaviors and tackling complex problems (Zhang et al., 2014). The conceptual model categorized manufacturing systems into enterprise, shopfloor, and operation (or process) levels and addressed sustainability related system behaviors at each level. For the next step from the conceptual model, applicable research shall be done to solve real world problems, as demonstrated herein.

5.2.2 Current Cost Models for Manufacturing Systems

Activity-based costing (ABC) emerged as a more efficient alternative to traditional costing methods (Staubus, 1971). In ABC, each activity is treated as a cost involved in the production of a product or service. Factory and corporate support costs are all allocated, from the top down, to individual product models (Kaplan & Bruns, 1987). Costs are allocated through resource drivers and activity drivers. Resource drivers include units such as time, equipment depreciation, or labor; these are used to determine the cost of an activity. The resource costs, once assigned to an activity, are then allocated to cost objects through the use of an activity driver. Activity drivers measure the frequency of the activity (Goebel et al., 1998). ABC recognizes that direct labor hours or dollars sales do not always correctly account for allocation of overhead and other market-based activities, making it a powerful tool for assessing the value of a single product. However, ABC is often difficult to effectively implement in high mix low volume SMEs due to lack of data, limited technical and financial resources, and inadequate computerization (Roztocki, 2005). ABC may also produce data that is too complex for analysis by less experienced managers.

Process-based costing (Banerjee, 2006; Lee et al., 2003; Shim & Siegel, 2000) is a method used most often in enterprises that produce just a few identical products in large batches. In contrast to ABC, costs in process-based costing are allocated to a few processing departments. Processing departments are organizational units that perform a specific job on the product, such as punching or breaking. As in ABC, overhead costs are allocated to these units rather than calculated separately (Phillips et al., 2011). Process-based costing can be more effective than ABC at accurately representing cost information because of its simplicity; however, Sievanen and Tornberg (2002) noted in their case study that processes must be clearly defined. Process-based costing is a less viable option in HMLV SMEs due to the large number of different models and products produced.

Similar to process-based costing, job order costing allocates overhead and enterprise costs to a single unit. In job order costing, costs are allocated to a batch of products rather than to a particular process (Horngren, 1967). As each batch of products will have different production needs, job order costing is better-suited to a manufacturing enterprise with a wider variety of products. Overhead is allocated to batches, often simply by using direct labor hours (Hoque, 2005). For an SME with a HMLV of products, job order costing has the potential to be an effective cost model. However, direct labor hours correlate to overhead costs less reliably in an enterprise where machines replace most direct labor, as they do in a metal product manufacturing enterprise.

Life cycle costing (LCC) takes into account the entire life of a product when calculating or projecting costs. LCC is the total cost of ownership of machinery and equipment, including its cost of acquisition, operation, maintenance, conversion, and decommissioning (SAE, 1999). Life cycle costs are summations of all the costs related with the material use, length of equipment life, and also annual time increments over the equipment life when considering the time money value (Barringer & Weber, 1996). The objective of LCC analysis is to choose the most cost effective approach from a series of alternatives to achieve the lowest long-term cost of ownership. The best balance among cost elements is achieved when the total LCC is minimized (Landers, 1995). As with most engineering tools, LCC provides best results when conducting a project that is limited to a specific period of time. On shopfloor, LCC can be utilized to assess the equipment and facility cost with time value.

Environmental accounting categorizes environmental behavior costs into four aspects, environmental protection costs (emissions treatment and pollution prevention), costs of wasted materials, and costs of wasted capital and labor (Jasch, 2003). Environmental accouting identified cost elements in each category and proposed measures for environmental protection. Veltri and Ramsay (2009) developed a method to account costs associated with enterprise ESH practices. It categorizes a practice into upfront, acquisition, use, post disposal, and closure stages and calculates net present value (NPV) of the behavior to inform practitioners of the benefits that can be gained over the life of the practice

5.2.3 Intervention Method and System Dynamics

The intervention method includes two conceptual theory concepts, total system intervention and creative design of methods. Total systems intervention (TSI) was developed by Robert Flood and Michael C. Jackson in late 1980s and early 1990s based on the philosophy and theory formulated as Critical Systems Thinking (Flood, 1990). TSI can be used in a coherent manner to promote successful intervention in a complex organizational and societal problem situation. Sociological awareness, human well-being, and emancipation comprise the philosophical base for TSI, which aims to take technical, practical, and emancipatory interests into consideration to address different aspects of problem situations (Flood, 1990). There are three phases in TSI (Jackson, 2003), i.e., creativity, choice, and implementation, taken in order to understand the problem context, choose the appropriate system approach, and solve the problem. Because the problem context changes over time, TSI is a dynamic meta-methodology.

Creative design of methods (CDM), sometimes called TSI2, was developed by Gerald Midgley (1997), who posited that the drawing of boundaries is crucial for determining how improvement is to be defined and what action can be contemplated. At the beginning of a system intervention, it is necessary to gather the people involved in the system from different perspectives to define th problem. He also argued that justifying systems intervention requires continually redrawing the boundaries to "sweep in" stakeholders previously excluded from consideration. The proposed creative design of methods (changed to creative design methodology in 1997) looks at a problem as a series of systematically interrelated research questions. Each question is addressed using different methods or part of a method. Then, synthesis is completed to allow individual questions to be addressed as a part of a whole system of questions. One difference between TSI and CDM is that TSI encourages the use of one methodology at a time, while CDM encourages the creative design of ad hoc methodologies to the particular problem context (Calvo-Amodio et al., 2011).

System dynamics was developed in the middle of the twentieth century by Forrester to understand the time variant behavior of systems, and is based on feedback control theory (Porter, 1950; MacMillan, 1951; Brown & Campbell, 1948). System dynamics models use positive and negative feedback loops to identify the dynamics that arise from these interactions. In system dynamics, a causal loop diagram reveals the structure of a system. By understanding the structure of a system, it becomes possible to ascertain the system's behavior over a period of time (Meadows, 2008). System dynamics also adopts mental models, which are relative, enduring, and accessible internal conceptual representations of an external system whose structure maintains the perceived structure of that system, to build and understand the structure of the complex system (Doyle & Ford, 1998).

As the philosophy of CDM is consistent with the idea of integrating systems thinking into sustainable manufacturing, the approach proposed herein adopts principles from CDM. Thereby, cost assessment, environmental impact assessment, and social impact assessment methods can be integrated into a system dynamics model that can assist in understanding manufacturing behaviors and system sustainability performance.

5.2.4 Limitations of Current Research and the Role of This Research

As discussed above, current sustainable manufacturing methodologies often focus on assessment of a single domain of sustainability. A methodology is lacking to assist practitioners solve complex sustainability-related problems in a systemic way. Meanwhile, traditional costing methods are deficient in addressing hidden sustainability-related behavior costs. A full cost model that will assist manufacturing decision makers uncover the underlying system behavior relations and the associated costs can aid in addressing these deficiencies. An integration of related methods from sustainable manufacturing and systems thinking is desired for the full cost model development. Based on the total system intervention method and the system dynamics method, this integration can be realized in a modeling framework that is reported in the next section.

5.3. Research Methodology

In this section, the full cost model developed under this work is reported. The model aims to answers two research questions. First, what is the model structure that could integrate sustainability assessment and the systems approach to represent the decision making consequences of manufacturing behaviors? Second, how are environmental and social impacts of manufacturing linked to product?

5.3.1 The Intervention Method for Model Development

The intervention method is developed upon creative design of method (CMD) theory, which allows system practitioners apply methods from various domains involved in solving a specific problem. As the purpose of developing a full cost model is to assist managerial and engineering decision making, the intervention method shall be a decision making model that could integrate all aspects of a manufacturing system including production behaviors, economic behaviors, environmental behaviors, and social behaviors. Meanwhile, the model shall be able to separate and connect factors from all three manufacturing system levels so that cross-level impacts can be evaluated. With all the requirements above, system dynamics (SD) proved to be an effective modeling method as the basis of this intervention method (Zhang et al., 2013). In addition to the merits above, SD also provides performance over time of system factors from a decision impact, which allows decision makers to evaluate the impact in both short term and long term.

5.3.2 The Full Cost Model Structure

The proposed model includes two sub-models, a static model and a dynamic model (Figure 5.1). The dynamic model is developed from the static model, including system decision making behaviors.

The static behaviors are expected to serve as the fundamental structure for the dynamic model. Production processes, energy usage, material use, labor time, safety cost, environmental impact, etc. are the production behaviors included in the static model. When developing this model, cost assessment, environmental impact assessment, and social impact assessment are embedded since their relations are usually direct and well defined.

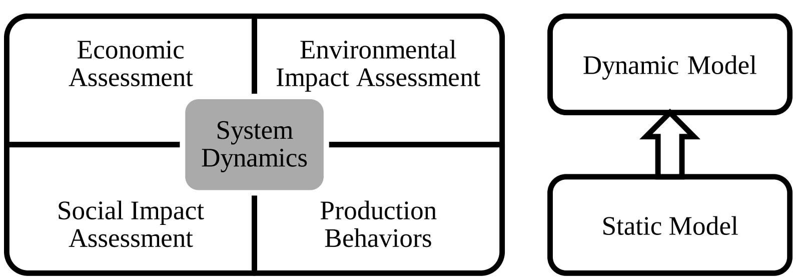


Figure 5.1. The Intervention Method of the Full Cost Model.

Built upon the static model, the dynamic model serves as the decision support method for decision makers to simulate the consequences of certain behaviors over an effective decision period (predetermined time length). Decision makers are able to see to what extent manufacturing system behaviors would affect specified outcomes (e.g., production cost, energy use, or wages) during the effective decision period. Manufacturing system behaviors may include production behaviors (e.g., adjusting machining settings or production rate) or environmental and safety behaviors (e.g., implementing an ESH policy or program). The behaviors should follow the eleven system archetypes elaborated by systems thinkers, e.g. Senge (1990), and represented with stock flow diagrams, i.e., accidental adversaries, balancing loop, drifting goals, escalation, fixes that fail, growth and underinvestment, limits to success, reinforcing loop, shifting the burden, success to the successful, and tragedy of the commons. All the decision making behaviors can be described with these archetypes, individually or combined.

5.4. Application

In order to illustrate the application of this full cost model, a manufacturing system is modeled and an injury cost system behavior scenario is simulated. Additionally, selected sustainability factor relations are tested with the full cost model.

5.4.1 Model Development

The model is developed based on a medium sized metal product manufacturing enterprise. Manufacturing processes include punching, bending, welding, painting, assembly, packaging, and shipping. At the operation level, process information (e.g., power, process time, and labor) and associated costs are collected. At the shopfloor level, lighting, heating, material use, building maintenance are collected. At enterprise level, administrative costs, selling cost, marketing cost, and aggregated manufacturing cost are collected.

The static model development involves economic assessment, environmental impact assessment, and social impact assessment. For cost assessment, a Microsoft Excel based cost model was built. For environmental impact, life cycle assessment was applied to evaluate GWP (kg CO_2e) and material depletion from nature units. For social impact assessment, injuries have been selected as the main impact to be considered. The shopfloor level sub-structure of this static model is shown in Figure 5.3. In the static model, relations among the factors are linear as there are no behaviors added in the model.

Dynamic model development involves behavior simulation. In this model, an injury behavior from OSHA is simulated. The data is retrieved from OSHA recorded injuries database (Moore, 2014). The total number of injuries accumulates with the control of injury rate and healing rate. The injury rate is affected by practices that enhance safety and prevent injuries. The healing rate is assumed to be the same as injury rate which means all the injuries will be healed after a delay. Meanwhile, the company sets a goal of a certain number of allowable injuries for each month. When the gap between the current number of injuries and the goal goes up, more practices will be adopted to reduce the injury rate. The goal, however, can be affected by some unexpected incidents of injuries. In that case, the company will modify the goal and try to close the gap. The company also invests in savings covering injury costs every month. The investment comes from fund from an established ESH program. This investment, however, decreases when manufacturing cost increases. The structure of the behavior is shown in Figure 5.2, and the system dynamics model of this behavior is shown in 5.4. The injury cost change overtime can be seen in Figure 5.5.

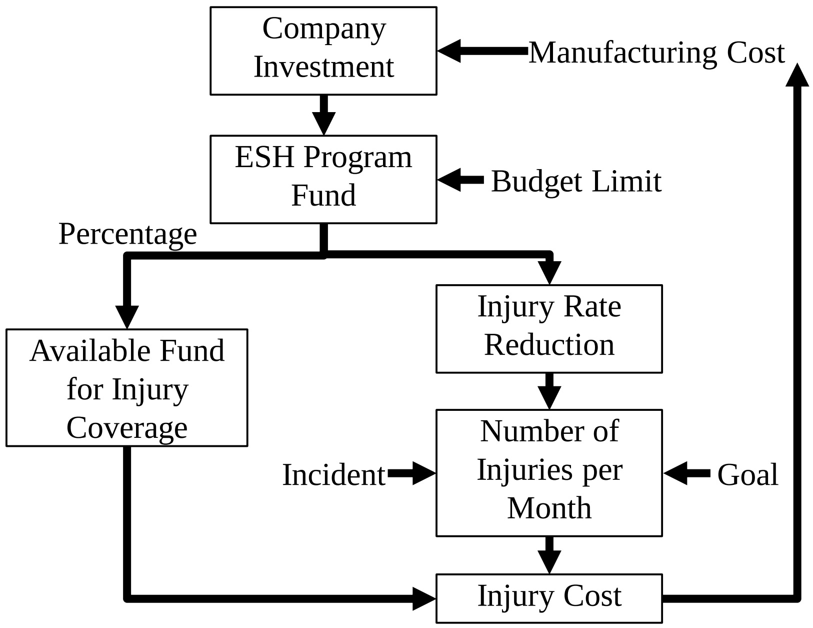


Figure 5.2. Injury Cost Behavior Structure

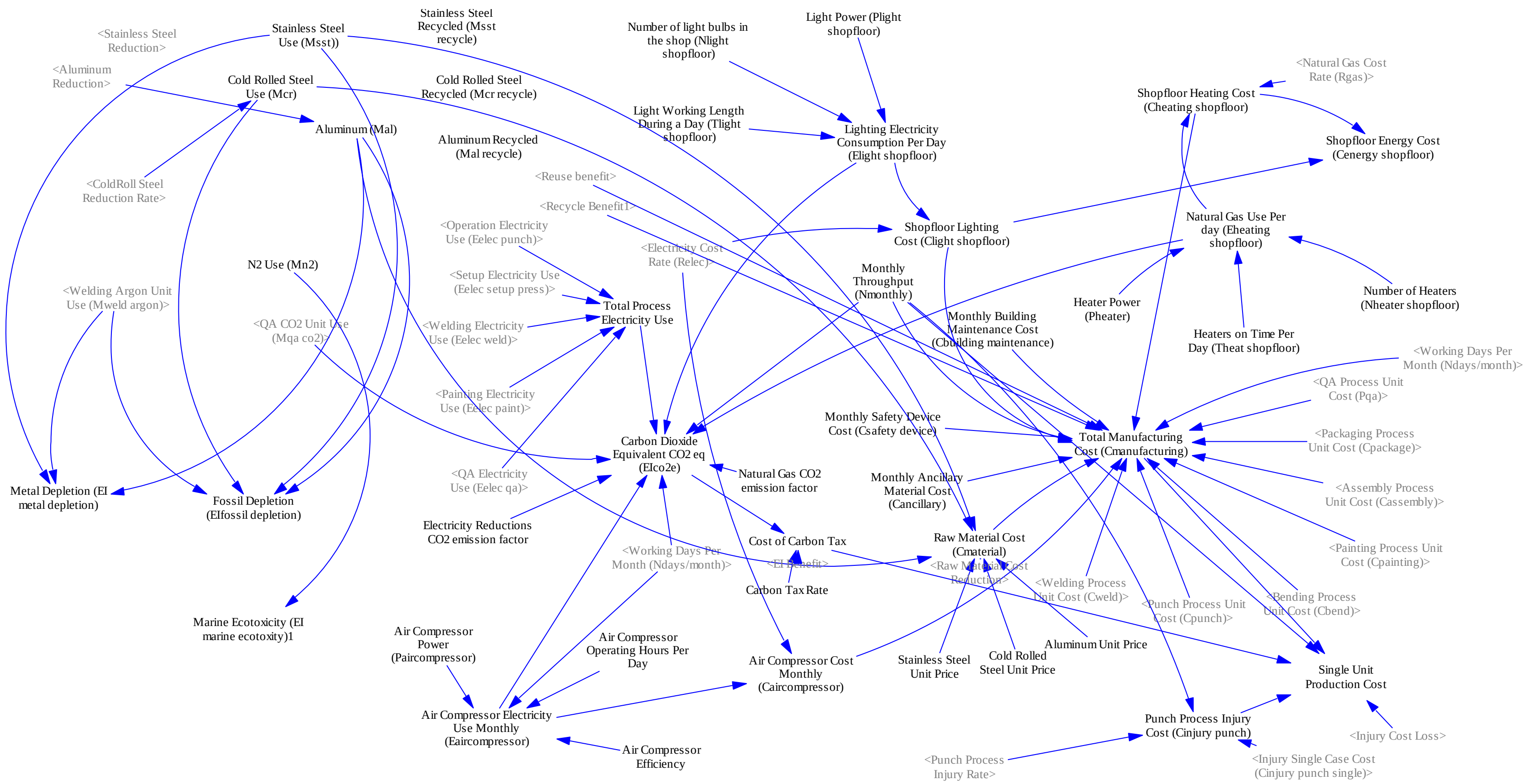


Figure 5.3. Snapshot of the Static Model – Shopfloor Level Structure

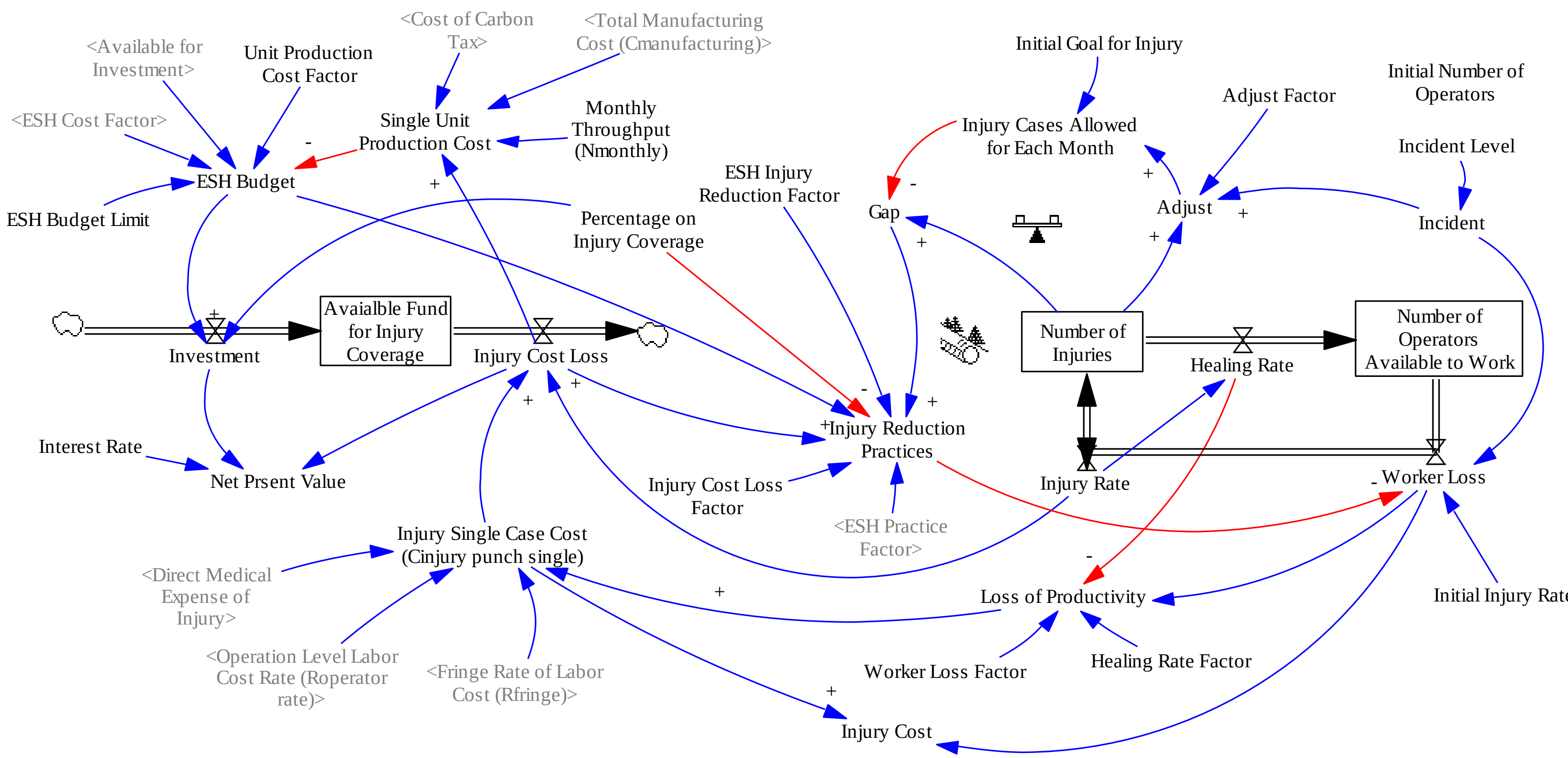


Figure 5.4. Dynamic Model – Injury Cost Behavior

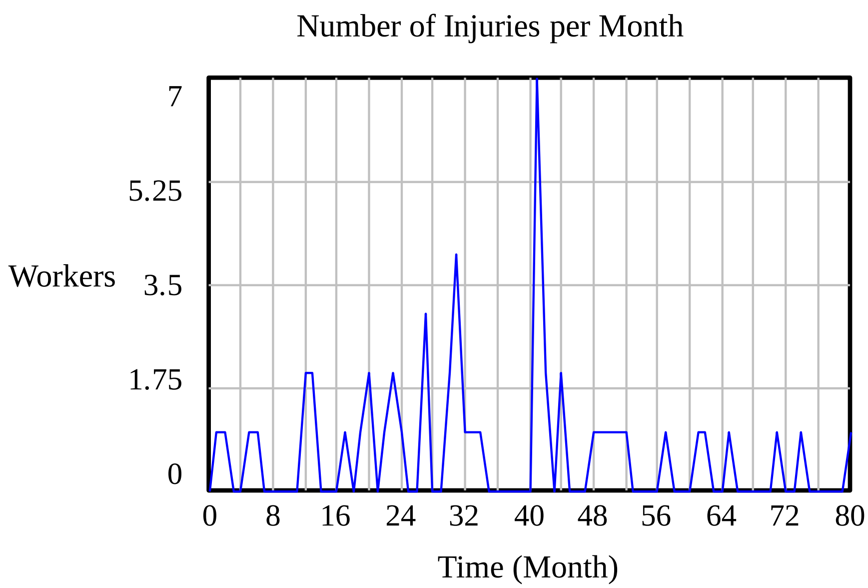


Figure 5.5. Number of Injuries over time.

Figure 5.5 shows the result from the developed system dyanmics model. It shows that the number of injuries increased at from month 0 to month 40, and then droped to a stable number after month 40. A comparison of historical injuries and the model generated injuries is shown in Figure 5.6.

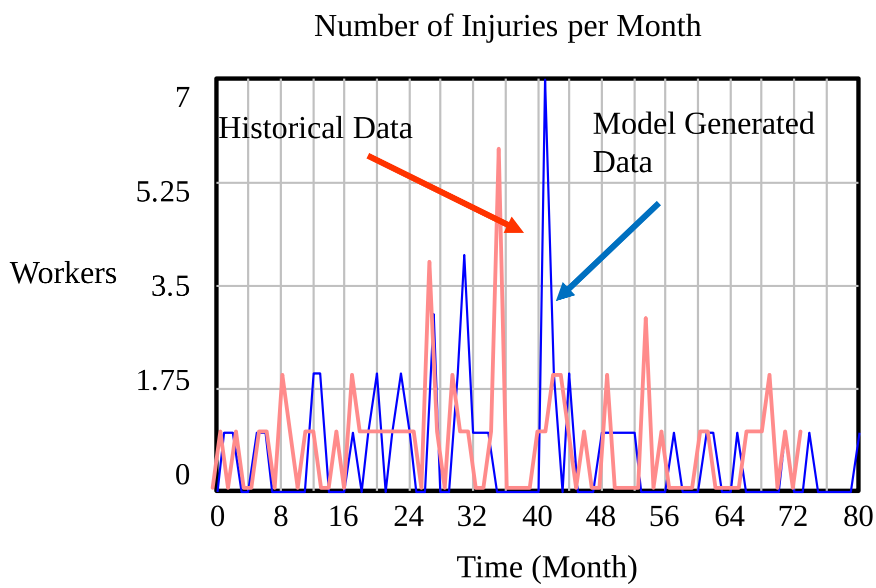


Figure 5.6. Comparison of Number of Injuries using Historical Injury Data and Model Generated Injury Data

In order to study the impact of percentage of injury cost coverage from the budget, a sensitivity analysis (with built-in function in Vensim) is run on injury cost. It is shown in Figure 5.7.

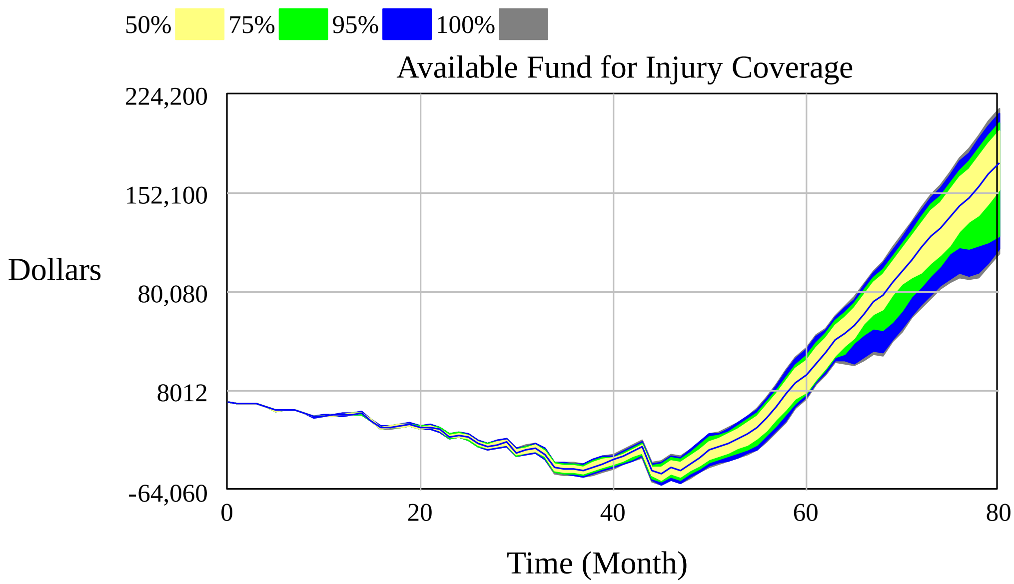


Figure 5.7. Sensitivity of Available Injury Funds to Percentage of Injury Cost Coverage

Figure 5.7 shows that the available funds for injury coverage experienced a decrease before month 50, and then an increase after that. During the first stage (before month 50), all the investments are devoted to covering injury cost and there are not fund available to implement more injury reduction practices. During the second stage, however, with steady investment and a decreasing injury rate, available fund starts to increase over time. Meanwhile, more injury reduction practices are implemented to reduce injury rate, which will further reduce injury costs and consequently increase available funds. The implications of this model is that managers who would like to establish an injury reduction program, can determine the amount of investment needed during the first stage and second stage to effectively reduce injuries, as well as evaluating the short term and long term cost benefit tradeoffs of the program.

5.4.2 Relationships among Sustainability Factors

This section shows how each of the hypotheses introduced in Chapter 1 will be tested with experiments. Hypothese are restated below.

General Hypothesis 1: Underlying manufacturing system behaviors influence environmental and social impacts and their related cost.

Sub-Hypothesis 1: The variation of manufacturing activity variables (e.g., product material use, setup time, and machining time) independently affects environmental impact and social impact.

Sub-Hypothesis 2: The simultaneous changes on manufacturing activity variables affect environmental impact and social impact

General Hypothesis 2: Manufacturing cost changes over time as a result of internal and external policy decisions.

Sub-Hypothesis 1: Manufacturing cost changes over time as a result of internal policy decisions.

Sub-Hypothesis 2: Manufacturing cost changes over time as a result of external policy decisions.

Three parameters are selected to represent metrics of interest for evaluating sustainability performance, i.e., They are: *manufacturing cost* ($C_{manufacturing}$) representing economic performance, GWP cost (Cco_{2e}) representing environmental impact performance, and injury rate (IR) representing social impact performance.

Product redesign and reduction of waste are two common sustainability practices in manufacturing systems. Therefore, the environmental and social consequences of the two practices are of interest. For product redesign, variable *product material use* ($M_{material}$) is the selected metric, as material is directly related to cost and environmental impact, while for waste reduction practices, process setup time (T_{setup}) and machining time ($T_{machining}$) are selected, as they are often the target of process improvement.

To assess internal policy, the percentage of available funds for covering injury costs (P_{fund}) is selected as the variable to investigate the effect on injury cost (C_{injury}) and environmental impact cost (C_{EI}). As for external policy, in order to study the impact of the carbon tax policy that has been adopted by many other countries, *carbon tax rate* ($r_{carbon\ tax}$) is selected to investigate the effect on manufacturing cost ($C_{manufacturing}$), and injury cost (C_{injury}).

5.4.2.1 Test 1: The underlying manufacturing system behaviors influence environmental and social impact and their related cost

Parameters of Test 1 sensitivity analysis are shown in Table 5.1. In this section, impacts of setup time (T_{setup}), machining time ($T_{machining}$), and stainless steel use are tested and analyzed. The values of such parameters are varied over a 30% range.

Table 5.1. Sensitivity Analysis Parameters of Test 1

Input	Value Range ($\underline{+}$15%)	Output
Setup time (T_{setup})	Triangular Distribution Min:2040s; Max: 2760s	GWP (C_{CO2e})
Machining time ($T_{machining}$)	Uniform Distribution Min: 1443s; Max: 1952s	Injury Cost
Stainless Steel Use	Uniform Distribution Min: 72.79lb; Max: 98.49lb	

The effect chain from setup time in the model is shown in Figure 5.8. Setup time affects manufacturing cost by impacting energy consumption when machine is idle and labor cost on machine setups. As the amount of ESH budget is affected by total manufacturing cost, injury reduction practices can also be affected by manufacturing cost. With less injury reduction practices, injury cost may go up.

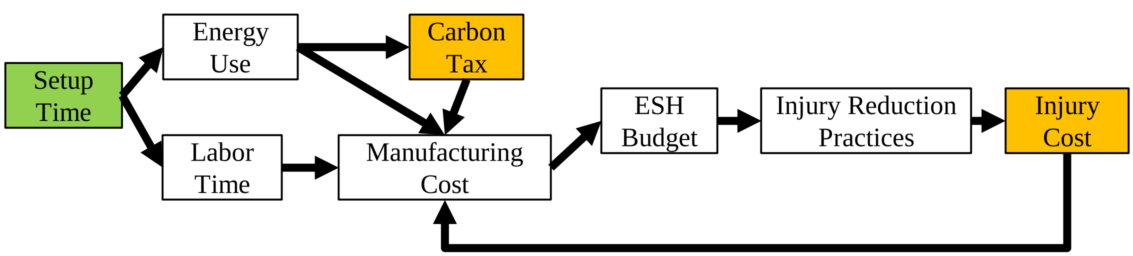
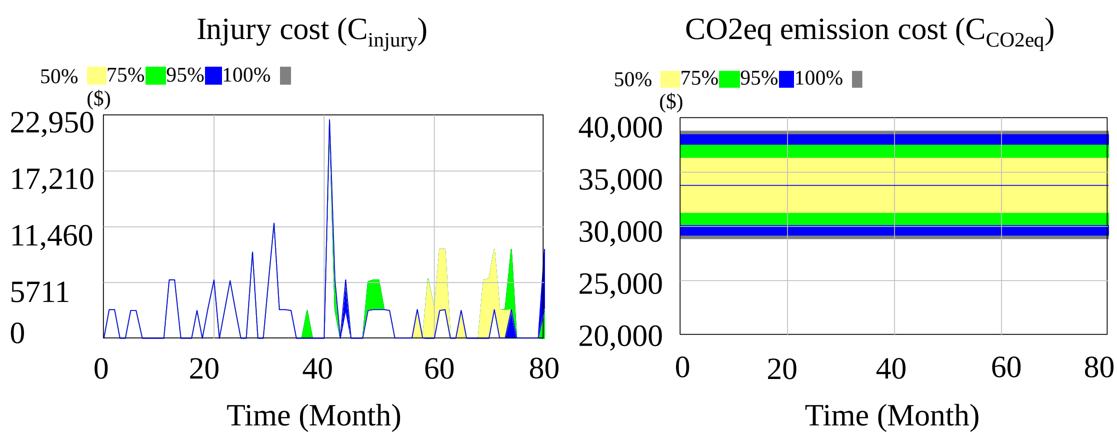


Figure 5.8. Effect Chain of Setup Time on Carbon Tax and Injury Cost

Sensitivity analysis is conducted with embedded function in Vensim. Setup time is vaired over a 30% range from 2040s to 2760s. The results are shown in Figure 5.9 a&b and show that setup time has impact on injury cost after around 40 months. That is because the injury cost fund availability starts to increase at around time 40 and more practices are adopted due to this investment increase. Due to the direct relation of energy consumption during setup time, GWP has a linear relation to setup time whose impact is clearly shown in Figure 5.9 b.



(a) (b)

Figure 5.9. Sensitivity Analysis of Setup Time on Injury Cost (C_{injury}) and CO2eq emission Cost (C_{co2eq})

“Machining Time” Effect on Outputs: The effect chain embedded in the model is shown in Figure 5.10. Manufacturing cost is affected by both energy use and labor time, which are related to machine time. Injury cost, which is part of the manufacturing cost, can be affected by injury reduction practices and ESH budge. The feedback arrow from injury cost to manufacturing cost indicates that injury cost is counted as part of the manufacturing cost.

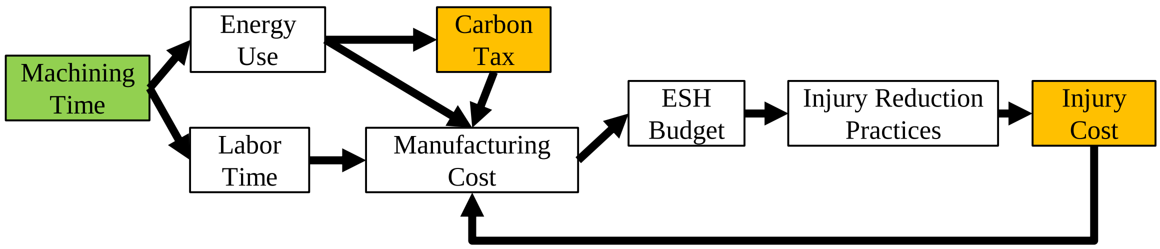


Figure 5.10. Effect Chain of Machining Time on Carbon Tax and Injury Cost

Sensitivity analysis is conducted with embedded function in Vensim. The results are shown in Figure 5.11. From the results in the figure, there is no clear impact on injury cost. The factor relations can be reflected from sensitivity analysis results. Therefore in order to see the changes happened in the effect chain, sensitivity analysis results on manufacturing cost, ESH budget, and injury reduction practices are also conducted (Figure 5.12).

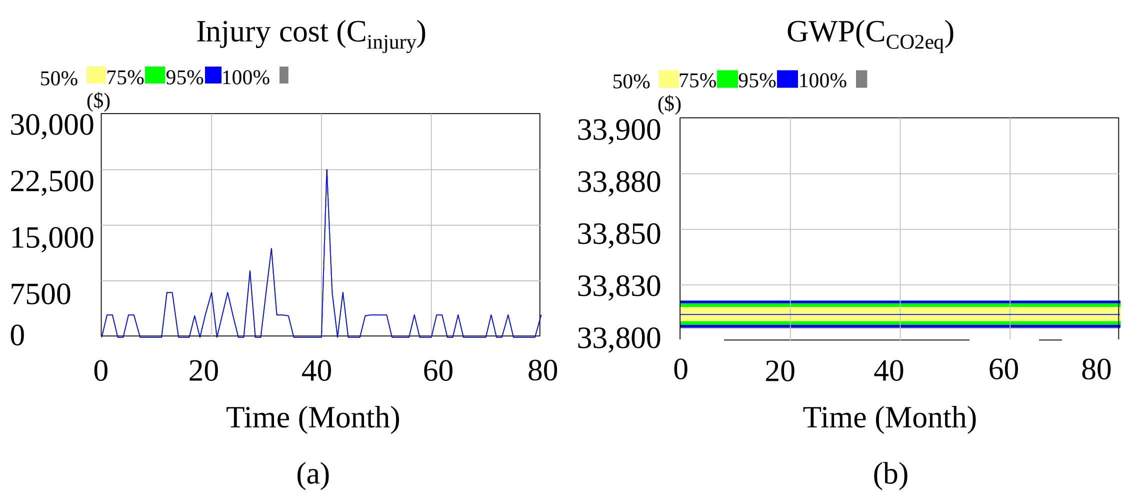
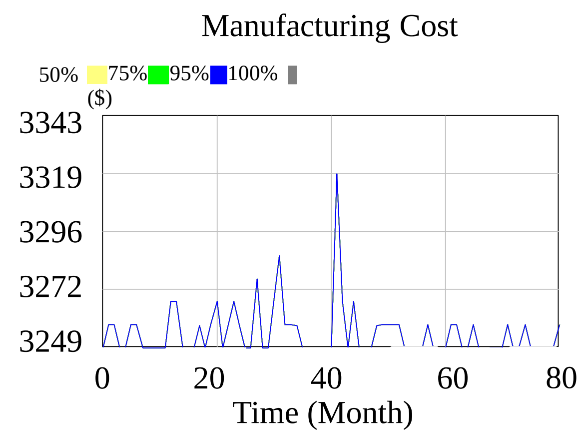
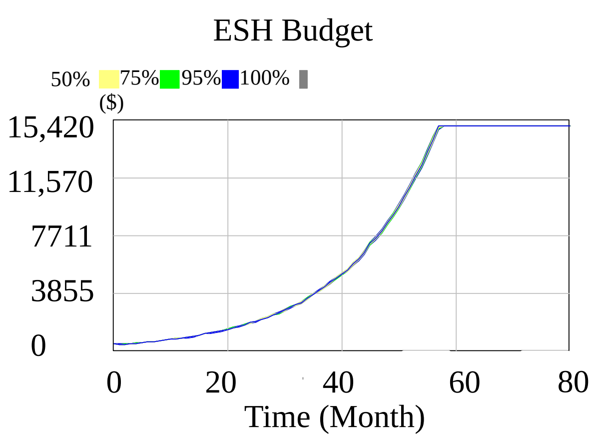


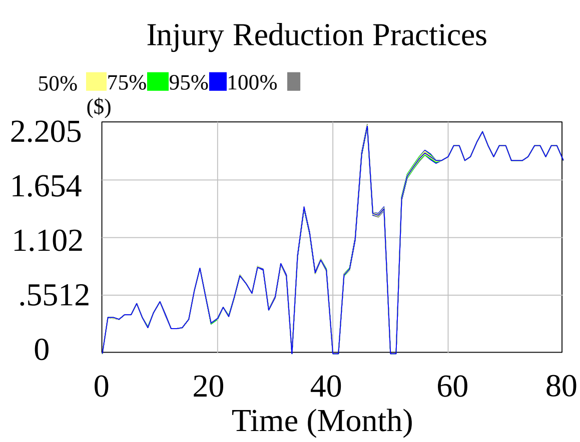
Figure 5.11. Sensitivity Analysis of Machining Time on Injury Cost (C_{injury}) and GWP (C_{co2eq})



(a)



(b)



(c)

Figure 5.12. Sensitivity Analysis of Machining Time on (a) Manufacturing Cost, (b) ESH Budget, and (c) Injury Reduction Practices

Figure 5.12 shows that manufacturing cost is affected by machining time, while its impacts on ESH budget and injury reduction practices appear to be negligible. The effect of machining time decreases along the effect chain and thus its effect cannot be seen on injury cost.

As raw material of the product, stainless steel use directly affects manufacturing cost and hence impact injury cost through ESH budget and injury reduction practices. As shown in Figure 5.13, carbon tax is not affected by stainless steel because in the current manufacturing system, the energy consumption is not affected by steel use when the cutting path is not changed. Carbon tax, however, could be affected if there are cutting path changes, which will consequently affect energy consumption.

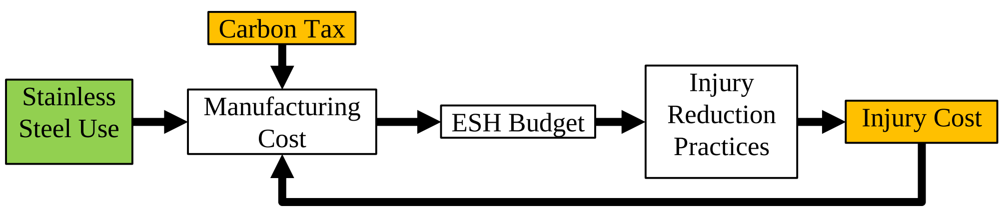


Figure 5.13. Effect Chain of Stainless Steel Use on Carbon Tax and Injury Cost

Sensitivity analysis results are shown in Figure 5.14. Because the relation between stainless steel use and carbon tax is not depicted in the model, there is no impact on CO2eq emission cost in this model. The relation, however, is dependent on the manufacturing case. For example, stainless steel use can affect machining time and energy consumption. In this way, CO2eq emission cost will be affected. The injury cost shown in Figure 5.14 shows that there is only a clear difference at right before month 60. In order to analyze of this phenomenon, sensitivity analysis on manufacturing cost, ESH budget, and injury reduction practices are conducted (Figure 5.15).

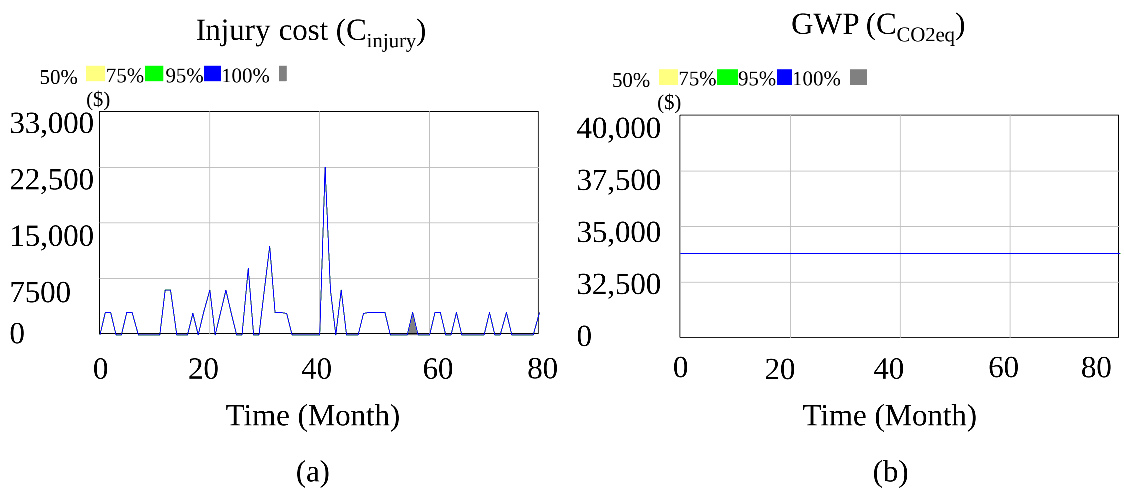


Figure 5.14. Sensitivity Analysis of Stainless Steel Use on (a) Injury Cost (C_{injury}) and (b) GWP Cost (C_{co2eq})

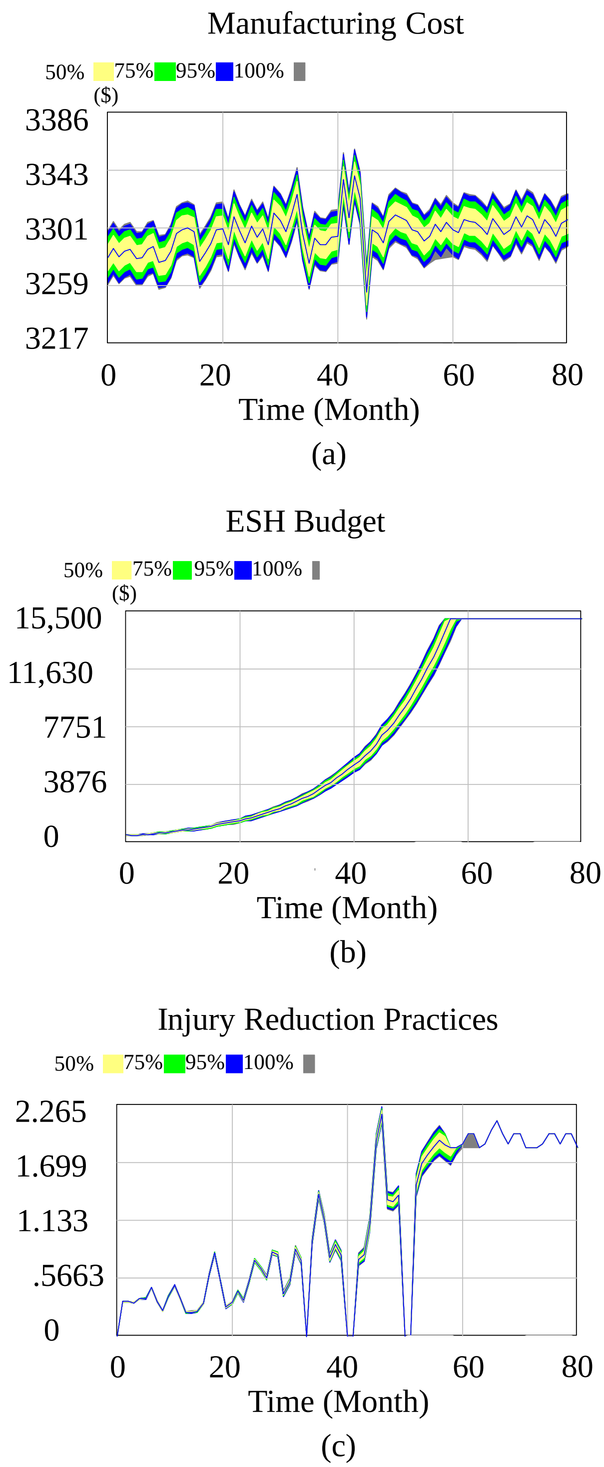


Figure 5.15. Sensitivity Analysis of Stainless Steel Use on Manufacturing Cost, ESH Budget, and Injury Reduction Practices

The figure shows that stainless steel use has a clear impact on manufacturing cost and ESH budget. As ESH budget is closely related to injury reduction practices, injury reduction practice costs are clearly affected when the ESH budget increases. When ESH budget reaches its limit, it will no longer affect injury reduction practice costs.

Effect of simultaneous change of setup time, machining time, and stainless steel use is an integration of three separate effects from each of the parameter. The value of the impact, however, is not simply a summation of the three because the three separate impacts can affect each other as well.

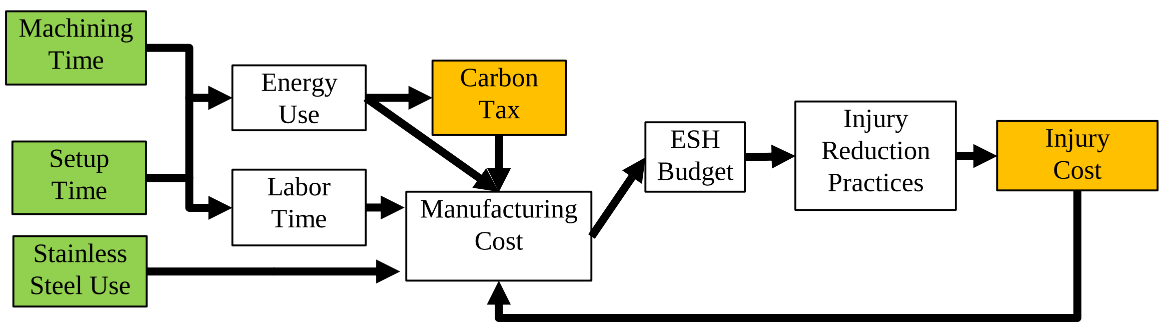


Figure 5.16. Effect Chain of Simultaneous Change of Machining Time, Setup Time, and Stainless Steel Use on Carbon Tax and Injury Cost

Sensitivity analysis results are shown in Figure 5.17. The results show that injury cost is affected by the simultaneous change starting from around time 40, while GWP cost result is similar to the one that was affected solely by setup time cost. Therefore, in this case, setup time is a major contributor to GWP cost change compared with other two factors.

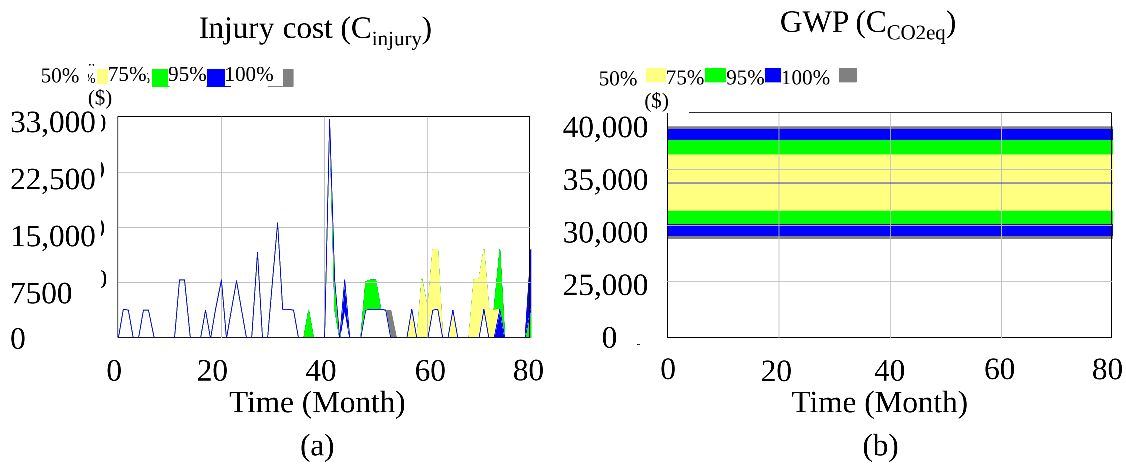


Figure 5.17. Sensitivity Analysis of Simultaneous Change of Machining Time, Setup Time, and Stainless Steel Use on (a) Injury Cost (C_{injury}) and (b) GWP (C_{co2eq})

Figure 5.18 shows sensitivity analysis results on manufacturing cost, ESH budget, and injury reduction practices. With the increasing impact of simultaneous change on ESH budget, the impact on injury reduction practices is also increasing.

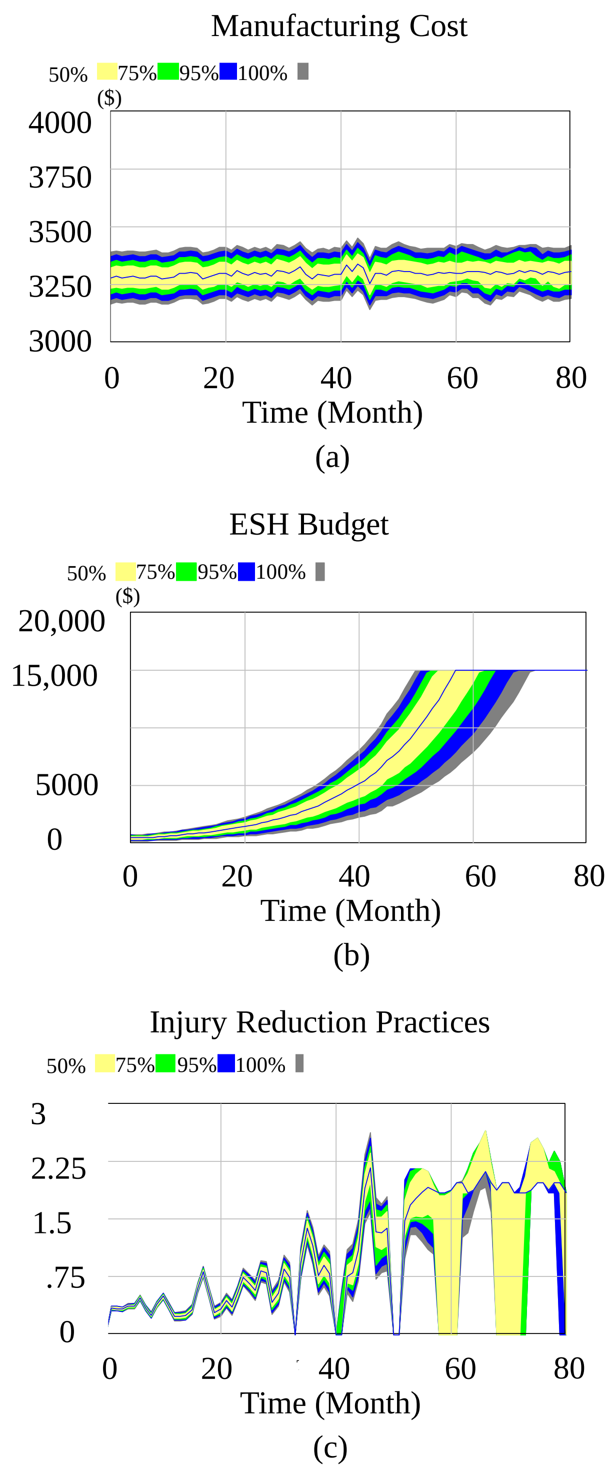


Figure 5.18. Sensitivity Analysis of Machining Time, Setup Time, and Stainless Steel Use on (a) Manufacturing Cost, (b) ESH Budget, and (c) Injury Reduction Practices

5.4.2.2 Test 2: Manufacturing cost is changed over time as a result of internal and external policy decisions.

Parameters of this sensitivity analysis are shown in Table 5.2. In this section, impacts of Percentage of ESH fund available and Carbon tax rate are tested and analyzed. The values of such parameters are varied in a 30% range.

Table 5.2. Sensitivity Analysis Parameters of Test 2

Input	Value Range (±15%)	Output
Percentage of ESH fund available (P_{fund})	Uniform Distribution Min: 47.81; Max: 64.69	GWP cost (C_{CO2eq})
Carbon tax rate ($r_{carbontax}$)	Uniform Distribution Min: \$17; Max:\$23:	Injury Cost

Percentage of ESH funds available (P_{fund}) affects the amount of money invested in injury reduction practices, and consequently impacts injury cost and manufacturing cost. Figure 5.19 shows the effect chain of this relationship.

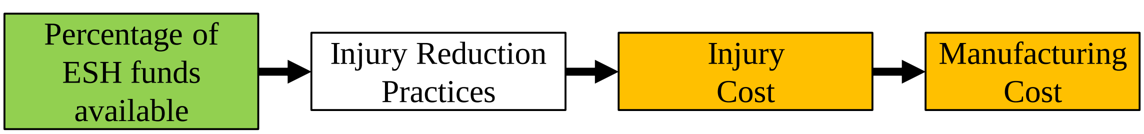


Figure 5.19. Effect Chain of Percentage of ESH fund available on Injury Cost and Manufacturing Cost

From the injury behavior structure and Figure 5.19, we can see P_{fund} impacts injury reduction practices and injury cost. In turn, manufacturing cost is affected by injury cost.

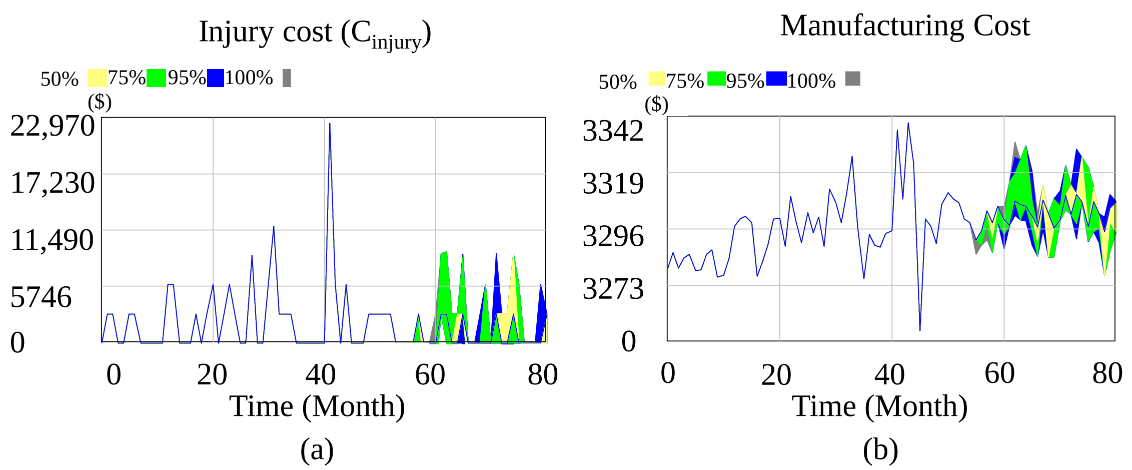


Figure 5.20. Sensitivity Analysis of Percentage of ESH fund available on (a) Injury Cost and (b) Manufacturing Cost

Figure 5.20 shows that due to available funds for injury cost coverage start to accumulate at around time 60, and more injury reduction practices are implemented, which reduces injury cost and manufacturing cost.

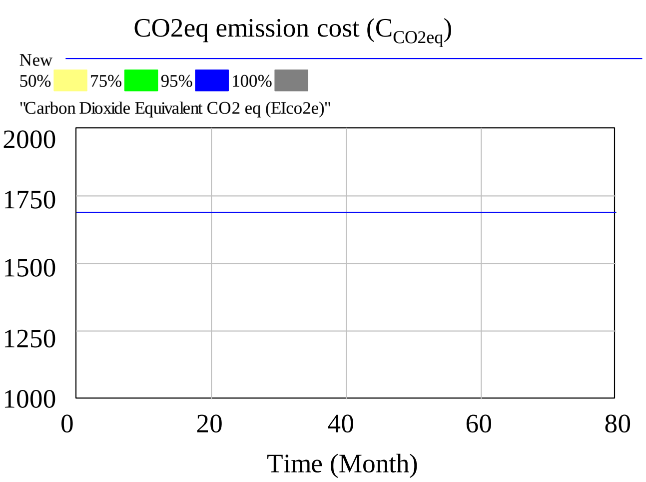


Figure 5.21. Sensitivity Analysis of Percentage of ESH fund available on CO2eq emission Cost

Currently, there is no activity connects “Percentage of ESH fund available” and CO2eq emission cost. Thus, Figure 5.21 shows there is no impact between the two factors.

Carbon tax rate affects manufacturing cost through carbon tax. Injury cost, same as above, is affected by manufacturing cost through ESH budget and injury reduction practices. Figure 5.22 shows the effect chain from carbon tax rate.

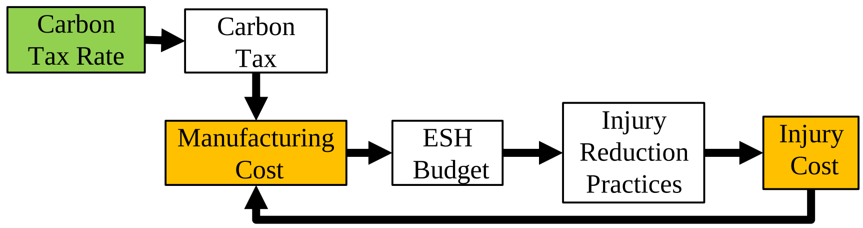


Figure 5.22. Effect Chain of Carbon Tax Rate on Injury Cost and Manufacturing Cost

Carbon tax rate affects injury cost through manufacturing cost and injury reduction practices. The sensitivity analysis results of carbon tax rate on injury cost and manufacturing cost are shown in Figure 5.23.

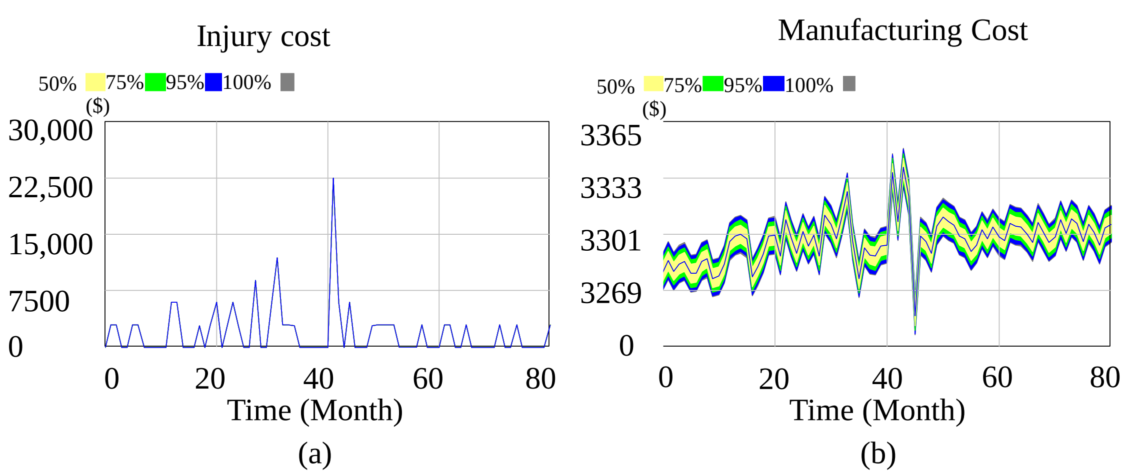


Figure 5.23. Sensitivity Analysis of Carbon Tax Rate on (a) Injury Cost and (b) Manufacturing Cost

Figure 5.23 shows that there is no clear effect of carbon tax rate on injury cost. Manufacturing cost, however, is clearly impacted by carbon tax rate. Therefore, in order to determine where the impact was reduced to a negligible level in the effect chain, sensitivity analysis on injury cost and manufacturing cost are conducted (Figure 5.24). The results in the figure show that the sensitivity of the ESH budget and injury reduction practices to carbon tax rate are low. With limited impact on injury reduction practices, injury rate is not clearly affected and thus injury cost is not clearly affected.

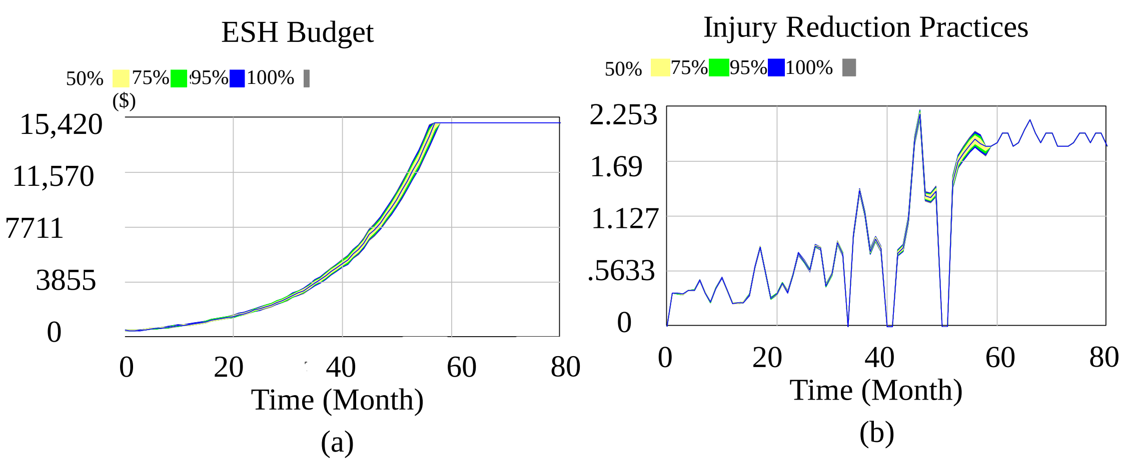


Figure 5.24. Sensitivity Analysis of Carbon Tax Rate on (a) ESH Budget and (b) Injury Reduction Practices

Simultaneous change of “Percentage of ESH fund available (P_{fund})” and “Carbon tax rate” affects both manufacturing cost and injury cost. Figure 5.25 shows that both Carbon Tax Rate and Percentage will affect Injury Cost and Manufacturing Cost through Injury Reduction Practices.

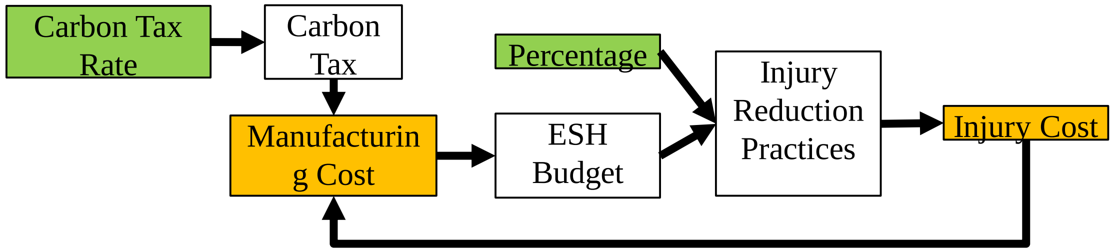


Figure 5.25. Effect Chain of Simultaneous Change of "Carbon Tax Rate" and "Percentage of ESH Fund Available" on Injury Cost and Manufacturing Cost

Sensitivity analysis results are shown in Figure 5.26. As both carbon tax rate and percentage are affecting injury reduction practices, the impact on injury cost is a result of both factors. Percentage of ESH funds available, however, is the main contributor to the change after month 60.

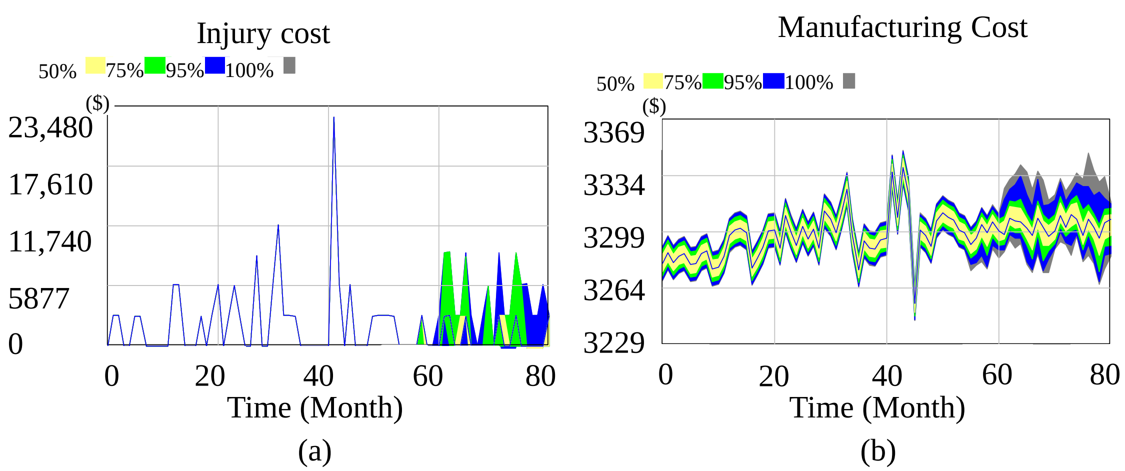


Figure 5.26. Sensitivity Analysis of Simultaneous Change of "Carbon Tax Rate" and "Percentage of ESH Funds Available" on (a) ESH Budget and (b) Injury Reduction Practices

5.5. Discussion

This paper presented a full cost model for sustainable manufacturing systems. The full cost model, which is based on system dynamics, aims to assist manufacturing engineering and managerial decisions by modeling system behaviors and decision scenarios from cost perspective. Additionally, this cost modeling method is able to assist engineers and managers gain in-depth understanding of sustainability factors relations in their manufacturing systems. In order to illustrate the application of this model, an injury cost decision-making scenario in a medium sized steel product manufacturing system was modeled, and relations of selected scenario related factors were analyzed. Several findings can be drawn from this study and the analysis. First, all the production factors in a medium sized steel product manufacturing system can be related, and it is the system activities that connect these factors. Second, for indirect relations between two factors, the impact of one factor reduces or falls to a negligible level at a certain intervening factor. Third, system behaviors can create non-linear changes in performance of system factors over time. Fourth, the behavior-based full cost model is able to simulate manufacturing decision making scenarios to make strategic, tactical, and operational decisions. The findings from this study are able to establish the sustainability-related systemic structures and behaviors to assist companies to design full costing methods and make sustainability decisions, and will be instrumental in assisting SMEs to incorporate sustainable manufacturing practices.

One limitation of this study is the lacking of embedded behaviors in the model. Sustainability factors relations cannot be fully captured with insufficient system behaviors. Besides, the model can only be partially validated with the studied manufacturing system. Findings from this research may not be generalized. The relations need to be further validated with more real-world applications.

Future research of this study will incorporate more manufacturing system behaviors in the full cost model to explore further understanding of sustainability factors relations. Applications beyond manufacturing arena will also be explored with this behavior based cost modeling method.

5.6 Summary

This chapter presented a manuscript including the methodology of developing a full cost model for sustainable manufacturing systems, and its application in an actual metal product manufacturing system. With the developed cost model, an injury cost behavior was modeled and the factors relationships were tested to answer research question 2. Chapter 6 will concluse the whole dissertation with discussion of findings, limitations of this research, and future research ideas.

Chapter 6. Conclusion

Sustainable manufacturing practitioners are not equipped with systems thinking methods that will assist holistic decision making. A theoretical foundation is required to guide researchers and practitioners, and a methodology is lacking to relate sustainability factors to each other and to assess manufacturing sustainability performance using a monetary value. This dissertation developed a framework to integrate systems thinking methodologies into sustainable manufacturing behavior assessment – a framework that assists researchers gain an in-depth understanding of manufacturing sustainability behaviors. This dissertation also developed a full cost model under the proposed theoretical framework. Practitioners will be able to predict system behavior performance, under both short-term and long-term perspectives. By analyzing costs related to sustainability behaviors, environmental impact and social impact will be expressed with monetary value. Hence, manufacturing practitioners can make sustainability-related decisions from the cost perspective based on the developed full cost model. In this chapter, a summary of the work reported is provided. Findings from this research are presented. This chapter also presents contributions of this research and addresses limitations and some future research ideas.

6.1 Findings

First, all sustainability factors can be related in a manufacturing system. The relations can be established by system activities. The static model and the dynamic model developed in this research captured the qualitative relations between sustainability factors, which are linked by system activities. Test 1 results proved this with a sensitivity analysis of process settings (i.e., process setup time) on social impact (injuries) and environmental impact (GWP).

Second, for indirect relations, one factor is related to another through a series of factors in between. Process setup time for example affects injury cost through process labor cost, manufacturing cost, injury cost coverage investment, injury reduction practices, and injury rate. Machining time affects GWP emission through electricity consumption. In indirect relations, the impact of one factor could reduce or reach a negligible level in the effect chain.

Third, changes in manufacturing system behaviors create non-linear performance of system factors over time. The dynamic model of the injury cost behavior for example includes a goal-seeking archetype and balancing loops, which caused fluctuations of injury cost over time. Incidents resulted in significant changes in injury cost; and incidents dropped after more injury reduction practices were implemented. This means that incidents will only affect the system performance in the short term and will not affect the system performance in the long term when a behavior (injury reduction practice) is established.

Fifth, the full cost model is able to assist strategic, tactical, and operational decision making by simulating a decision making scenario. The available funds for injury coverage for example demonstrated a decrease until month 50, followed by an increase. This showed that injury reduction practices have an impact on reducing injury cost, and the savings resulting from such a fund increases over the long term. In this case the decision can be made by the manager that an initial investment to cover first 50 months of injuries needs to be in place in order to smooth the pressure of unsufficient injury cost coverage.

6.2 Limitations of This Research

This study has several limitations.

First, the model needs further validation. According to Barlas (1996), model validation should go through direct structure test, structure-oriented structure test, and behavior pattern test. In this study, the model is built based upon a real manufacturing system and the model can only be partially validated with the studied manufacturing system. Findings from this research may not be generalized. The relations need to be further validated with more real-world cases.

Second, due to limitations of data availability, several assumptions were made. The data from OSHA recorded injuries of a manufacturing system may not be the same as the studied metal product manufacturing system. The injury cost behavior modeled in the dynamic model is only intended to illustrate how the full cost model could assist decision making.

Third, in this developed full cost mode, behaviors are limited to injury cost. An actual manufacturing system includes many related activities creating various behaviors. The limited embedded behaviors in the model will not be able to capture all the relations in the system. For example, process setup time can be directly related to number of injuries because the more time operators are exposed to the machine and tooling, the higher the possibility that an operator will get injured. Relations not modeled as such might weaken the learnings from this study. The model shown in this dissertation is an example on how companies can develop and validate their own models.

6.3 Contributions of This Research

The findings from this dissertation establish the sustainability-related systemic structures and behaviors to lead companies to design full costing methods and make sustainability decisions. The outcomes (the conceptual model and the full cost model) advances knowledge of how to align a costing structured to sustainability goals (and vice-versa) based on the company's economic, environmental and social policy and practice. The approach developed addresses a generic problem (how to align sustainability efforts with the financial bottom line) and has the potential to be transferred to other SME industries (besides metals product manufacturers). This dissertation also addresses the fundamentals of costing model design principles given a particular context (sustainable manufacturing), especially in justifiably monetizing sustainability-related metrics (e.g., environmental impacts and employee well-being). The findings will be instrumental in assisting SMEs to incorporate sustainable manufacturing practices that will impact their surrounding communities and society at large.

6.4 Future Research

Several opportunities for future research are outlined below.

First, because a manufacturing system is a complex system, more system behaviors need to be captured in this full cost model developed as a part of this work. One of the findings from this research is that all factors are related to a certain extent. System behaviors will connect manufacturing system factors that do not seem closely related. For example, product redesign not only affects raw material cost, but also affects manufacturing processes. In this case, product redesign specifications and process settings can be related by a product redesign behavior. Other system behaviors that can be captured include production rescheduling, implementation of a new equipment, and change of a supplier.

Second, one finding shows that for indirect factor relations in the manufacturing system, the impact of one factor reduces at a certain distance from another fator and may not be able to impact a significant level of impact on the other examined factor. More needs to be done to investigate how long the impact path is for pairs of factors and for which pairs are impact truly unaccoutable. For example, on the one hand, the injury cost behavior indicates that manufacturing cost affects the availability of the injury coverage budget, which influences injury rate. On the other hand, machining time affects manufacturing cost through energy consumption and labor time cost. Further study can look into how much the machining time impact reduces at each step of the influence.

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Appendix A: A Conceptual Model for Assisting Sustainable Manufacturing through System Dynamics

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Abstract

Industry is confronted with the challenge of balancing economic and financial priorities against environmental and social responsibilities. Current methods are deficient in aiding proactive engineering management decision making and elucidating broader sustainability opportunities within manufacturing systems, often resulting in reactive decisions to circumvent fines, resource costs, or simply poor public perception. While these challenges are long recognized, research has focused on increasing efficiencies toward reducing costs and environmental burdens – individually and simultaneously – with cursory integration of social metrics. This work seeks to facilitate decision making by incorporating systems thinking into sustainable manufacturing assessment and to develop an understanding of the complex interplay of factors from the operational (micro) scale through the enterprise (macro) scale. In this research, a combined approach utilizing principles of sustainable manufacturing and systems thinking (in the form of systems dynamics) is explored, which leads to development of a conceptual model being explored in ongoing research.

A.1. Introduction

Manufacturing systems have advanced through three major phases. First, mass production brought the principle of improving efficiency in manufacturing in place of labor productivity, which had been thought of as the primary measure of productivity (Suh, Cochran, & Lima, 1998). Next, globalization was one of the drivers that triggered manufacturers to adopt lean manufacturing principles, the result of which is improved quality, delivery time, and labor productivity (Suh et al., 1998). Finally, increasing demands for sustainable products, ecological concerns, and social responsibility policies have motivated sustainable manufacturing (Karl R. Haapala et al., 2011), which can be defined as “design of human and industrial systems to ensure that humankind’s use of natural resources and cycles do not lead to diminished quality of life due either to losses in future economic opportunities or to adverse impacts on social conditions, human health, and the environment(Mihelcic et al., 2003).

A manufacturing system targeted at sustainability shifts from focusing solely on economic benefits to balancing economic, environmental, and social objectives. Engineering research, however, has failed to provide an applicable tool to assist such decision making due to the developing nature and complexity of the sustainable manufacturing research field. Systems science offers an alternative to understand the relations among affecting factors within a system and to solve engineering problems holistically (J. Calvo-Amodio et al., 2011), (Mihelcic et al., 2003).

Presented herein is an overview of current challenges for sustainable manufacturing and provide an introductory background on systems thinking. A conceptual systemic model is then presented to lay down the foundations to build a generalizable system dynamics model for assisting sustainable manufacturing enterprise systems.

A.2. Current Challenge for Sustainable Manufacturing

With a changing environment and increasing concerns for the human-ecology system, manufacturers have begun to take responsibility for reducing industrial emissions to the atmosphere (Rusinko, 2007). Gradually, more environmental and social protection policies have been enacted by the government, which have prompted manufacturers to consider environmental and social impact due to production (Barrett, 1994). Increasing environmental and social concerns have led to a need to confront challenges of balancing economic and financial priorities against environmental and social responsibilities. The changes in system characteristics usually result in dynamic changes in economic, environmental, and social factors, all of which are important to decision makers.

Design of sustainable manufacturing systems requires concurrent consideration of economic, environmental, and social factors. In the past decade, methods and approaches have been developed to assist sustainable system design. Anastas and Zimmerman (Anastas & Zimmerman, 2003) presented twelve principles of green engineering to be applied in the design of new materials, products, processes, and systems that are benign to human health and the environment. Manufacturing companies and researchers have developed a myriad of design decision support methods, referred to as Design for X (DFX) methods, where X represents any one of a variety of design considerations occurring over the product life cycle, e.g., quality, manufacturing, production, or environment (Herrmann et al., 2004). Recently, European researchers undertook the SIMTER project to utilize Discrete Event Simulation (DES) to improve manufacturing system optimization by considering parameters that were grouped into three modules: a) ergonomics, b) levels of automation, and c) environmental impacts, in addition to conventional production simulation parameters (Lindahl, Sakao, Sundin, & Shimomura, 2009).

Several other methods and tools have been developed to analyze environmental and social impacts of manufacturing systems. Life cycle cost assessment (LCCA) analyzes costs from a product life cycle perspective, which provides a framework for specifying the estimated total incremental cost of developing, producing, using, and retiring a particular item (Asiedu & Gu, 1998). Life cycle assessment (LCA) offers a holistic tool encompassing all environmental exchanges (i.e., resources, energy, emissions, and wastes) occurring during product life cycle (Klöpffer et al., 2007). Environmentally-focused manufacturing process modeling has investigated various operations (Dalquist & Gutowski, 2004), (Gediga et al., 1998), (Gutowski, Dahmus, & Thiriez, 2006), (K. Haapala, Khadke, & Sutherland, 2004) (Jeswiet & Nava, 2009) (Masanet & Horvath, 2004), (Munoz & Sheng, 1995), and (Jawahir & Dillon, 2007).

Currently, there is no commonly accepted method to adopt social impact assessment of manufacturing systems. Several efforts have been undertaken to include social assessment into product and process design (Hutchins & Sutherland, 2008), (O’Brien et al., 1997), (Dreyer, Hauschild, & Schierbeck, 2006), (W.-T. Lee et al., 2010). Social LCA guidelines for product-based assessment have been developed by UNEP (Benoît et al., 2010), which follow the structure of environmental LCA (ISO, 2006), but a detailed methodology is needed apply social assessment to manufacturing systems. Moreover, no tools exist that seamlessly integrate analysis of industrial, societal, and natural systems to facilitate manufacturing decision making by engineers and company/government policy makers (Karl R. Haapala et al., 2011). Research in sustainability is typically focused on a particular domain or conducted to solve a single problem. Previous research has not focused on addressing the potential far reaching consequences resulting from the solution of a particular problem. For example, a justification for a machine setting may increase production rate, but a negative social outcome may be operator fatigue. Without systems thinking, researchers are impeded by the scope of analysis and may have a limited view of complex problems.

A.3. Systems Thinking and System Dynamics

Systems thinking science offers a holistic approach to understand the interactions between factors within a system; it also provides an approach to understand complex problems as a system of interconnected set of problems. Systems thinking science provides a framework to holistically analyze and understand system behaviors. Approaches to systems thinking include hard systems thinking, system dynamics, soft systems methodology, and total system intervention, among others.

A.3.1 Hard Systems Thinking

The term ***hard systems thinking*** was given by Checkland (Checkland, 1985) to label various systems approaches including Operations Research (OR), Systems Analysis (SA), and Systems Engineering (SE). Such approaches aim to build models, primarily mathematical, to capture the working of real world problems as accurately as possible. In hard systems thinking, systems are defined to be goal seeking. Hard systems thinkers believe the world is a set of systems and that these can be systematically engineered to achieve objectives. Hard systems thinking is criticized, however, in that the modeling is about simplification following a logical positivistic or reductionist approach. It also demands the goal of the system of concern to be clearly defined before analysis and minimizes the effect of human behavior on the system.

A.3.2 Soft Systems Methodology (SSM)

Soft Systems Methodology (SSM) is "a methodology, setting out principles for the use of methods, that enables intervention in ill-structured problem situations where relationship-maintaining is at least as important as goal-seeking and answering questions about 'what' we should do as significant as determining 'how' to do it" (Michael C. Jackson, 2003). SSM mainly focuses on the learning that occurs when ideal systems are confronted with reality. Compared with hard systems thinking, which is goal-seeking oriented and assumes the world contains systems which can be "engineered," soft systems thinking is system learning oriented and assumes that the world is problematic but can be explored by using systems models (Checkland, 1985). Approaches include Soft Operational Research (Soft OR), which is concentrated on defining the situation, resolving conflicting viewpoints, and coming to a consensus about future action.

Jackson (Michael C. Jackson, 2003) classified applied systems thinking approaches within four sociological paradigms according to their problem context nature (Figure 1). The horizontal axis in the figure shows the nature of relationships among those concerned with the problem context – participants. Participants in a unitary relationship share similar values, beliefs, and interests. Those in a pluralist relationship do not share the same values and beliefs. Participants in coercive relationships have few interests in common and hold conflicting values and beliefs. The vertical axis shows the complexity of problems to be studied. Complexity continuously changes from simple to complex. The two system types are conceptualized at two extremes (M. C. Jackson & Keys, 1984), (M. C. Jackson, 1990), (Robert L. Flood & Jackson, 1991).

<table>
<tr><th colspan="2"></th><th colspan="3">Relationship Between participants</th></tr>
<tr><th colspan="2"></th><th>Unitary</th><th>Pluralist</th><th>Coercive</th></tr>
<tr><td rowspan="2">System Complexity</td><td>Simple</td><td>Statistical Quality Control, System Dynamics Economic Sustainability</td><td rowspan="2">General Systems Theory, Interactive Planning, Soft Systems Methodology, System Dynamics, Social Sustainability</td><td>Creative Problem Solving, Critical Systems Heuristics</td></tr>
<tr><td>Complex</td><td>System Dynamics, Viable System Model, Environmental Sustainability</td><td>Not Defined</td></tr>
</table>

Figure A.1. Grid of problem contexts

A.3.3 System Dynamics

System dynamics was developed in the middle of the twentieth century by J. Forrester to understand the time variant behavior of systems, and is based on feedback control theory (Porter, 1950), (MacMillan, 1951), (Brown & Donald Campbell P., 1948). System dynamics not only assists understanding of system structures and dynamics of complex systems, but also provides a rigorous modeling method to build simulations of complex systems. Such simulation models can be used to design more effective policies and organizations (Sterman, 2000). System dynamics has been applied to issues as diverse as corporate strategy, the dynamics of diabetes, the cold war arms race between the US and USSR, and even the combat between HIV and the human immune system (Sterman, 2000).

System dynamics models use positive and negative feedback loops to identify the dynamics that arise from these interactions. In system dynamics, a causal loop diagram (Figure 2) reveals the structure of a system. By understanding the structure of a system, it becomes possible to ascertain the system's behavior over a period of time (Meadows, 2008). System dynamics also adopts mental models, which are relative, enduring, and accessible internal conceptual representations of an external system whose structure maintains the perceived structure of that system, to build and understand the structure of the complex system (Doyle & Ford, 1998). Another characteristic is that system dynamics describes complex systems using quantitative and qualitative modeling methods(J. W. Forrester, 1961a). This approach can facilitate the modeling of a manufacturing system's sustainability policy and management decisions.

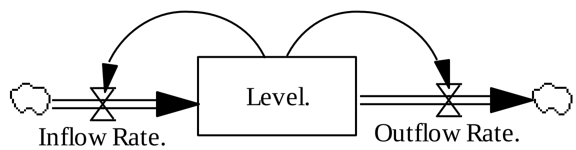

Figure A.2. Causal loop diagram

An effective model relies on a wide range of information about the system (J. W. Forrester, 1980). Information can be classified into three categories: mental, written, and numerical data (Figure 3). Carried information decreases from mental databases to numerical databases (J. W. Forrester, 1991). A mental model contains information for decision making points and behaviors, e.g., reasons for certain responses (J. W. Forrester, 1991). The written database contains information from published literature that has been processed. The numerical database is only available for certain parameter values and contains less information than the mental model database and written database.

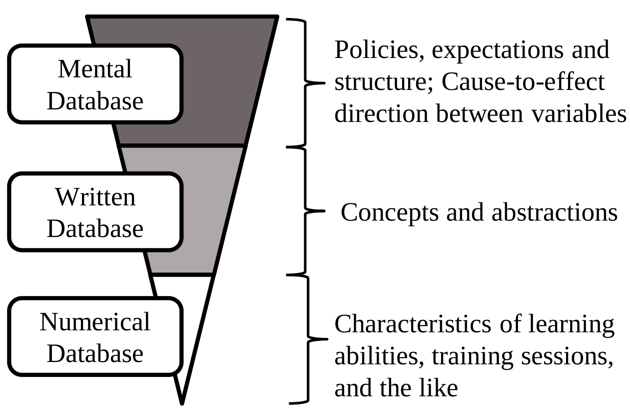

Figure A.3. Decreasing information content in moving from mental to written to numerical databases

System dynamics modeling can satisfy the goal of manufacturing enterprise decision making based on sustainability assessment. Variables captured in a model to support this goal would include both hard variables (relates to attributes that are quantifiable and quantification can be validated) and soft variables (relates to the attributes of human behavior). Wastes, energy consumption, material use, and related factors are primary concerns for environmental impact assessment; labor cost, material cost, transportation cost, and related factors are major concerns for economic impact assessment; and injury rate, noise level, wage level, and related factors are concerns for social impact assessment.

The actual decision making process is another system modeling domain, which involves considering human behavior and values from the operational level through the enterprise level of the system. The decision making process within each level specifically serves the purpose of satisfying the goals of each substructure of the system model. These substructure representations can accept the complexity, nonlinearity, and feedback loop structures that are inherent in social and physical systems.

A.3.4 Systems Thinking and Sustainability Assessment

A sustainable manufacturing system is a complex system with various factors that influence each other not only through various systemic levels (e.g., the enterprise, facilities, and operations), but also across sustainability domains (economic, environmental, and social). A study by Zhang and Haapala (Zhang & Haapala, 2012a) demonstrated that a machining process setting change can increase production rate and lead to cost savings. On the other hand, however, that setting change may cause additional environmental and social impacts, including energy consumption, material use, and operator health effects. In addition, although a process setting change may have promising sustainability performance at the operational level, the decision may conflict with a facility manager's strategy; a decision made at the facility level may have greater sustainability benefits than at a lower operational performance level. This utilitarianism philosophy is a common engineering ethic in solving such problems in management level decision making. A criticism is that the distribution of goods and harms may not be fair (Manion, 2002). Therefore, research shall analyze those conflicts within the system in order to solve problems in a practical way. System thinking allows researchers to identify not only relations of certain human behaviors, but also the dynamics of assessment that results from each sustainability domain. With this ability, decision makers can address problems holistically, ensure economic, environmental, and social policies and goals are achieved.

Researchers have applied systems dynamics to solve sustainability-related problems for several decades (Wolstenholme, 1983), but studies are limited in modeling sustainable systems. Since the 1980s, efforts have investigated modeling sustainability development (Wolstenholme, 1983), (Bockermann et al., 2005) and industry environmental impact (Rehnan et al., 2005), (Anand et al., 2006). In addition, others ((Oyarbide et al., 2003), (Kantardgi, 2003), (Tesfamariam & Lindberg, 2005), and (Seidel et al., 2008)) have adopted system dynamics in modeling of manufacturing systems, yet few environmental impact and social considerations have been involved in the analysis.

In recent years, researchers (Kalninsh & Ozolinsh, 2006), (Kondoh & Mishima, 2011)and (Kibira et al., 2009) have proposed frameworks for using system dynamics in sustainable manufacturing to improve collaboration, sharing and reusing of systems dynamics models through a defined vocabulary and structured data. These have not led to operational methods and tools, however. Unless sustainable manufacturing practitioners adopt systems thinking principles, system dynamics will not be properly utilized in modeling sustainable manufacturing. Therefore, work needs to be done to educate researchers in systems thinking and then to advance the use of system dynamics models to analyze the dynamics of sustainable manufacturing systems and improve their performance.

A.4. Conceptual Model

The practice of modeling sustainable manufacturing systems must address three critical questions as a starting point. First, what is the problem? A model must have a clear purpose and that purpose must be to solve the problem of concern (Sterman, 2000). Second, what is the boundary of the system? According to the purpose of the problem, a boundary shall be defined to serve the purpose. Otherwise, the nature of problem is changed. Third, what are the components of the system? By identifying the interrelated factors, the model can better serve analysis of the problem. A general conceptual model for assisting sustainable manufacturing enterprise decision making is presented below. The approach includes three primary steps: variable definition, model development, and model validation.

A.4.1 Variable Definition

Within system dynamics (SD) modeling, a system is represented by a number of variables (factors) and their interactions (behaviors) that establish and inform the goal and scope definition of the proposed model. Identifying these factors and their behaviors thus becomes the first step for model developers. A well-represented system serves reliable model development and performance analysis, therefore, variables must be identified with respect to system functionality and decision maker's considerations. In sustainability assessment, three metric sets (economic, environmental, and social) are quantified, as reviewed briefly below (Feng et al., 2010), (Jawahir & Dillon, 2007), (Jawahir et al., 2006), (Dreher et al., 2009), (UNDSD, 2001), (Parris & Kates, 2003b), (Brent & Labuschagne, 2006), (Hutchins & Sutherland, 2008), (Lu et al., 2010), (Graedel & Allenby, 2002).

Economic Metrics. The capital and operating expenditures required to create a product have a direct effect on a manufacturer's economic performance, but also affect the economics of operations, facilities, and the enterprise as a whole. Product and process-related economic performance metrics should reflect the impact on the company, as well as on the broader economy. Economic metrics can be quantified in terms of monetary value, and may include operating cost, retained earnings, and locally-based spending. Financial performance is a familiar topic to engineers and other decision makers, being necessary to ensure competitiveness. Moreover, monetary data is straightforward to analyze and communicate to a diverse audience.

Environmental Metrics. At the enterprise level, environmental indicators are based on the external (e.g., emission limits) and internal (e.g., waste reduction goals) policies. The scope is broadened from the facility to the supply chain and, ultimately, to the whole life cycle to include indicators about recycling and logistics processes (e.g., transportation CO_2 emissions). At the operations (micro) level, environmental indicators relate to the materials and energy use, byproducts, emissions, and wastes. These indicators aggregate with non-process related metrics (e.g., water for potable uses, heating energy, and lighting energy) at the facility level.

Social Metrics. The social domain of sustainable manufacturing considers human safety and societal benefits. Manufacturers are responsible for creating a safe and healthy environment – considering worker safety and workplace illumination and noise levels, for example. Meanwhile, companies have responsibilities to the local community, such as creating job opportunities, purchasing insurance, providing worker compensation, and complying with laws and regulations.

It is important to note that research on analyzing the social impacts of manufacturing is limited. Lee et al. [23] proposed a set of dimensions for human work to assist industrial sustainability assessment. Based on the effect variation, different aspects are categorized into individual and societal levels. The dimensions identified include compensation, physical and mental safety, demand, variety of tasks and roles, social interaction, growth of skills and knowledge, opportunities for accomplishments and status, value of work, autonomy, and growth and personal development. These dimensions form the basis of social metric definition in this work.

A.4.2 System Dynamics Model Development

The model is comprised of three substructures (Figure 4): an operation level substructure that models unit process factors (e.g., materials, wastes, and worker fatigue); a facility level substructure that models shopfloor production activities including manufacturing process flows; and an enterprise level substructure that models supply chain and management activities, such as employee recruitment and sustainability policy making.

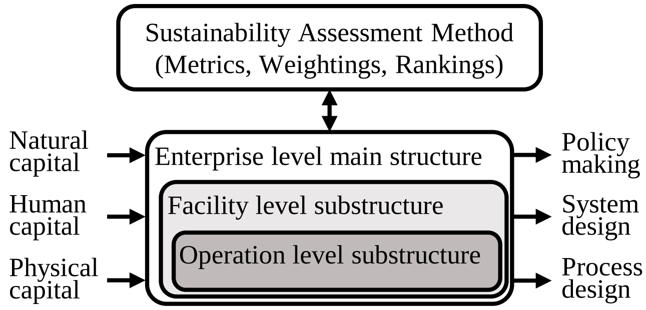

Figure A.4. Sustainability assessment–system dynamics model structure

Sustainability assessments are integrated into the appropriate SD model substructure by identifying the types of human (e.g., knowledge and skills), natural (e.g., materials and energy), and physical (e.g., facilities and equipment) capital inputs. Environmental, economic, and social assessment methods are then used to quantify the variables and identify the loops between and among variables. Assessment results are the output from the SD model in a manner to facilitate system design and assist decision making at three levels: corporate policy making, manufacturing system design, and manufacturing process design. As such, environmental impacts, economic costs, and social responsibility measures will more holistically inform decision making within and across organizational levels.

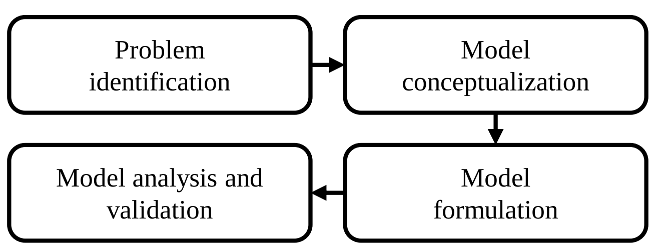

Figure A.5. System dynamics modeling procedure (Barlas, 1996)

The SD model development procedure is based on an approach proposed by Barlas (Barlas, 1996), and starts with problem identification, where all related variables are identified (Figure 5). In the second step, model conceptualization, feedback loops between variables are identified and examined, creating the required causal loop diagrams to model the dynamic behaviors of the system. The dynamic behaviors of the system can then be modeled through dynamic hypotheses. For example, the effects of an enterprise-level environmental policy change on facility-level and process-level behaviors can be tested and studied. The third step is to formulate the main SD model structure and substructures based on the conceptual model developed in the second step. During model formulation, calibration of variables and equations are completed concurrently. The model will thus simulate the system and show how behaviors change over time. Simulation results guide the decision maker in system design and sustainability realization.

It is envisioned that the structuring of an SD model for sustainable manufacturing enterprise decision support, to be developed under future work, will be based on this method, by starting with building a mental model and moving to a written model and then to a numerical model.

A.4.3 Model Verification and Validation

The developed SD model must be verified and validated to ensure repeatable and reliable results. The validity of a model is closely related with its purpose, and so the validity of the purpose of the model must be substantiated (Barlas, 1996). Therefore, a sustainable manufacturing SD model should support system design with the goals of energy efficiency, pollution prevention, employee friendliness, social responsibility, and market competitiveness among other factors. The developed model will be tested according to the process shown in Figure 6, based on the validation framework summarized by Barlas (Barlas, 1996), which includes direct structure testing, structure-oriented behavior testing, and behavior pattern testing.

The structure confirmation test, a direct structure test method, assesses the validity of a model's structure. It can be carried out by comparing the equations and their form to existing relationships in the system modeled and to system information reported in the literature (Barlas, 1996). In future work, tests will be conducted by examining the structure of equations to ***in situ*** systems studies, as well as by reviewing relevant prior research. Thus, real industrial systems will be utilized in model development, and literature will provide supplementary sources to validate the model structure.

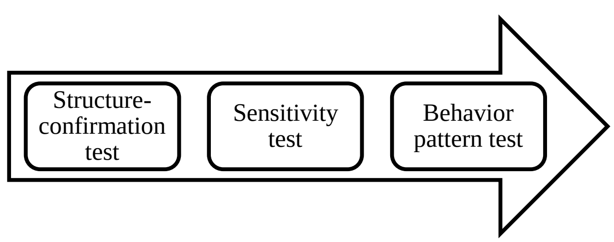

Figure A.6. Model validation process (Barlas, 1996)

The sensitivity test, a structure-oriented behavior testing method, indirectly assesses model structure validity (Barlas, 1996). Highly sensitive parameters in the system model are determined and investigated to ascertain whether the real system would exhibit similar sensitivity. For example, an environmental policy modification may cause a change in operation-level behaviors and, consequently, impact waste treatment methods and energy use. Such a policy change can be simulated within an SD model, and then historical data applied to compare results for the simulated and real systems. The behavior pattern test is preceded by the prior two tests, and designed to measure the differences the model can reproduce in the behavior pattern exhibited by the real system (Barlas, 1989).

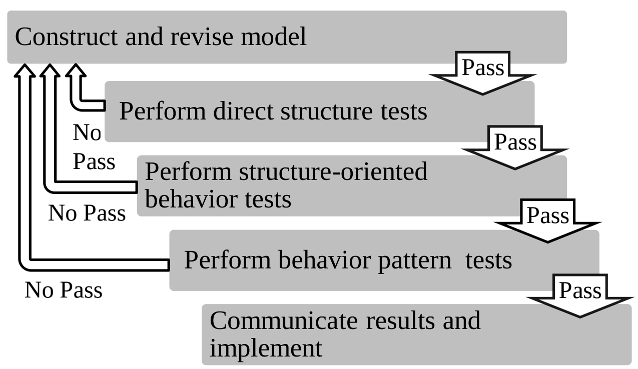

Figure A.7. Model validation procedure (after (Barlas, 1996))

It should be noted that model construction and revision should be conducted in concert with the validation process. Figure 7 summarizes the logical sequence of steps for the model validation process, based on the research by Barlas (1996).

A.5. Conclusions

Sustainable manufacturing decision makers are required to employ systems thinking when approaching operation level, facility level, and enterprise level issues. These complex problems involve the interaction of human behaviors with system elements. System dynamics provides an appropriate framework for modeling manufacturing systems for sustainability assessment. The main advantages of system dynamics include a means to understand the system by identifying relationships among factors, the use of a structured model that allows decision makers to simulate current functioning of the system and to explore opportunities for improvement, and assistance for decision makers in predicting system sustainability performance metrics for various system alternatives. Most importantly, it offers engineers and managers an approach to adopt systems thinking to solve sustainable manufacturing problems holistically.

With the conceptual model approach presented for sustainable manufacturing enterprise assessment, future work must begin with building a system dynamics model based on real world manufacturing cases. Data must be gathered and analyzed to formulate the conceptualized model, simulate the current system, and predict system performance metrics at the various system levels. Model refinement will need to proceed as new knowledge and information are acquired through verification and validation activities.

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Appendix B: A Systems Thinking Approach for Modeling Sustainable Manufacturing Problems in Enterprises

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Abstract

Increased environmental and social burdens and related demands from customers and broader society have prompted manufacturing enterprises to adopt sustainability principles. Current practices are often focused on environmental impacts alone or combined with economic factors within a limited scope and, thus, tend to overlook potential cause and effect relationships. A systemic approach is desired to address the potential consequences of *ad hoc* engineering decisions. In this research, systems thinking is adopted to examine this problem by considering three levels of a manufacturing system - operation, shopfloor, and enterprise. A conceptual, complementarist systems thinking model embracing sustainability assessment methods is presented. The conceptual model is embedded in a system dynamics model, with substructures presented at the operation level and the shopfloor level. This work stands to benefit the engineering management community, and in particular sustainable manufacturing, by sharing a novel approach using systems thinking principles to enhance sustainable manufacturing research and manufacturing system sustainability management.

B.1. Introduction

The new era requires engineers to design production systems to bring concurrent benefits to various stakeholders including the manufacturer, society, and environment (Rusinko, 2007; Gunasekaran & Spalanzani, 2012). On one hand, environmental policies and social protection policies have been enacted in different countries due to pollution and waste emitted from production (Barrett, 1994). On the other hand, manufacturers seek practices to sustain their business activities by conforming to those policies. Increasing environmental and social concerns have led to a need to confront the challenges of balancing economic and financial priorities against environmental and social responsibilities (Zhang et al., 2013). Under this background, the sustainable manufacturing concept has emerged over the past 40 years, and can be defined as "the creation of manufactured products that use processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound" (USDOC, 2011). This requires developing strategies to balance interests of all stakeholders, and presents new challenges to engineering management research and practice.

Current sustainability assessment methods are deficient in aiding proactive engineering management decision making and elucidating broader sustainability opportunities within a manufacturing enterprise, often resulting in *ad hoc*, reactive decisions to circumvent fines, energy/waste costs, or simply poor public perception. While these challenges are long-recognized, industrial and academic research has focused on increasing efficiencies with the goal of reducing costs and environmental burdens – individually and simultaneously – with cursory integration of social sustainability metrics. Thus, traditional methods remain insufficient and inadequate to embrace sustainability considerations, and understanding system behaviors within a manufacturing system is urgent to solve sustainable manufacturing issues and challenges, holistically.

Since the 1970s, there have been efforts to develop an applied holistic approach to management problems –known as systems thinking – for better understanding an organizational system's behavior. Systems thinking as a science arose as the result of the efforts of researchers from varied backgrounds such as biology, sociology, philosophy, and cybernetics to holistically explain the organizational systems they studied (Jackson, 2000). Thus, systems thinking offers a holistic approach that can help understanding the influence among sustainability factors by looking at problems as the result of root causes (and not symptoms) and being composed of interconnected parts. Nevertheless, systems thinking encourages practitioners, such as engineering managers, to adopt sociological awareness, human well-being, and emancipation philosophies (disadvantaged groups being assisted to get what they are entitled to), and aims to take technical, practical, and emancipatory interests into consideration to address different aspects of problem situations. With more knowledge gained, engineering managers will be able to make predictions of system behaviors, which is seen as the essence of management (Deming, 1993). Therefore, incorporating systems philosophies into sustainable manufacturing will not only benefit the scientific body of knowledge, but, more importantly, benefit engineering management by assisting manufacturing decision makers (engineers, managers) in understanding the interactions of behaviors among sustainability factors within the system. This approach can play an integral role for improving cost efficiency and environmental and social responsibility.

B.2. Background

Manufacturing systems have spanned three major phases: mass production, lean manufacturing, and now sustainable manufacturing. First, mass production introduced the principle of improving job efficiency in place of improving labor productivity (Suh, et al., 1998). Second, globalization triggered manufacturers to adopt lean manufacturing principles of waste reduction and continuous improvement (Suh et al., 1998). Third, increasing demands for eco-friendly products from customers, environmental concerns, and social responsibility have motivated sustainable manufacturing (Dornfeld, 2013; Jawahir & Dillon, 2007; Duflou et al., 2012; Hutchins & Sutherland, 2008; Rickli & Camelio, 2010; Overcash et al., 2009; Haapala et al., 2011). Manufacturers continue to pursue sustainable manufacturing not only in favor of market demands, but also as a way of production cost reduction. To build a sustainable manufacturing system, engineering managers shall concurrently consider economic, environmental, and social factors. Twelve principles of green engineering (Anastas & Zimmerman, 2003) and Design for X approaches (Chiu & Kremer, 2011) describe the common theories around the design of sustainable manufacturing systems.

Predicting a manufacturing system's behavior is based on the amount of knowledge gained from the system (Deming, 1993). As a novel approach, sustainability assessment of a manufacturing system involves several methods to predict behavior, including environmental impact assessment (e.g., Life Cycle Assessment), cost assessment (e.g., Life Cycle Cost Assessment), and social impact assessment (e.g., Social Life Cycle

Assessment) methods. Life cycle assessment (LCA) is a holistic tool encompassing all environmental exchanges (i.e., resources, energy, emissions, and wastes) occurring over the product life cycle (Klöpffer et al., 2007; Rebitzer et al., 2004; Pennington et al., 2004). Life cycle cost assessment (LCCA) analyzes costs from a product life cycle perspective, and provides a framework for specifying the estimated total incremental cost of developing, producing, using, and retiring a particular item (Asiedu & Gu, 1998). During the last two decades, various manufacturing processes from the unit process level to shopfloor flow level have been studied with environmental impact assessment methods (e.g., Dalquist & Gutowski, 2004; Gediga et al., 1998; Gutowski, Dahmus, & Thiriez, 2006; Masanet & Horvath, 2004; Munoz & Sheng, 1995; Skerlos et al., 2008; Haapala et al., 2009; Kellens et al., 2012). Currently, social impact assessment, however, still remains a challenge. Several efforts have been attempted to include social assessment into LCA (Hutchins & Sutherland, 2008; O'Brien et al., 1997; Dreyer, Hauschild et al., 2006; Lee et al., 2010). Social LCA guidelines developed by United Nations Environment Program (UNEP) follow the structure of environmental LCA (Benoît et al., 2010), but a detailed methodology is needed in order to be applied to manufacturing systems.

Currently, manufacturers with the intention to achieve sustainability resort to reactive behaviors to address environmental and workplace regulations, or are reluctant to play an active role in taking these responsibilities. Nevertheless, manufacturers that undertake sustainability practices find it more of a marketing strategy than a practical means of achieving system optimization. The reason is often the lack of knowledge of the interplay of sustainability factors within the manufacturing system. Unless engineering managers understand this interplay among economic, environmental, and social behaviors, it will remain a challenge to realize adopting sustainable manufacturing is not merely a marketing strategy, but also, more importantly, it can be a tool to achieve win-win strategies for all stakeholders. Such a situation triggers the idea of integrating systems thinking principles to analyze the behavior over time of relevant factors within sustainable manufacturing systems to assist engineering manager decision making.

B.2.1 Systems Thinking

Systems thinking presents a viable alternative to mechanistic thinking (reductionism/logical positivism) for explaining systemically organized conceptions of the world (Flood & Jackson, 1991). Approaches to systems thinking include the general system theory of Ludwig von Bertalanffy (1950), system dynamics by Jay Forrester (1961), soft systems methodology of Peter Checkland (1981), total systems intervention by Robert Flood and Michael C. Jackson (1991), and the creative design of methods by Gerald Midgley (1997), among others. In the following sub-sections, a brief description of the systemic methodologies employed to develop the systemic approach for modeling sustainable manufacturing problems in enterprises are briefly introduced.

B.2.2 A System of Profound Knowledge

Deming (1993) introduced the concept of the system of profound knowledge to provide an outside view to understand the system, which he believed cannot be understood by itself. The layout of profound knowledge includes four parts – appreciation for a system; knowledge about variation, which admits that system performance has variation; theory of knowledge, namely prediction is based on the understanding of the system; and psychology, which is to understand people's behavior within a system. As the theory can be applied to the various aspects of sustainable manufacturing system behaviors, it can be a link to connect sustainable manufacturing research and systems thinking research. The connection is described within the conceptual model presented herein.

B.2.3 System Dynamics

Developed in the middle of the twentieth century by Forrester (1961), system dynamics intends to help understand the time variant behavior of systems, and is based on feedback control theory (Porter, 1950; MacMillan, 1951; Brown &Campbell, 1948). System dynamics not only assists understanding system structures and dynamics of complex systems, but also provides a rigorous modeling method to build simulations of complex systems. Such simulation models can be used to design more effective policies and organizations (Sterman, 2000).

B.2.4 Total Systems Intervention

Total systems intervention (TSI) was developed by Robert Flood and Michael C. Jackson in late 1980s and early 1990s based on the philosophy and theory formulated as Critical Systems Thinking (Flood, 1990). TSI can be used in a coherent manner to promote successful intervention in a complex organizational and societal problem situation. Sociological awareness, human well-being, and emancipation comprise the philosophical base for TSI, which aims to take technical, practical, and emancipatory interests into consideration to address different aspects of problem situations. There are three phases in TSI (Michael C. Jackson, 2003), i.e., creativity, choice, and implementation, taken in order to understand the problem context, choose the appropriate system approach, and solve the problem. Because the problem context changes over time, TSI is a dynamic meta-methodology.

B.2.5 Creative Design of Methods

Creative design of methods (CDM), sometimes called TSI2, was developed by Gerald Midgley (1997), who posited that the drawing of boundaries is crucial for determining how improvement is to be defined and what action can be contemplated. At the beginning of a system intervention, it is necessary to gather the people involved in the system from different perspectives. He also argued that justifying systems intervention requires continually redrawing the boundaries to "sweep in" stakeholders previously excluded from consideration. The proposed creative design of methods (changed to creative design methodology in 1997) looks at a problem as a series of systematically interrelated research questions. Each question is addressed using different methods or part of a method. Then, synthesis is completed to allow individual questions to be addressed as a part of a whole system of questions.

One difference between TSI and CDM is that TSI encourages the use of one methodology at a time, while CDM encourages the creative design of *ad hoc* methodologies to the particular problem context (Calvo et al., 2011). Thereby, cost assessment, environmental impact assessment, and social impact assessment methods can be integrated into a system dynamics model that can assist in understanding manufacturing behaviors and system sustainability performance. As the philosophy of CDM is consistent with the idea of integrating systems thinking into sustainable manufacturing, the approach proposed herein adopts principles from CDM.

B.3. A Systemic Approach for Sustainable Manufacturing Enterprises

A manufacturing system can be defined to include three behavioral levels: 1. The enterprise level, which deals with strategic decisions of management and production (e.g., sustainability policy making and employee recruitment); 2. The shopfloor level, which deals with production organizing decisions (e.g., manufacturing process flow and scheduling); and 3. The operation level, which deals with single unit process decisions (e.g., energy, waste, and workload). Zhang et al. (2013) proposed a sustainability assessment-system dynamics (SD) model structure (see Figure 1) that encompasses these three levels of a manufacturing system. At each level, sustainability assessments are integrated into the appropriate SD model substructure by identifying the types of human (e.g., knowledge and skills), natural (e.g., materials and energy), and physical (e.g., facilities and equipment) capital inputs. Environmental, economic, and social assessment methods are then used to quantify the variables and identify the relations between and among the variables. Assessment results are output from the SD model in a manner to facilitate system design and decision making at three analogous levels: corporate policy making, manufacturing system design, and manufacturing process design. As such, environmental impacts, economic costs, and social responsibility measures will holistically inform decision making within and across organizational levels. The refined model will be comprised of three substructures to respond to manufacturing decision paradigms (see Figure 2).

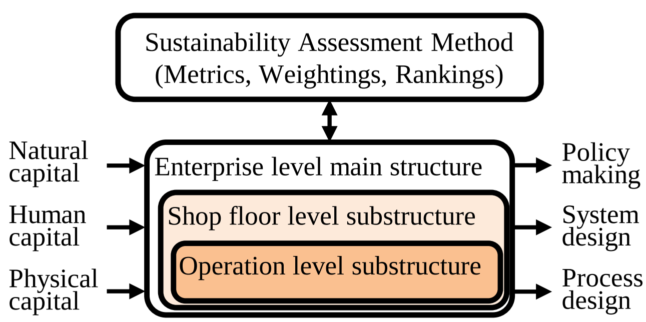

Figure B.1. Sustainability Assessment–System Dynamics Model Structure (Zhang et al., 2013c).

This systemic methodology allows sustainability assessment methodologies to be integrated into the appropriate SD model substructure by identifying the appropriate types of human (e.g., knowledge and skills), natural (e.g., materials and energy), and physical (e.g., facilities and equipment) capital inputs. Environmental, economic, and social assessment methods will be used to quantify the variables and identify the feedback loops between variables, as described below. Assessment results will facilitate system design and assist decision making at three levels. As such, environmental impacts, economic costs, and social responsibility measures will more holistically inform decision making within and across organizational levels.

B.3.1 The Conceptual Model

Each model solves a different problem. Three model substructures, represented with causal loop diagrams following standard notation by Sterman (2000), are presented with each solving a different sustainable manufacturing problem. The problem, however, may cause cascading effects across different levels of the manufacturing system. Therefore, a comprehensive solution for a manufacturing system requires an integrated model of the system with these substructures. Nevertheless, as defined by Deming (1993), “a system is a network of interdependent components that work together to try to accomplish the aim of the system.” The model substructure should have an aim, a boundary, components, and relations among components. To illustrate the model, this section, accordingly, describes the conceptual model from each substructure level standpoint by considering its system definition, variable identification and system behavior, and model verification and validation. Meanwhile, Deming's theory of profound knowledge is integrated as a link to connect sustainable manufacturing and systems thinking.

B.3.1.1 Enterprise Level Substructure

The enterprise level system includes management activities, the goal of which are to lead to strategic decisions for balancing enterprise economic benefits and environmental impacts from production, along with social responsibilities. The decision makers at this level usually include the chief executive officer (CEO), chief financial officer (CFO), production manager, and others who are involved in enterprise strategic decision making.

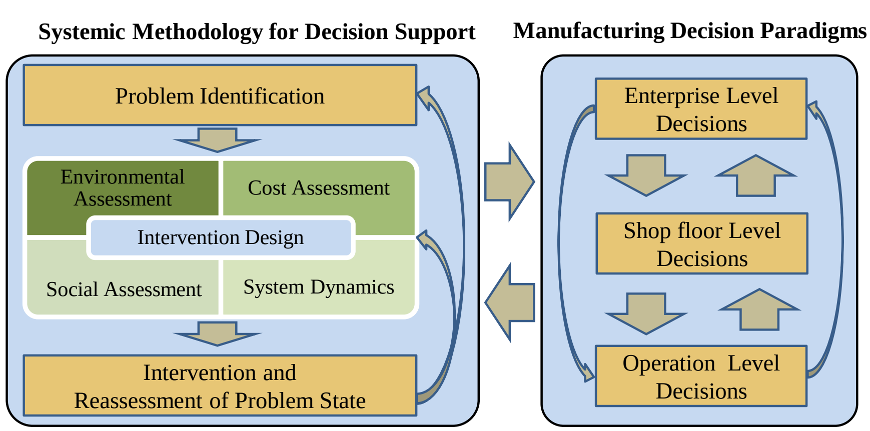

Figure 2. The Systems Thinking Approach for Sustainable Manufacturing Problems in Enterprises.

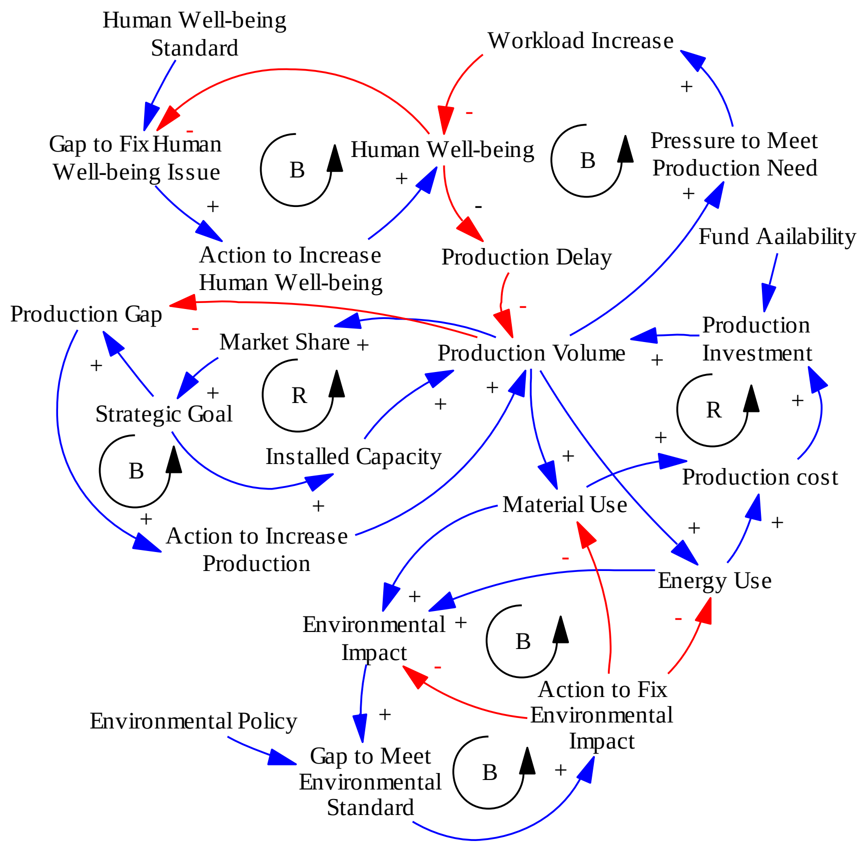

Figure B.3. Example Enterprise Level SD Model.

Variable Identification and Behaviors. The system includes various components, which in this model are identified as variables, and whose performance can be stable or unstable. The prediction of system performance is based on the amount of knowledge known about the system (Deming, 1993). Therefore, variable identification becomes crucial. Governmental agencies (e.g., NIST), non-governmental organizations (e.g., GRI), and individual enterprises (e.g., Wal-Mart) have developed sustainability metrics and indicators, which cover economic, environmental, and social aspects. The variables in the conceptual model herein are identified based on these developed indicators, as well as the sustainability behaviors of the manufacturing system. For example, environmental performance variables are selected from GRI indicators (Global Reporting Initiative, 2011). When building the model, however, practitioners may select variables respective to the sustainability behaviors of the investigated system. The example enterprise level substructure model (see Figure 3), which uses Sterman system dynamics modeling standard notation, describes basic behaviors related to sustainability practices in an enterprise. For instance, at this level, the production volume is not only affected by the internal situation, including installed capacity, production investment, environmental impact from production, and human well-being, but also affected by the external situation, such as enterprise market share. A reinforcing loop (noted as an R in the figure) is formed by production volume, material use, production cost, and production investment, but this loop is limited by enterprise funding capabilities. Environmental impact results from material and energy use of the enterprise system. The enterprise will undertake environmental impact reduction activities when the performance is lower than the environmental impact regulation standard or enterprise's satisfaction level.

From social impact standpoint, Deming (1993) noted that people are born with a need for relationships with other people, and need for love and esteem by others. The management of people thus affects a worker's physical and psychological health. In Exhibit 3, human well-being, which may include many aspects (e.g., esteem, need, interaction, and health), is affected by production because of the workload that has been caused by production requirements. Thus, the balancing loop (noted as a B in the figure), including production volume, workload, human well-being, and pressure to reduce production rate, is limited by the human well-being standards of the production environment. It should be noted that these behaviors change over time and delays may occur from one to another.

Model Verification and Validation. The aim of modeling a system is to predict, and prediction depends largely on knowledge of the system (Deming, 1993). To have the model provide high quality sustainability performance prediction results (especially over time), the conceptual model must be further verified and validated through a model validation procedure, such as proposed by Barlas (1989), which includes a structure confirmation test, sensitivity test, and behavior pattern test. Verification can be carried out by comparing the equations and their form to existing relationships in the system modeled and to system information reported in the literature (Forrester & Senge, 1980; Barlas, 1996). In this study, tests will be conducted by examining the structure of equations to *in situ* systems studies, as well as by reviewing relevant prior research. Thus, real industrial systems will be utilized in model development, and literature will provide supplementary sources to validate the model structure.

B.3.1.2 Shopfloor Level Substructure

The shopfloor level system includes shopfloor production activities, the goal of which is to utilize less material to fulfill the needs of production and, meanwhile, to generate the lowest environmental and social impacts. Behaviors include production scheduling, material use and handling, production rate, and actions to control production. The decision makers at this level usually include industrial engineers, schedulers, and production managers, as well as those who are involved in production decision making in other capacities (see Figure 4).

Variable Identification and Behaviors. The knowledge required for the system at the shopfloor level includes all the production related behaviors, based on which variables are identified. The sustainability performance of the system can be assessed based on the production data collected and interpreted. The more comprehensive data collected, the better the understanding that will be gained about the system (Deming, 1993). An example conceptual model substructure of the shopfloor level is shown in Exhibit 4 with some identified production behaviors.

To meet the needs of production, production volume and production rate is scheduled accordingly. Consequently, material, energy, and labor can be defined. Material use and energy use contribute to the environmental impact of production, as well as economic cost. The overburdened production will, in return, be limited by production capacity and market share. Meanwhile, environmental policies will also limit the production through fines and incentivized environmental impact reduction practices, the cost of which will contribute to the production cost (Global Reporting Initiative, 2011). In addition, product variety is another factor that affects production rate (Zhang & Haapala, 2012). A higher production rate shortens break time and puts workers under higher workload and pressure. Although compensation may increase, the overall workload and pressure may result in body injury and affect mental health (W.-T. Lee et al., 2010). Therefore, the behavior of increasing production rate is also limited by worker safety policy.

Model Verification and Validation. To move from a conceptual model to a dynamic decision support tool, the causal loop diagram model will be converted to a stock and flow diagram, and the variables will be both qualitatively and quantitatively measured. The model should replicate the actual production performance, and variables and behaviors shall be adequately justified with respect to the investigated system. The verification and validation procedure is similar to that described above.

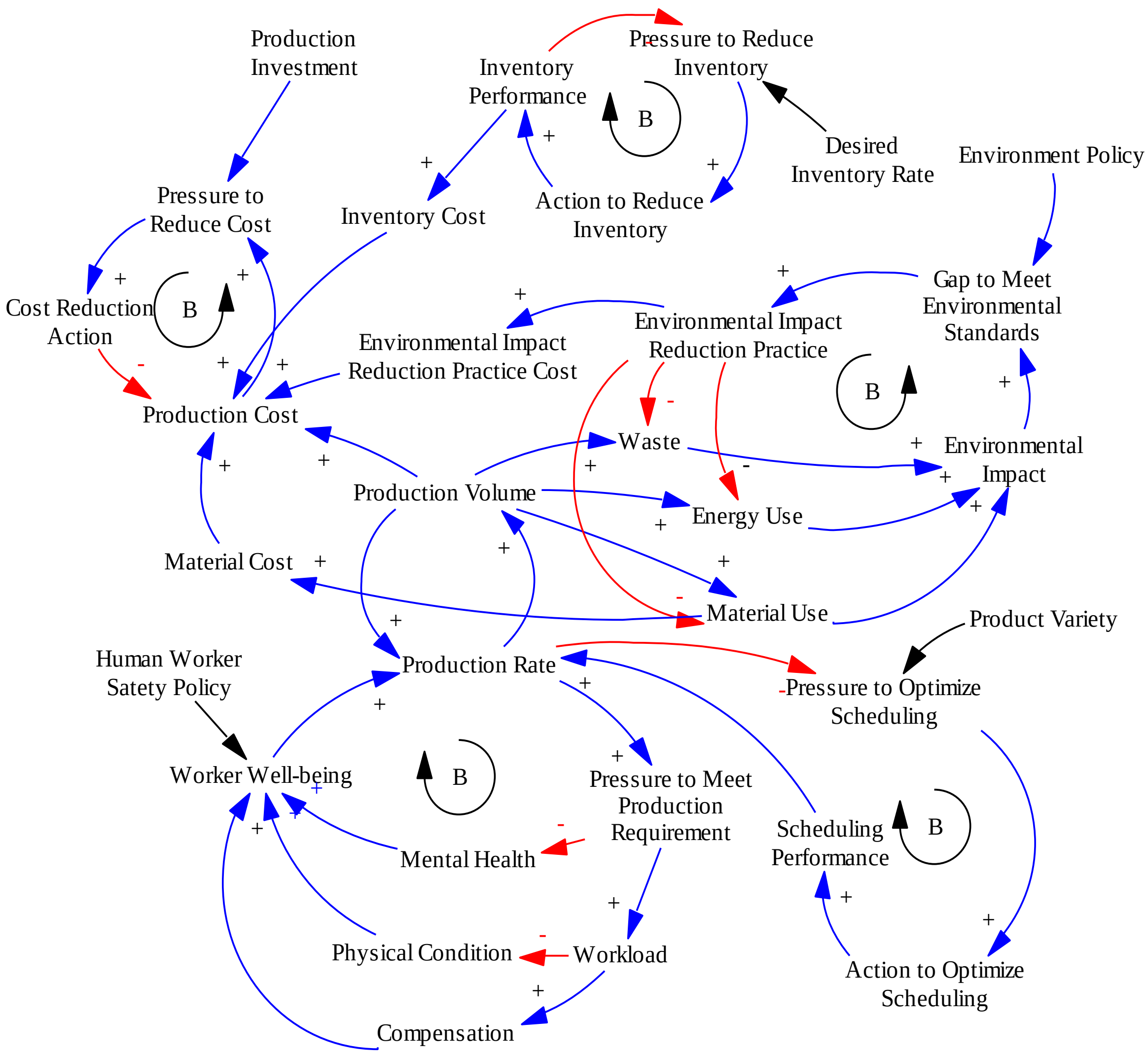

Figure B.4. Example Shopfloor Level SD Model.

B.3.1.3 Operation Level Substructure

The operation level system considers the mechanistic operating activities of each unit process (e.g., a machining operation). The goal of this substructure is to complete the required unit operations with compliance to product design, production specifications, and environmental and safety regulations. Due to the nature of this level, the decisions of engineers and operators usually have less of an impact on the shopfloor and enterprise level decisions; however, bottom-up feedback may affect product design and other strategic decisions (e.g., safety and welfare). An example conceptual model substructure of this level is shown in Figure 5.

Variable Identification and Behaviors. At the operation level, the economic and environmental variables are identified based on the unit process life cycle inventory (UPLCI) method (Overcash et al., 2009). Economic behaviors around production are related to material cost, energy cost, labor compensation, and waste handling cost. The overuse of materials, energy, and labor cost will conversely increase the pressure of production investment, and motivate engineers to redesign the operations to reduce cost. As for environmental impact behaviors, production environmental impact is directly related to process material use and energy consumption. Since physical and mental health are affected by production rate (Zhang & Haapala, 2012), work design is another factor that affects worker well-being. Well-designed work will address ergonomic issues in the work area and avoid injury. The complexity of work fills operator’s need of skill learning, but, on the contrary, overcomplexity will result in frequent human errors (Lee et al., 2012) and psychological effects, as noted by Deming (1993). People have both sources of extrinsic motivation and intrinsic motivation, and overcomplexity may reduce the enjoyment of their work. Thus, a loop in the model has been formed for through worker well-being and work design.

Model Verification and Validation. When modeling a single operation, process-based modeling provides a guideline for developing economic and environmental impact behaviors. A dynamic model, however, means more than a hard system simulation. At this level, interactions between operators, the way in which operators make certain decisions, will affect other processes, quality of the product, and so forth. Therefore, actual operation data must be applied to the conceptual model, which should be modified accordingly.

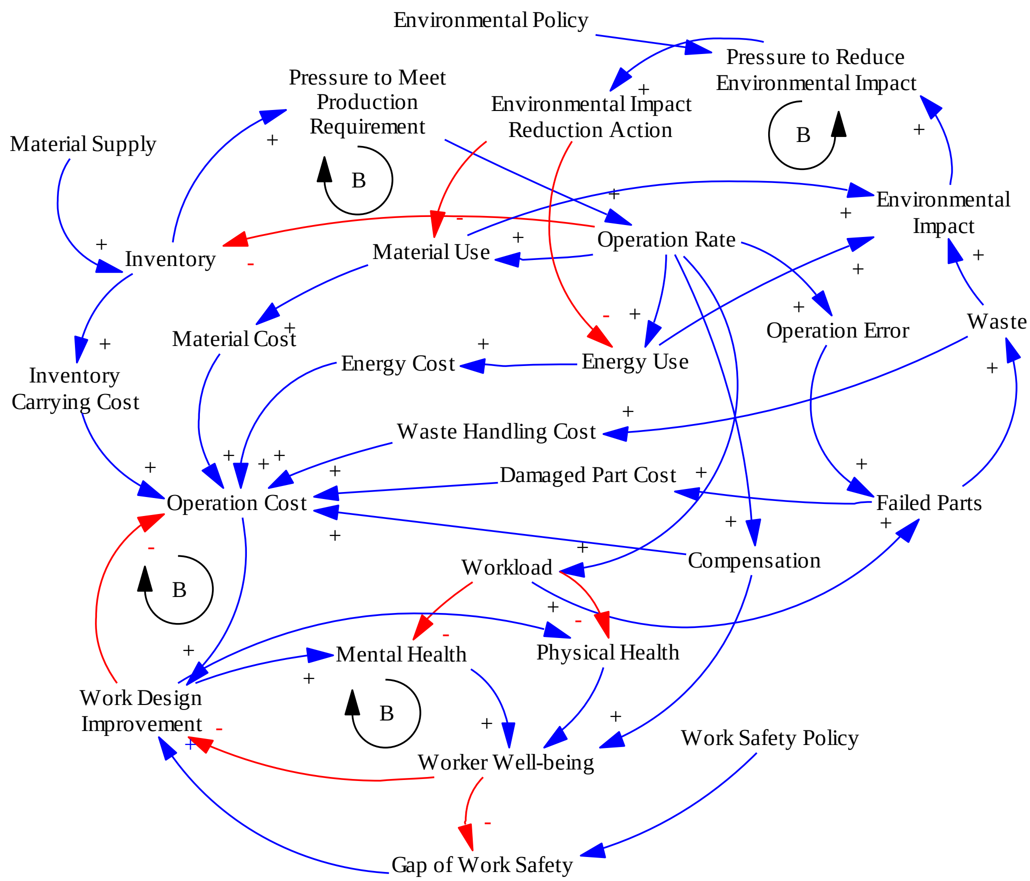

Figure B.5. Example Operation Level SD Model.

B.4. Discussion and Future Work

Sustainability concerns from customers and society have prompted manufacturers to take environmental and social practices into consideration in production decisions. Current sustainable manufacturing methods, however, are deficient in addressing issues holistically, the result of which has engineering managers undertaking reactive behaviors instead of playing an active role in managing sustainability. The primary reason lies in the insufficient understanding of the interplay of sustainability factors in manufacturing systems. The approach presented in the foregoing aims to integrate systems thinking principles with sustainable manufacturing practices. Deming's system of profound knowledge framework provides the theoretical backbone to identify critical variables to be employed in the combined sustainable engineering and systems thinking approach. As such, the approach presented considers sustainability issues from a systems perspective and investigates the relations among system behaviors within and across three levels: the enterprise level, the shopfloor level, and the operation level. A causal loop diagram conceptual model with two substructures is presented addressing some basic sustainable manufacturing behaviors based on the theory of profound knowledge.

This approach will not only benefit engineering management research by adopting systems thinking philosophies into the emerging sustainable manufacturing research and practice, but also will assist enterprises in making strategic, tactical, and operational decisions by providing a deep understanding of the behavior change over time. Future research will focus on applying this approach to actual manufacturing systems to facilitate refinement, verification, and validation toward a generalized framework that can be more broadly implemented within manufacturing industry for sustainability decision making.

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Appendix C: Establishing Foundational Concepts for Sustainable Manufacturing Systems Assessment through Systems Thinking

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Abstract

The foundational concepts of sustainability have emerged over the past forty years, and have attracted the interest of academic researchers and manufacturing industry practitioners, particularly in understanding how the concepts can be applied to increase competitiveness. Consumers are demanding affordable, eco-friendly products that are produced in a socially responsible manner. Challenges of achieving sustainability span all levels of the manufacturing system. The assessment of a system can be a complex problem which requires systems thinking as guide for theory development. The work presented seeks to provide operational definitions for sustainable manufacturing assessment by applying systems thinking methods as a first step to defining a unified theoretical framework. Thus, operational definitions are developed based on content analysis of existing sustainable manufacturing literature and common definitions. A discussion of the integration of systems thinking and sustainable manufacturing assessment then follows.

C.1. Introduction

The market has moved in the direction of ethical consumerism (Irving, 2002) by consumers, especially Millennials, who desire eco-friendly, ethically made products. Meanwhile, limited resources have triggered governments to place restrictions on levels of environmental impact. Manufacturers must confront challenges to balance the benefits for economic, ecological, and human systems. The conflict of interest between short term and long term benefits may prevent manufacturers from finding comprehensive solutions to manufacturing problems. Difficulties (e.g., resistance of change) also exist in shifting from conventional or lean manufacturing systems to sustainable manufacturing systems. In order to assist manufacturers in producing sustainable products and systemically accomplish this shift, this research aims to develop a platform for decision makers and other value chain participants to design cost efficient manufacturing systems that reduce natural resource consumption and enable corporate social responsibility.

To achieve this goal, an integration, or merging, of two research disciplines – sustainable manufacturing and systems thinking – is initiated. The work reported herein identifies the most common terms/concepts in the field through a literature survey, and provides a brief overview of relevant systems thinking theory and practice. The review from the literature survey, with assistance from systems thinking concepts, provides 23 root (operational) definitions for *sustainable manufacturing systems thinking* as the foundation for future tools and methods to assist industrial decision making in the context of sustainability.

C.2. Literature Survey Methodology

Selected prior research in sustainable manufacturing is reviewed using the State of the Art Matrix (SAM) Analysis literature review method (Beruvides & Omachonu, 2001). The selected literature was catalogued in a designed matrix categorized into four areas: sustainable manufacturing assessment methodologies, sustainability indicators, sustainable manufacturing decision making, and sustainability assessment of manufacturing processes Then, content analysis and coding was conducted to identify the patterns and research limitations using Checkland's (1981) CATOWE categories to inform the codes. The selected articles are intended to represent the key efforts in the development of sustainable manufacturing research over the past 40 years. For example, in the 1980s and 1990s, fundamental concepts, including life cycle assessment (LCA), life cycle costing (LCC), sustainable manufacturing, manufacturing systems, and environmental impact assessment databases, were established, and in 1990s and 2000s, various sustainability indicators were developed. Over the past two decades industrial companies have been actively engaged in sustainable manufacturing practices, which provide a large number of case studies in different manufacturing disciplines. The literature surveyed is not intended to provide a comprehensive state-of-art review, but to assist in defining operational terms with representative works in the sustainable manufacturing field.

This research also utilizes elements from a systems-based methodology for tackling unstructured problems developed by Checkland (1981) called Soft Systems Methodology (SSM). In one of its forms it is composed of seven stages, i.e., 1) express unstructured problem situation, 2) express structured problem situation, 3) define root definitions of relevant system, 4) build conceptual model, 5) compare 2 and 4, 6) make feasible, desirable changes, and 7) take action to improve the problem situation (Checkland, 1981). The first three stages of SSM were used to accomplish the objective of this paper.

Stages 1 and 2 are represented in the collection, selection, and cataloguing of the sustainable manufacturing literature into four areas, and by then expressing the current research situation of each area. Then, within Stage 3, 23 operational definitions are proposed to describe *sustainable manufacturing systems thinking*.

C.3 Sustainable Manufacturing Research

The authors selected 85 articles from the 1980s to the present (2013), and catalogued them into the four areas of sustainable manufacturing research introduced above. Among the 78 articles, about 40 representative articles were selected for content analysis. Several articles that duplicated information for the operational definitions were omitted. Several state-of-the-art literature reviews were reviewed, including Westkämper et al. (2000), Ramani et al. (2010), Duflou et al. (2012), Umeda et al. (2012), and Haapala et al. (2013), which provided insights to structuring the problem situation.

C.3.1 Sustainable Manufacturing Assessment Methodologies

Fundamental methodologies around sustainable manufacturing are categorized into assessment methods and research concepts. The life cycle assessment (LCA) environmental impact assessment method has been widely used by practitioners to investigate environmental impacts associated with a product or system over the past twenty years. According to ISO 14040, the method comprises four stages: goal and scope definition, life cycle inventory, life cycle impact assessment, and interpretation (ISO, 2006, p. 14040). Besides LCA, three other approaches are commonly used, including process-based modeling methods, input and output (I/O) methods, and hybrid methods (Zhang & Haapala, 2011). Life cycle costing (LCC) concerns examining costs in monetary terms, taking into consideration all the cost factors related to an asset during the operation life (Woodward, 1997). It has been applied in cost assessment since 1970s (Woodward, 1997) and to sustainable manufacturing practices since the 1990s (Westkämper et al., 2000). Material flow cost accounting (MFCA), developed by Japanese manufacturers, is a tool to reduce environmental impact and cost over the product life cycle (Jasch, 2008). With increasing attention from consumers, social impact has become a critical concern for manufacturers. The social domain of sustainable manufacturing considers human safety and societal benefits. A framework for social life cycle assessment (Social LCA), which aligns with ISO14040 and ISO14044 standards, was developed by UNEP intending to provide enterprises a guideline of conducting social impact assessment (Benoît et al., 2010). Besides Social LCA, Hutchins and Sutherland (2008) studied the degree to which social impacts have been included in LCA and how social metrics could be incorporated into input-output analysis. Though research on social life cycle approaches and its relationship with LCA was recognized in the 1990s (O'Brien et al., 1997), little work to advance social aspects of sustainability assessment was done in 2000s (Hunkeler, 2006).

Since the 1990s, several life cycle impact assessment (LCIA) methods have been developed. For example, CML 2002 (Guinee, 2002) was built upon the CML 1992 method (Heijungs, 1992), which operationalized the ISO 14040 LCA standards. It includes recommended normalization methods but no weighting methods (ILCD, 2010). Eco-indicator 99, besides serving the general purpose of LCIA, simplified the interpretation of results which can be calculated in single point eco-indicator scores (Goedkoop & Spriensma, 2001). ReCiPe 2008 was developed based on the CML 2002 and Eco-indicator 99 methods. It integrates midpoint and endpoint approaches in a single framework, and includes both normalization and weighting methods (Goedkoop et al., 2009). EDIP 97 (Environmental Design of Industrial Products), developed in Denmark, supports the emission-related impact categories at a midpoint level as well as resources and working environment (Wenzel et al., 2000). EDIP 2003 extended EDIP 97 and includes exposure assessment based on regional information in the life cycle impact assessment of non-global emission-related impact categories at the midpoint level (Hauschild & Potting, 2005).

EPS 2000 was first developed in 1990 and last updated in 2000. The method is designed to be used with Monte Carlo analysis and was the first endpoint based method, the first method that used monetization, and the first method that fully specified uncertainties (ILCD, 2010). The TRACI method developed by the U.S. EPA (Environmental Protection Agency) is a midpoint method representing the environmental conditions in the United States as a whole or per state (US EPA, 2003). The BEES (Building for Environmental and Economic Sustainability) method, developed by U.S. NIST (National Institute of Standards and Technology) measures the economic and environmental performance of building products (Gloria et al., 2007). The environmental performance measures are based on the ISO 14040 standards (ISO, 2006). IMPACT 2002+ proposes implementation of a combined midpoint/damage approach, linking all types of life cycle inventory (LCI) results through 14 midpoint categories to four damage categories (Crettaz et al., 2002). LUCAS was developed in 2005 based on the EDIP2003, IMPACT2002+, and TRACI methods to support efforts of Canadian LCA practitioners (Toffoletto et al., 2007). The LIME method, recently updated to LIME 2 (Itsubo and Inaba, 2012), was developed in Japan, building on various inputs from experts from around the world, and is used widely in Japan (Itsubo et al., 2004). Other methods have been developed, for example the Ecological Scarcity Method (Ecopoints 2006), developed in Switzerland (Brand et al., 1998), and MEEuP (Kemna et al., 2005), developed on behalf of the European Commission.

C.3.2 Sustainability Indicators

Over the past two decades, there has been a motivated effort to develop sustainability indicators for evaluation and improvement within the manufacturing industry at a number of levels (Feng et al., 2010). At the sector level, or even higher (national level), material flow analysis (MFA) can be applied, which analyzes quantified flows and stocks of materials or substances (Brunner & Rechberger, 2004). Additionally, ecological footprinting (e.g., carbon, water, and nitrogen footprinting) has been undertaken, which measures human demand for natural capital that may be contrasted with the planet's ecological capacity to regenerate (Rees, 1992). Environmental pressure indicators developed for the European Union (EPI-EU) aim to give a comprehensive description of the most important human activities that have a negative impact on the environment (Kommission, 2000; Feng et al., 2010). Similarly, the Intergovernmental Panel on Climate Change (IPCC) developed an approach to assesses the scientific, technical, and socio-economic information relevant to understanding the risk of human-induced climate change (IPCC, 2004). The Organization for Economic Co-operation and Development (OECD) developed a core set of 50 environmental indicators, which covers a broad range of environmental issues to track the environment effects and responses by governments, industry, and households.

At the facility or corporation level, the Global Reporting Initiative (GRI) provides a framework for enterprises to assess sustainability performance and generate sustainability reports (GRI, 2013). The General Motors Metrics for Sustainable Manufacturing (GM M4SM) includes over 30 metrics in six categories: environmental impact, energy consumption, personal health, occupational safety, waste management, and manufacturing costs (Dreher et al., 2009). The Wal-Mart Sustainability Product Index Questions (Wal-Mart Qs) look at the supply chain as a whole to develop measurement and reporting systems for product sustainability (Wal-mart, 2009). Instead of developing internal methods, the standard ISO 14031 Environmental Performance Evaluation guidelines can be employed, and contain two categories of indicators: environmental condition indicators (ECIs) and environmental performance indicators (EPIs). Similarly, the Eco-Management and Audit Scheme (EMAS), which was developed by European Commission, enables organizations to assess, manage, and continuously improve their environmental performance (European Commission, 2006). The Dow Jones Sustainability Index (DJSI) is used to assess the sustainability performance of the top 10% of the companies in the Dow Jones Global Total Stock Market Index (DJSI, 1999). At the product and process level, there are several LCIA methods to be employed, as described above. ReCiPe 2008 includes 18 impact categories at the midpoint level and three impact categories at the endpoint level: damage to human health, damage to ecosystem diversity, and damage to resource availability (Goedkoop et al., 2009). The Ford Product Sustainability Index (Ford's PSI), which is based on external assessment (e.g., ISO 14040 and life cycle costing), includes eight indicators in environmental and health, societal, and economics categories (Ford, 2007). The Sustainable Manufacturing Indicator Repository developed by the U.S. NIST contains five major categories: environmental stewardship, economic growth, social well-being, technological advancement, and performance management (US Department of Commerce, 2013). Indicators presented above have been widely used by industry and government agencies. Practitioners, especially at small and medium enterprises (SMEs), however, in order to conduct reliable sustainability assessment for decision making, often select their own indicators in an *ad hoc* manner. A top-down approach has been proposed that comprises four steps: determine the goal of the assessment, choose a metric type, determine the manufacturing scope of the assessment, and determine the geographic scope of the assessment (Reich-Weiser et al., 2009). In terms of the metric selection quality, Feng et al. (2010) suggested well-defined sustainability performance metrics for the manufacturing industry should be measureable, relevant and comprehensive, understandable and meaningful, manageable, reliable, cost-effective data accessible, and be timely in manner. Focusing on product and process metrics, a framework for selection has been proposed where the product metrics are grouped under a range of metrics clusters to make them more structured (Lu et al., 2010). The process metrics are identified based on the inputs/outputs of a machining process and are categorized into a hierarchy structure including line level, workstation level, and operation level. A method was proposed by Sutherland and co-workers for self-identified green business SMEs to develop their own indicators (Clarke-Sather et al., 2011). Detailed operations were described to guide practitioners in conducting the indicator development process and assign weightings to indicators.

There has been work specifically focused on addressing the social aspects of sustainability through social indicators. Lee et al. (2010) proposed a set of dimensions for human work to assist industrial sustainability assessment and work design. Based on the effect, dimensions were categorized into individual and societal levels. The dimensions identified include compensation, physical and mental safety, demand, variety of tasks and roles, social interaction, growth of skills and knowledge, opportunities for accomplishments and status, value of work, autonomy, and growth and personal development. Lee et al. (2012) presented an approach to quantify these metrics through *identifiers* for the dimensions, and established a method for measuring the *fit* between work that is ideal for a society and the work the company offers to the workers of the society. Several other researchers have focused on developing social metrics of sustainability, which can be found in Parris and Kates (2003), Brent and Labuschagne (2006), and Hutchins (2010). However, currently there is no agreed upon approach that would appropriately assess social impact on manufacturing from the product/process level through the enterprise level.

C.3.3 Sustainable Manufacturing Decision Making

Research for integrating sustainable manufacturing assessment into decision making has been performed since as early as late 1980s. Malakooti and Deviprasad (1987) developed an interactive multiple criteria approach and decision support systems (DSS) for metal machining operations. They focused on minimizing machining cost and maximizing production without sacrificing workpiece quality. Over the past three decades, researchers have attempted different approaches to integrate environmental assessment into decision making, and many decision-making methods have been applied to assist manufacturing assessment, including the analytic hierarchy process, AHP (Avram et al., 2011), Markov processes (Milacic et al., 1997), and pairwise comparison analysis (Basu & Sutherland, 1999). Hersh (1999) pointed out that sustainability decision-making research is required in a number of different areas, including the development of improved models for decision making and problem classification, the development of improved user interfaces, and DSS based on different types of decision making models.

Further understanding should be gained regarding the types of decision makers, organizations, and situations to ensure appropriate decision making approaches are employed. Research on model classification should include the development of a taxonomy for the different types of problems that occur in sustainable decision making. Romaniw (2010) argued that detailed assessments are still lacking, as stakeholders need detailed impact assessments for their particular phase of life. More detailed assessments give stakeholders information that can be used for better environmental management and more environmentally benign operations.

Olson et al. (1999) proposed a method utilizing input-output analysis coupled with Markov decision making to assist plant managers in determining and modifying the environmental impacts of their facility. Markov decision making is preferred in dealing with stochastic environments, though it does not fit all manufacturing processes. Basu and Sutherland (1999) integrated multi-objective programming into decision making involving several sets of objective functions in order to optimize a process. Pairwise comparison analysis (PCA) was undertaken to assign importance to each objective. This work provides a foundation for assigning weights to criteria of such assessments. Avram et al. (2010) proposed a multi-criteria decision method for economic and environmental assessment of the use phase of machine tool system. AHP was used to structure the decision problem at both process and system level. In order to assist sustainable decision makers integrate assessment results from all three domains of sustainability, Clarke-Sather et al. (2011) utilized pairwise comparison for developing weights for economic, environmental, and social indicators. Zhang and Haapala (2012), took a further step and utilized AHP and pairwise comparison method to develop sustainability metric weightings, and used the PROMETHEE method to rank decision making alternatives. To assist practitioners model sustainable manufacturing problems, Zhang et al. (2013) developed a systems thinking approach for modeling sustainable manufacturing problems in enterprises. The approach provides systemic methodology support for manufacturing decisions in three paradigms: enterprise level, shopfloor level, and operation level.

C.3.4 Sustainability Assessment of Manufacturing Processes

Sustainability assessment has been conducted for various manufacturing processes since the 1990s. In the early stage of process analysis, researchers developed methods to conduct assessment. Munoz and Sheng (1995) developed a model to predict the environmental impact of machining processes. The model identified quantifiable dimensions including energy utilization, process rate, workpiece primary mass flow, and secondary flow of process catalysts. Jawahir and Jayal (2011) conducted sustainability evaluation for dry, near-dry, and cryogenic machining. Choi et al. (1997) developed an assessment method based on the material balance of a process and the relationship among the different processes. Later, with LCA methods gaining acceptance and wider use, literature tends to have two directions. First, specific models and approaches have been developed to analyze certain manufacturing or machining processes with LCA techniques. For example, Dahmus and Gutowski (2004) presented a system-level environmental analysis of machining, which includes not only material removal process, but also material preparation and cutting fluid preparation.

CO2PE! collaborative research developed a methodology for systematic analysis and improvement of manufacturing unit process life-cycle inventory (UPLCI), which leads to more accurate LCI data as well as identification of potential for environmental improvements of the manufacturing unit processes (Kellens et al., 2012). Rajemi et al. (2010) developed a model for optimizing the energy footprint of a turning process, identifying critical parameters in minimizing energy use and reducing energy cost and environmental footprint. Yuan and Dornfeld (2010) conducted sustainability analysis on atomic layer deposition processes through material and energy flow analysis, and suggested strategies and methods for sustainability performance improvement. Haapala et al. (2012) analyzed steel product manufacturing processes and developed models for improving environmental performance of steel making and casting processes. In addition, environmentally-focused manufacturing process modeling has investigated various operations (e.g., Dalquist & Gutowski, 2004; Gediga et al., 1998; Jeswiet & Nava, 2009; Masanet & Horvath, 2004; Skerlos et al., 2008). There are many case studies that directly apply LCA methodologies to manufacturing. Representative ones include that by Gamage and Boyle (2006), who conducted an LCA for furniture manufacturing, and Serres et al. (2011), who investigated the MESO-CLAD process and conventional machining.

C.4 Overview of Sustainable Manufacturing Research Problem Structure

The review of prior work above reveals that the community has been conducting research within the four areas identified for at least the past two decades. Although several have been developed, sustainability assessment methodologies still need a precise and well-accepted method to standardize practice. Social impact assessment, due to its complex nature, for example, remains a challenge to researchers, and associated normalization and weighting methods must be developed to properly assess social impact. Sustainability indicators have been well developed in literature, however, the method of how practitioners select or develop proper indicators and utilize those indicators must be a focus of researchers. Decision making research for sustainable manufacturing is primarily limited to a single sustainability domain (economic, environmental, or social). Multi-criteria decision making methods, including weighting of criteria and social assessment results, must be developed to better assist practitioners. Other decision making approaches (e.g., fuzzy logic) also need to be better applied to sustainable manufacturing problems. Sustainability assessment of manufacturing processes will continue to be a major component of manufacturing research – it is enabling processes that have led to technology advancements (Jawahir & Jayal, 2011).

Unfortunately, it can be seen that few efforts have been undertaken to assist practitioners in systemically utilizing research results in solving real-world sustainable manufacturing problems, which are often quite complex and rife with uncertainties in prediction. Past research has largely focused on a single sustainability domain or one manufacturing process. Designing a sustainable manufacturing system requires understanding not only individual processes, but also understanding the underlying relations among humans, processes, and environmental consequences. Nevertheless, economic evaluation of sustainability as an interest of industry remains a challenge to academia. Therefore, it is critical for SMEs to understand their systems from micro (operation) through macro (enterprise) levels and, using this understanding, diagnose the causes of certain behaviors for the design of more sustainable engineering and policy solutions (Figure 1). A systems thinking approach is lack for moving sustainable manufacturing research from theory to practice.

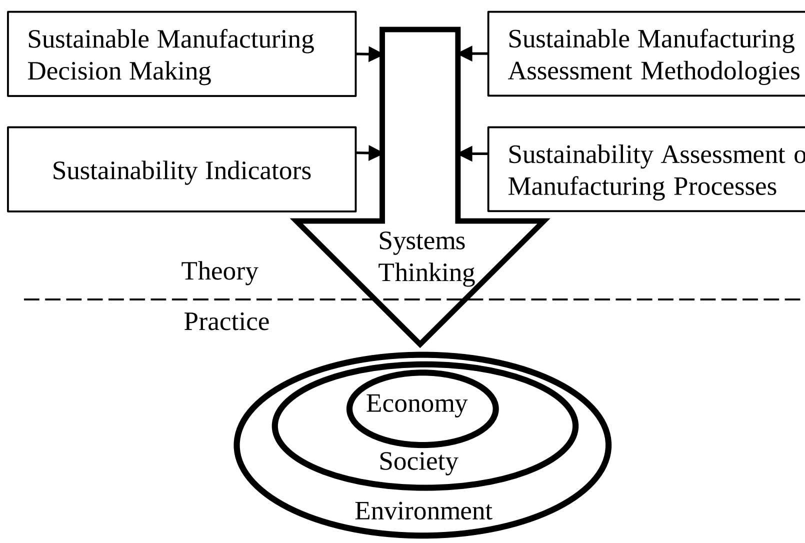

Figure C.1. Bringing Sustainable Manufacturing from Theory to Practice with Systems Thinking

C.5. Systems Thinking Theory

Systems thinking science provides a viable alternative to mechanistic thinking (reductionism/logical positivism) to understand the interactions between factors within a system. Systems thinking approaches also provide a way to understand complex problems as a system of interconnected set of problems. A brief description of the systemic methodologies that are relevant to sustainable manufacturing system problems is introduced below.

C.5.1 Soft System Methodology and Proposed Operational Definitions

Sustainable manufacturing problems are usually complicated by the interaction of economic, environmental, and social factors. Thus, categorizing the problem context becomes critical to practitioners. Flood and Jackson (1991) grouped system methodologies according to six “ideal-type” problem contexts which are: simple unitary, complex-unitary, simple-pluralist, complex-pluralist, simple coercive, and complex-coercive. Simple systems usually include a small number of elements, few interactions between elements, and well-defined laws governing behaviors. Complex systems usually have a large number of elements, many interactions, sub-systems, and attributes that are not predetermined. Participants are classified into unitary, pluralist, and coercive relationships. In a unitary relationship, participants share common interests, and they act in accordance with agreed objectives. In a pluralist relationship, participants have a basic compatibility of interest, but their values and beliefs diverge to some extent. Participants in coercive relationships have few interests in common and hold conflicting values and beliefs. Zhang et al. (2013) presented a system of system methodologies grid in a sustainability engineering setting, where different sustainable manufacturing problems have been associated with system methodologies. In that study, systems dynamics developed by Forrester (1961) has been identified as an ideal methodology to assist solve those sustainable manufacturing problems (Zhang et al., 2013).

One system methodology for solving complex problems is called the Soft System Methodology (SSM). As opposed to Hard System Methodology (HSM), which assumes that the system can be engineered, SSM perceives the complexity and confusion inside the system. It can be reorganized and explored as a learning system (Checkland, 1981). There are four main activities in SSM: finding out about a problem situation, building purposeful activity models, exploring the situation, and taking action. In the second activity, to build a purposeful activity model requires a clear definition (root definition) of the activity to be modeled. The CATWOE method was developed by Checkland (1981) to establish root definitions. Terms are evaluated according to the letters of the acronym for the method. "C" represents customers of the system, who are beneficiaries or victims affected by the system activities. "A" represents actors, which are the agents who carry out or cause to be carried out the main activities of the system. "T" represents transformation which is the main process for inputs being transformed into outputs. "W" represents Weltanschauung, a word for world view, which makes this operational definition meaningful. "O" represents ownership of the system, which has a prime concern for the system and the power to cause the system to cease to exist. "E" represents environmental constraints on the system which are the features of the system's environment. Ideally, an operational definition should encompass all six elements.

Using this approach, several operational definitions are proposed (Table 1) in the context of sustainable manufacturing systems thinking. The defined terms represent commonly used concepts in existing sustainable manufacturing research. The definitions were developed after reviewing prior explicit and implicit definitions in the context of sustainable manufacturing. The proposed definitions were structured based on the coded six elements of CATWOE from existing definitions.

C.5.2 Total System Intervention (TSI) and Creative Methodology Design (CMD)

Choosing a method to solve a sustainability related problem can be challenging in that different aspects of the problem need to be addressed with corresponding methods. A meta-methodology is required to integrate these methods to solve the complex problem. Total system intervention (TSI) was developed in late 1980s and 1990s (Robert L. Flood & Jackson, 1991) based on the philosophy and theory formulated by Critical Systems Thinking (CST). A variety of systems thinking methodologies, methods, and models can be used in a coherent manner to promote successful intervention in complex organizational and societal problem situations. Sociological awareness, human well-being, and emancipation are the philosophical basis for TSI, which aims to take technical, practical, and emancipatory interests into consideration to address different aspects of problem situations.

The three phases of TSI are creativity, choice, and implementation. In the first phase, the major concerns, issues, and problems that exist in the problem context should be identified. Morgan (2006) selected familiar metaphors (e.g., organization as machines) with which to explore issues of management. TSI uses these system metaphors as its favored method for addressing problems. The outcome from this phase is a set of significant issues and concerns. The second phase is choice. In this phase a strategy of choosing system methodologies need to be made. It can be one single methodology or a combination of several methodologies depending on the nature of problem identified. Traditionally, TSI has used the SOSM to address the relationship between different methodologies and real-world problem contexts. In the third phase, selected methodologies will be used to solve specific problems accordingly. Usually, one methodology will be the dominant method, which will be the primary tool used to address the problem situation.

Different than TSI, which encourages the use of one methodology at a time, CMD encourages the creative design of *ad hoc* methodologies to the particular problem context (J. Calvo-Amodio et al., 2011). This allows sustainable manufacturing methodologies to be integrated into problem solving. Creative design of methods was developed by Midgley (1997) who believes that the drawing of boundaries is crucial for determining how improvement is to be defined and what action can be contemplated. At the beginning of a system intervention, it is necessary to get people involved in the system from different perspectives. Midgley argues that justifying systems interventions requires continually redrawing the boundaries to "sweep in" stakeholders previously excluded from consideration. He proposed "creative design of methods", which was changed to be the "creative design methodology" in 1997. It looks at a problem situation as a series of systematically interrelated research questions. Each research question will be addressed by different methods or part of a method. Then a synthesis should be generated to allow individual questions addressed as part of a whole system of questions.

C.5.4 A System of Profound Knowledge

Integrating systems thinking into sustainable manufacturing assessment requires a theory that connects the two disciplines. A system of profound knowledge can be the guideline for this connection. Deming (1993) introduced this concept to provide an outside view to understand the system, which he believed cannot be understood by itself. There are four parts: appreciation for a system, which defines a system as a set of interrelated parts aligned for a common aim; knowledge about variation, or admitting that variation is inevitable in system performance; theory of knowledge, which states, without theory we cannot make predictions about what might happen and it is a prerequisite for learning; and psychology, which is to understand people's behavior within a system.

The theory and practice introduced can be integrated into sustainable manufacturing systems design, assessment, and decision making. Unfortunately, systems thinking has been mainly employed by disciplines outside of manufacturing (e.g., ecology system analysis, politics, and management). For engineers, when solving complex problems in the context of sustainability, it is especially critical to think and act as system thinkers.

C.6 A Vision for Sustainable Manufacturing Systems Thinking

Sustainable manufacturing in a systemic context remains a challenge for researchers and industrial practitioners. First, it is vital to understand system behaviors for each of the sustainability aspects (economic, environmental, and social) by applying the *Weltanshauung* for each simultaneously (perhaps sequentially and iteratively). The complex behaviors underlying the manufacturing system inhibit decision makers in establishing trustworthy predictions and applying certain judgment. According to Deming, predictions are based on theory and knowledge comes from theory (Deming, 1993). Thus, it is posited this uncertainty is largely due to the lack of theory and knowledge surrounding sustainable manufacturing system concepts, principles, and practice.

Second, understanding remains a challenge because it must be based on a large set of various manufacturing systems. This requires collaboration among researchers and industrial practitioners, often limited by self-seeking goals as a business imperative. It is desired that researchers and practitioners should contribute to the knowledge base of sustainable manufacturing systems thinking. Thereby, theory can be formed based on the knowledge gained.

Third, sustainable manufacturing systems thinking challenges traditional lean manufacturing thinking, as it mainly focuses on economic waste (resource and time) reduction. Having a broader scope and influence even than “lean” activities, practitioners of sustainable manufacturing must be conscious of the sources of potential resistance within their organization, and be educated with the proper toolset to systemically implement sustainability concepts in a manner that aligns with the prevailing corporate culture. At both the academic research level and the industrial implementation level, these efforts and activities will necessitate a “sustainability journey”, much as companies are familiar with their “lean journey”.

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Table 6.1. Root Definitions for Foundational Concepts in Sustainable Manufacturing Systems Thinking

Selected Term	***Proposed Operational Definition***	***Description***	***References Used to Construct Operational Definitions***
Sustainable Manufacturing	The set of systems and activities for the creation and provision of manufactured products that balance benefits for ecological systems, social systems, and economic systems.	"Creation" includes the design of products and manufacturing systems, and the manufacture of physical products. "Provision" includes delivery and recovery of products, through remanufacturing, recycling, and other activities. "Balanced benefits" shows that the benefits cannot be optimized for each subsystem, but a balance point can be reached to bring positive benefits to society and economy. This assumes there is a cost born by ecological system (the benefit usually is negative).	US Department of Commerce, 2013
Economic Weltanschauung *	An approach for analyzing and implementing organizational activities towards maximizing the financial benefits for internal and external stakeholders.	Internal stakeholders include employees, shareholders, and anyone who has interests in the organization. External stakeholders include suppliers, distributors, and other participants throughout the product value chain.	**** Weltanschauung***, a German word for "world view", refers to the framework of ideas and beliefs through which individuals interpret the world.
Environmental Weltanschauung	An approach for analyzing and implementing organizational activities towards minimizing the consequences of energy and natural resource consumption and waste	The stakeholders shall take environmental ethics in their organizational activities, especially economic activities. The "consequence" is commonly known as "impact".	

	releases.		
Social Weltanschauung	An approach for analyzing and implementing organizational activities towards maximizing the human well-being of internal and external stakeholders.	Human well-being includes multiple aspects of social life (see definition). The term here refers to the consideration of human well-being in activities and decisions throughout the product life cycle.	Benoît et al., 2010
Life Cycle Assessment	A technique for decision makers to evaluate the potential environmental impact of a defined product system for a given geospatial region and temporal period.	Life cycle assessment includes four stages: goal and scope definition, life cycle inventory, life cycle impact assessment, and interpretation. Product life cycle impact assessment evaluates the environmental impact throughout the product life cycle.	EPA, 2013; Goedkoop et al., 2009; Curran, 2006; Campanelli et al., 2011; Benoît et al., 2010
Environmental Impact Assessment	The process of identifying the consequences of the defined system activities on the environment, and measures that may help mitigate adverse effects.	Different from life cycle impact assessment, environmental impact assessment can evaluate a smaller scope or one stage of the product life cycle. In another words, environmental impact assessment is an evaluation technique for ***environmental weltanschauung***.	EPA, 2013; ISO, 2006; Curran, 2006
Decision Making	The process of selecting from among several alternatives which are generated to accomplish a specific goal with certain constraints.	Decision making involves alternatives, constraints, and a goal.	Avram et al., 2010
Stakeholder	Entities or individuals that affect or are affected by an organization's activities or products so as to gain interest with implementing their strategies.	“Stakeholders” here refers to the participants over the product life cycle, e.g., shareholders of manufacturers, distributors, product users, or employees. The ecosystem is also a stakeholder which affects	GRI, 2013; ISO, 2009

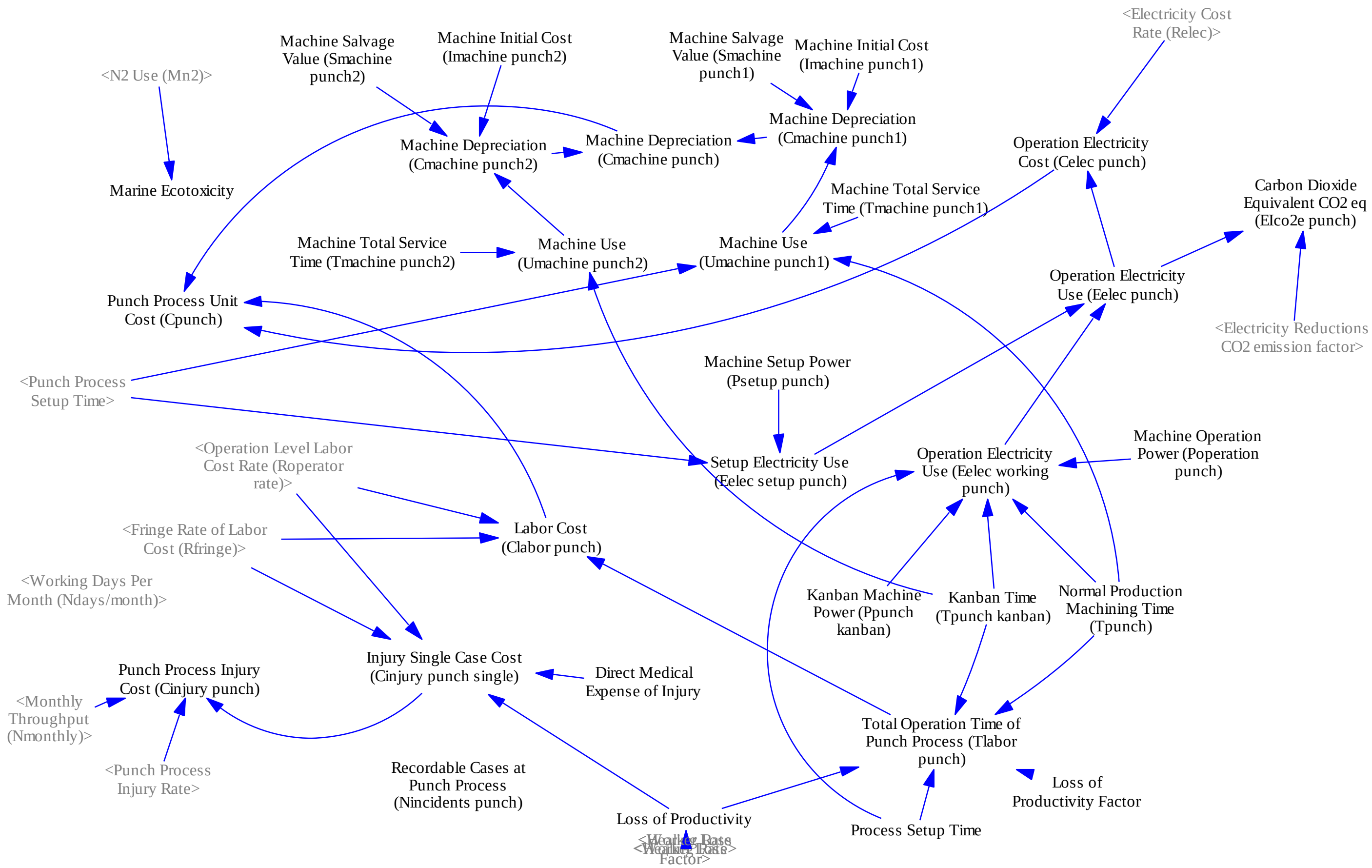
		manufacturing and is affected by manufacturing.	
Indicator	A parameter defined to provide a decision maker with quantitative or qualitative information about or describe the state of a target phenomenon.	Indicators, depending on the problem context, shall be defined by decision makers according to the goal and scope of the analysis. As reviewed in this paper, many indicators have been developed to assist decision makers.	EPA, 2013; Sheng et al., 1998; GRI, 2013; Curran, 2006 ; Benoît et al., 2010; ISO, 2013
Manufacturing System	A network of activities/processes that utilizes human resources and natural resources to produce products for targeted consumers regulated by laws, market forces, and internal policies.	This term is defined in the sustainable manufacturing system assessment context. The network shows there are underlying structures behind the manufacturing physical components. All the activities in this network meanwhile, are restricted by environmental constraints including laws, market forces, and internal (organizational) policies.	Lu et al., 2010; ISO, 2006; Campanelli et al., 2011
Life Cycle Costing	A compilation and assessment of all the costs associated with the product in its operational life cycle to optimize value during ownership for its stakeholders.	Life cycle costing evaluates the costs in two dimensions: costs associated with the product in its life cycle stages and the costs' monetary value that is changed over time.	EPA, 2013; US Department of Commerce, 2013; Benoît et al., 2010; Mearig et al., 1999
System Boundary	A set of criteria defined by practitioners specifying which unit processes and/or materials are included in the studied system.	Defining a system boundary requires a goal and scope for the study. In the boundary, not only are components included, but so are the relations of those components.	(ISO, 2006, p. 14040)

Social Impact Assessment	The process of identifying the social impacts that are likely to follow specific policy actions or defined system activities, to assess the significance of these impacts, and to identify measures that may help avoid or minimize adverse effects.	Social impact assessment, like environmental impact assessment for life cycle assessment, or ***environmental weltanschauung***, is a technique for the broader concept of social weltanschauung.	Benoît et al., 2010
Energy Use	Different forms of the conversion and application of energy to support human activities.	Five areas of energy use can be defined: direct energy, indirect energy, intermediate energy, primary source, and renewable energy	GRI, 2013
Human Well-Being	A concept that reflects a human individual's life situation, including knowledge, friendship, self-expression, affiliation, bodily integrity, health, economic security, freedom, affection, wealth and leisure in a defined societal situation.	In the context of sustainable manufacturing, human well-being usually refers to both human physical/mental safety, and the fulfillment of needs. Specifically, it involves ergonomic considerations in manufacturing, and psychological considerations in other organizational activities.	Benoît et al., 2010
Process	A set of interrelated or interacting activities that are organized to accomplish the transformation of inputs to outputs under existing constraints.	A process can occur at more than one level. A sub-process, if it is the smallest element, can be called a unit process.	ISO, 2006
Materials	Physical components that are extracted from the ecosystem and will be processed into matter or a product component used to assist manufacturing processes, during which value will be added.	Materials can include raw materials, associated process materials, semi-manufactured goods or parts, and materials for packing purposes.	GRI, 2013

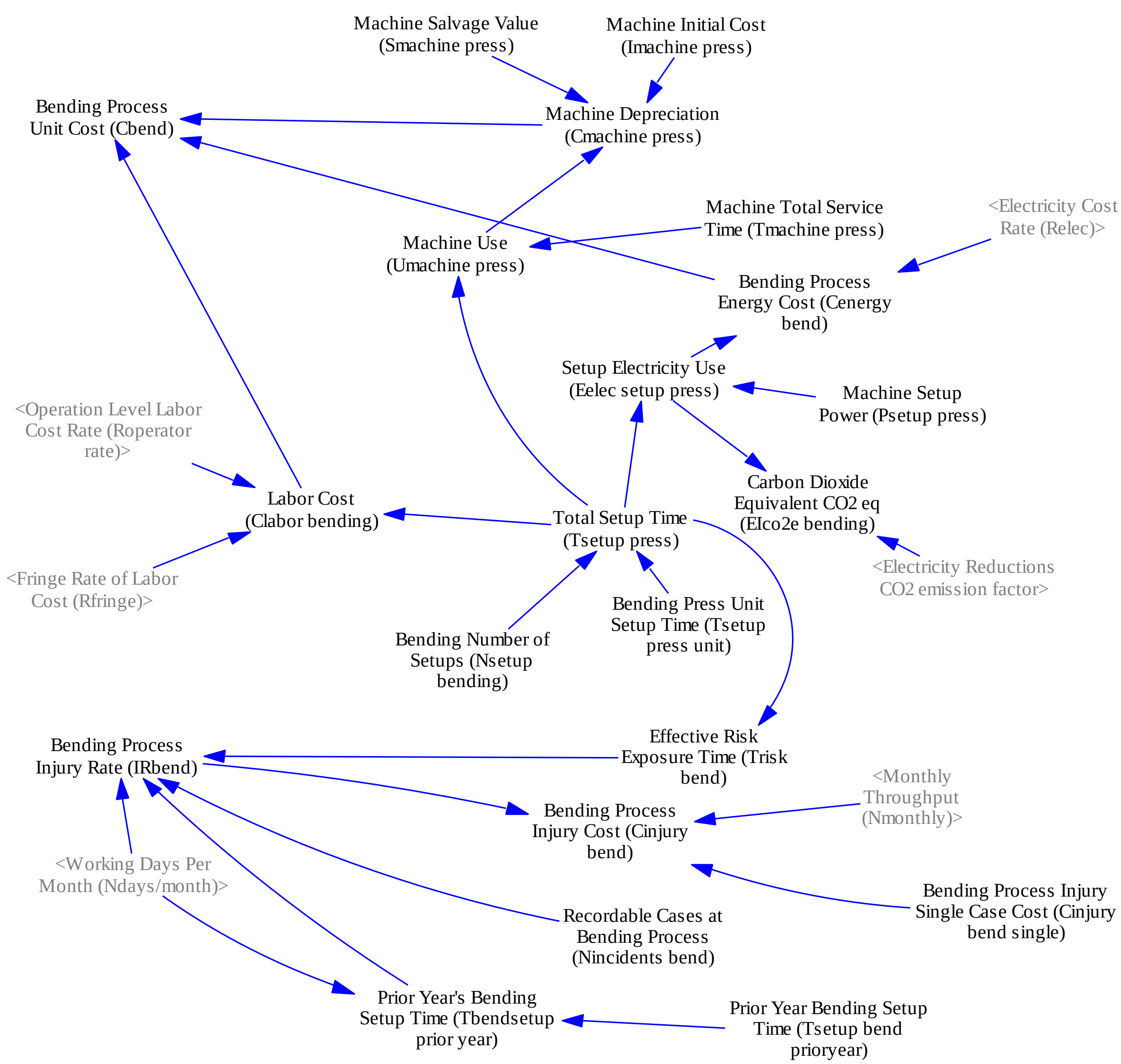
Unit Process	The smallest element considered to accomplish an activity in a manufacturing system.	An activity, if it is the smallest element of a process, can be called a unit process.	ISO, 2006
Waste	The substances or time which the manufacturer intends or is required to dispose of.	In addition to material waste, this definition refers to the concept of time waste from lean manufacturing, which is well-established.	ISO, 2006
Product	Any good or service offered to serve the needs of other members of society.	Service can be a co-product associated with a product, for example, maintenance and recycling activities. It can also be the main product with goods as co-products to support the service.	ISO, 2013
Recycling	The process of converting waste into a reusable material in order to add value.	Recycling is one form of product recovery. It changes waste into useful materials for producing new products.	ISO, 2006
Remanufacturing	A recovery process to rebuild, repair, and/or restore parts or an instrument to match the consumer expectations for a new product.	Remanufacturing is one form of product recovery. Usable parts of the product will be processed to be like-new parts in inventory, and later used to produce products equivalent or superior to new ones (Lund, 1984).	ISO, 2006

Appendix D. Model Details

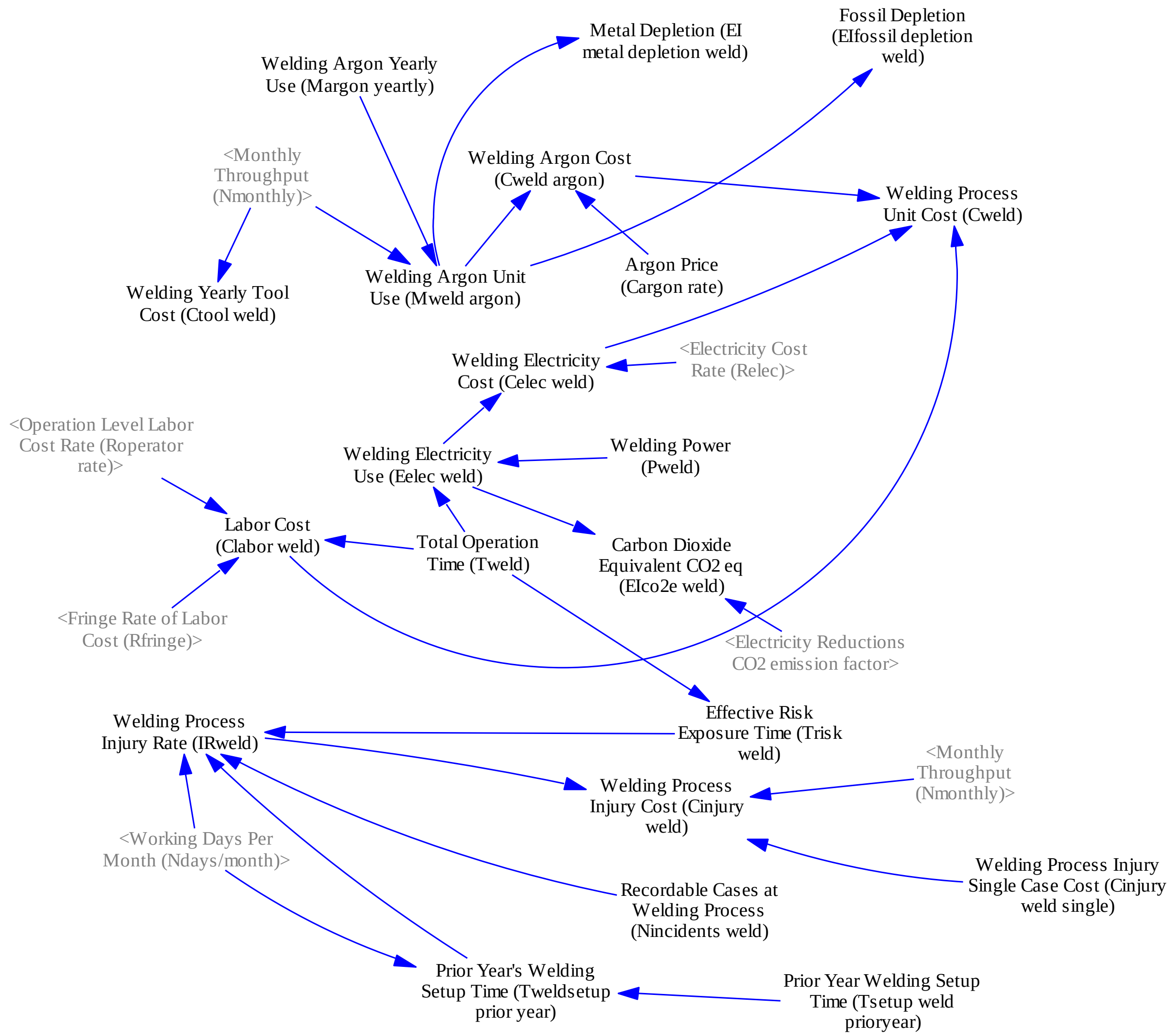
Operation Level Sub-Structure



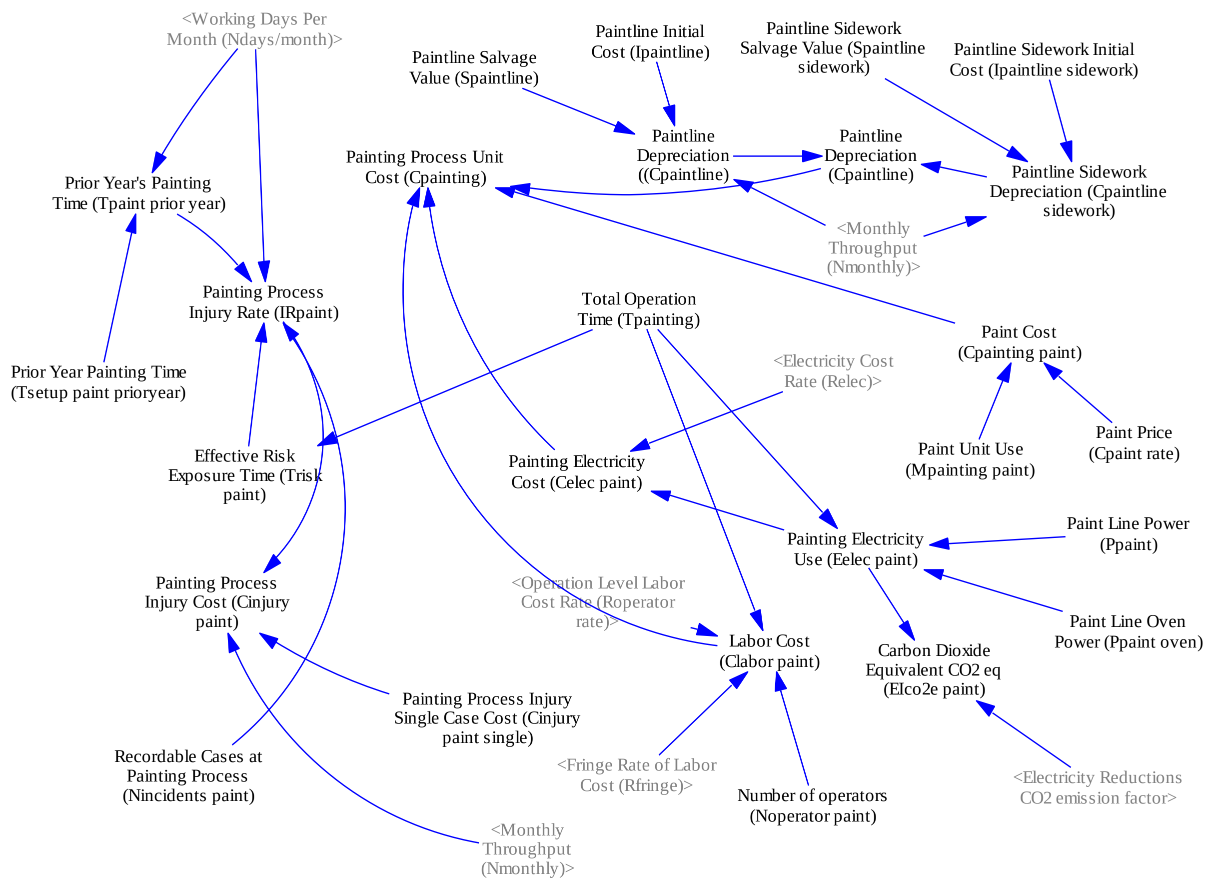
Welding Process



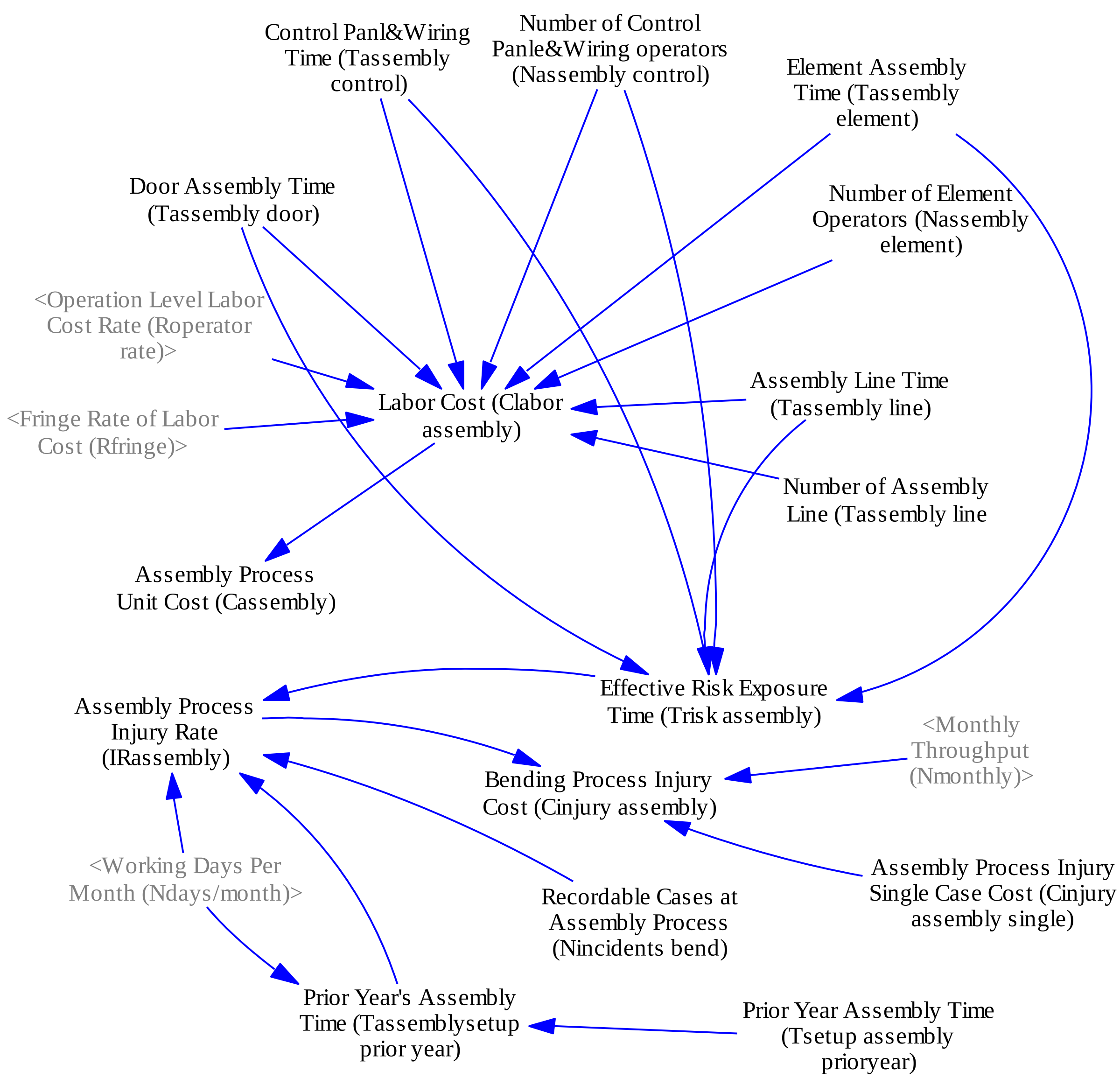
Welding Process



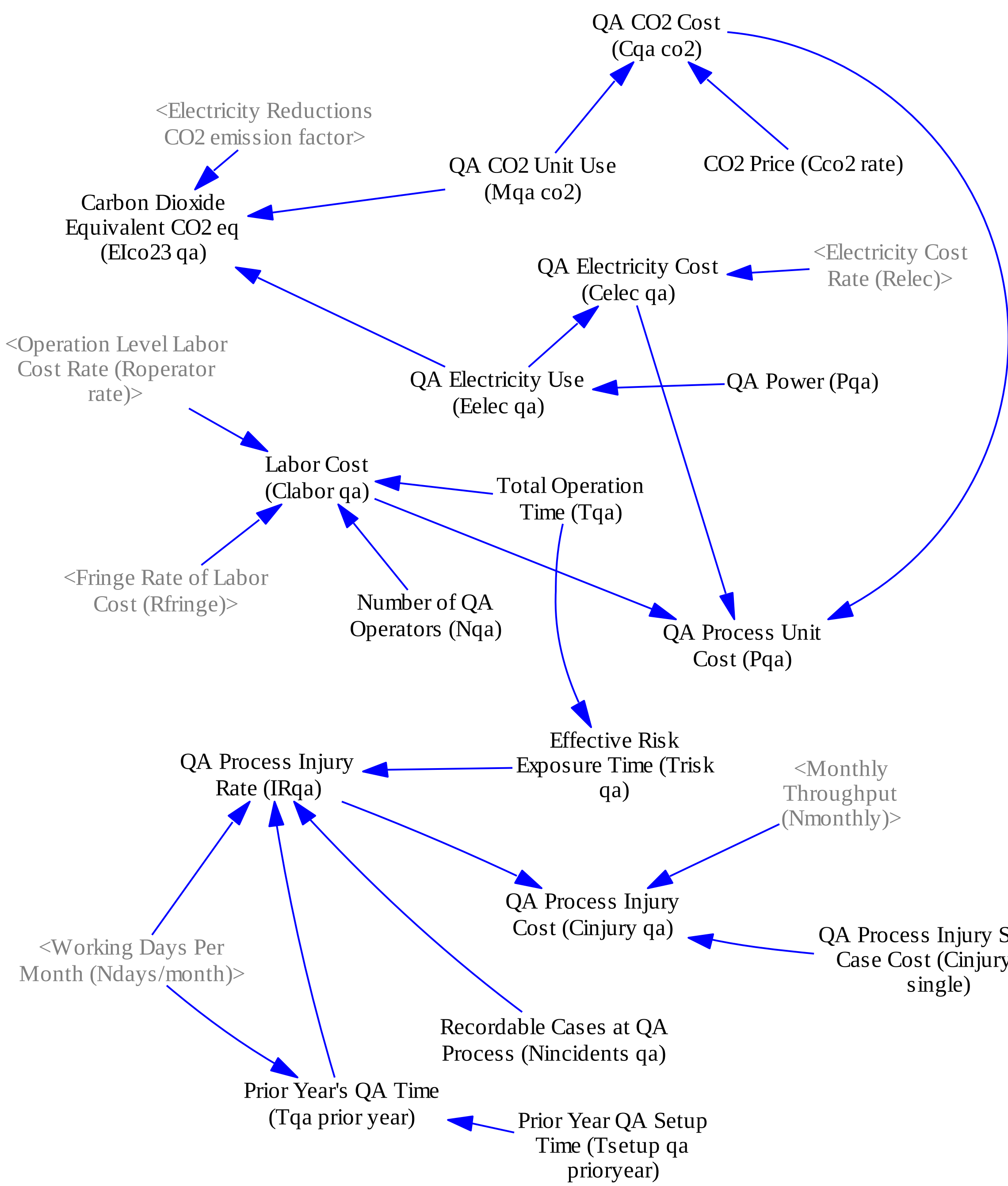
Painting Process



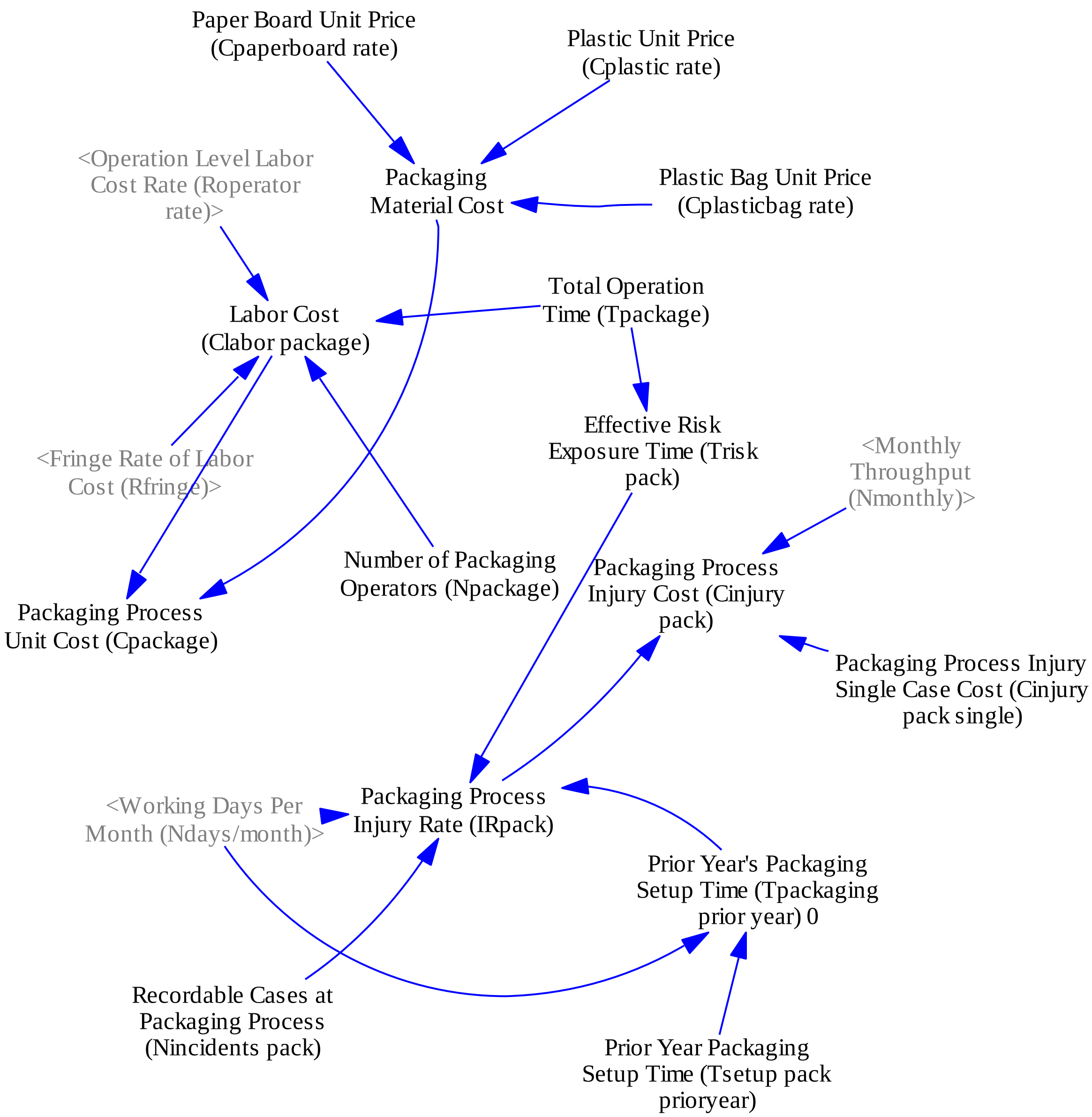
Assembly Process



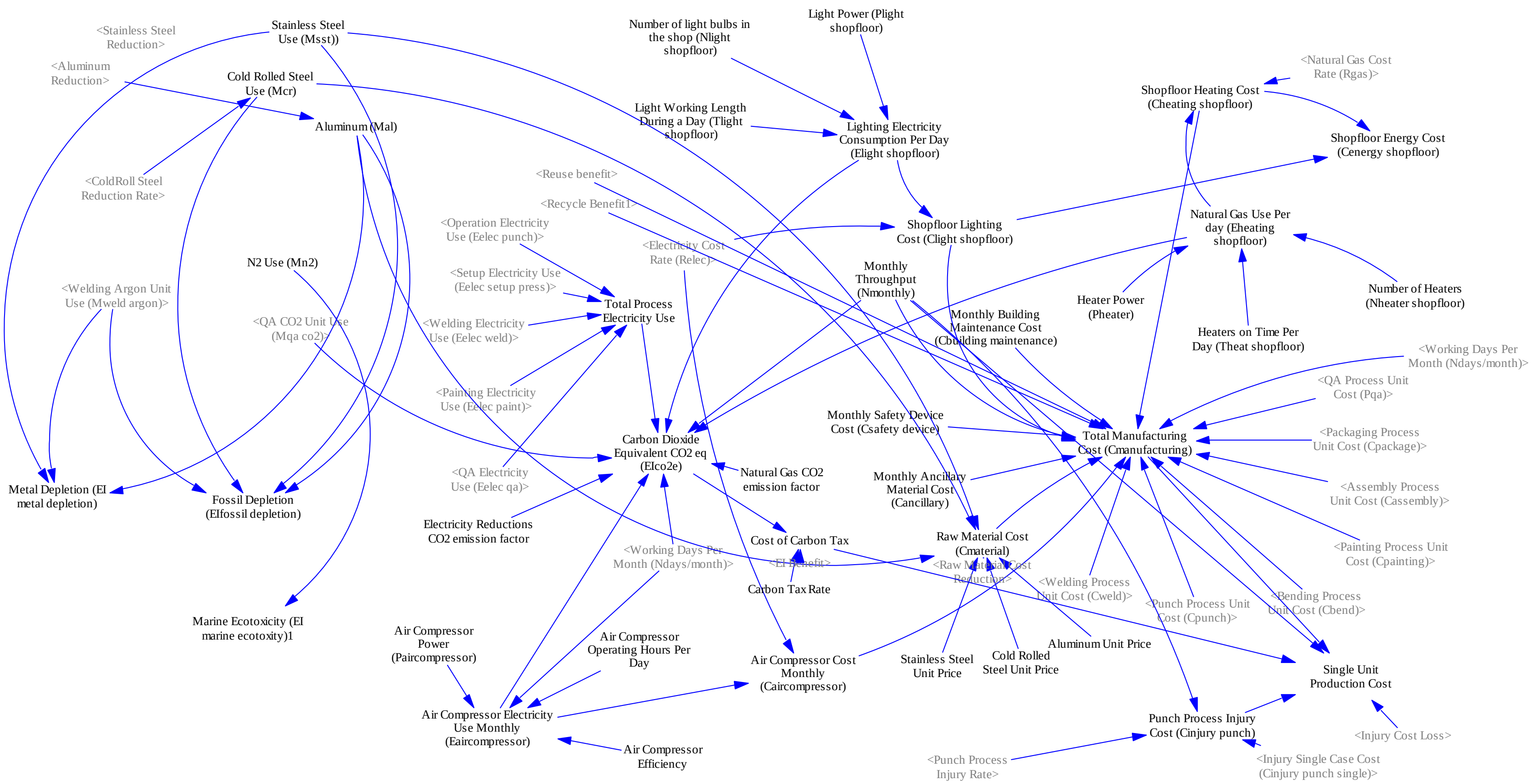
Quality Assurance Process



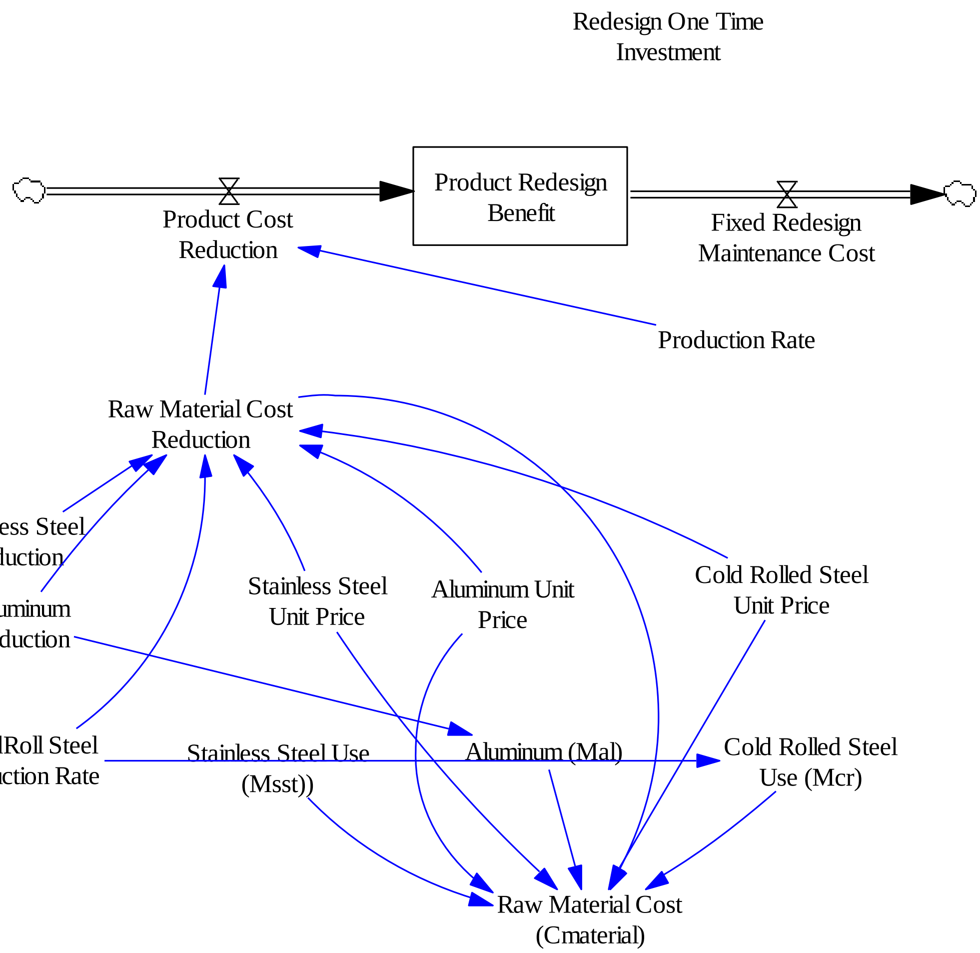
Packaging Process



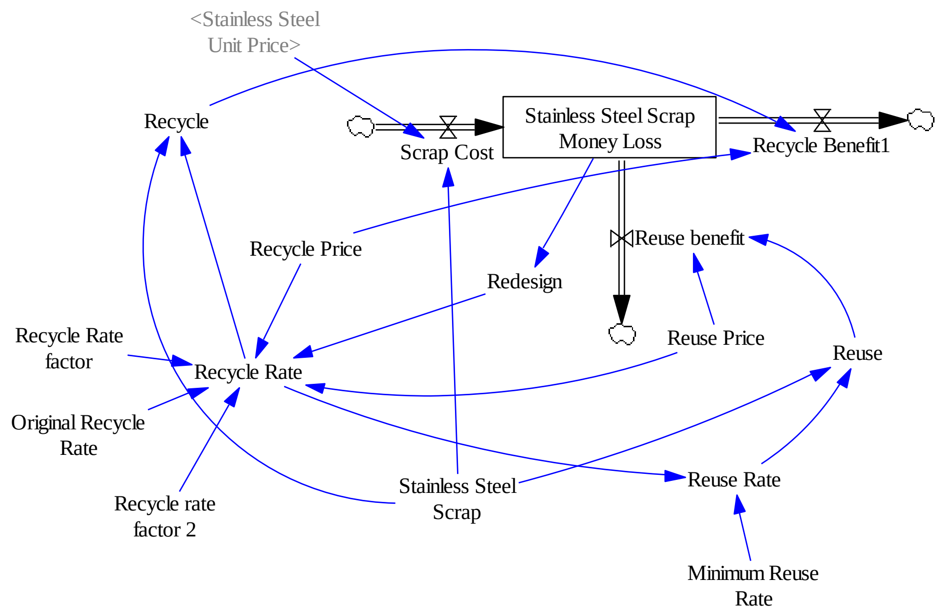
Shopfloor Level Sub-Structure



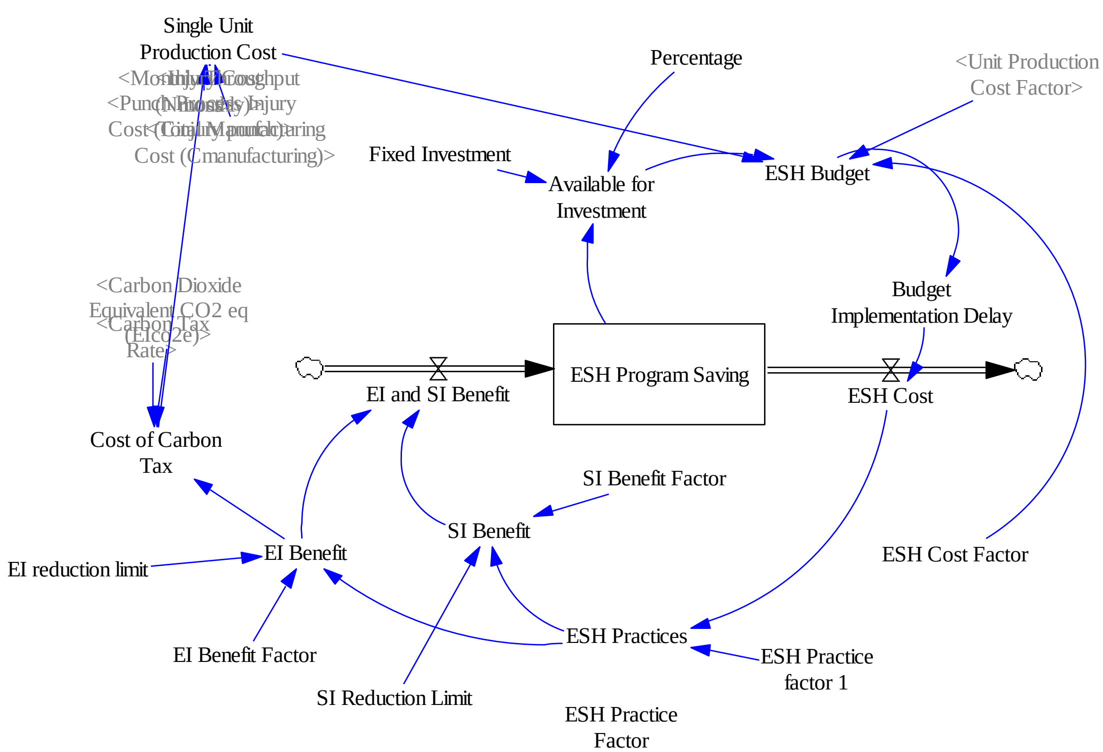
Product Redesign Behavior (Uncompleted model)



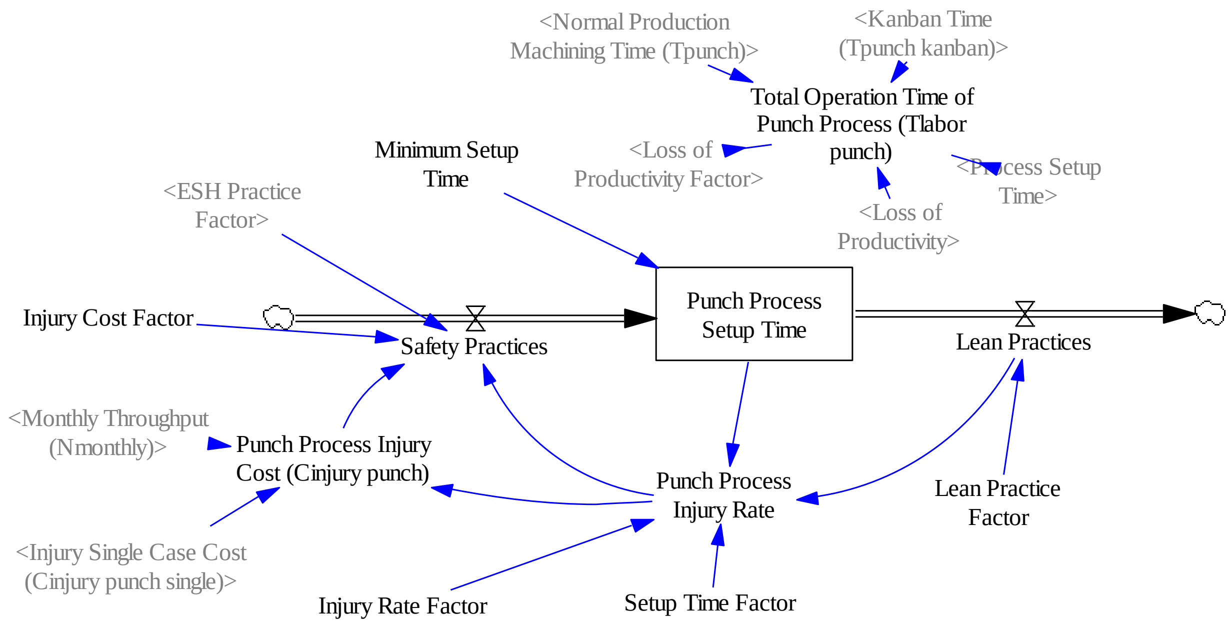
Product Redesign, Reuse, and Recycle Behavior (Uncompleted)



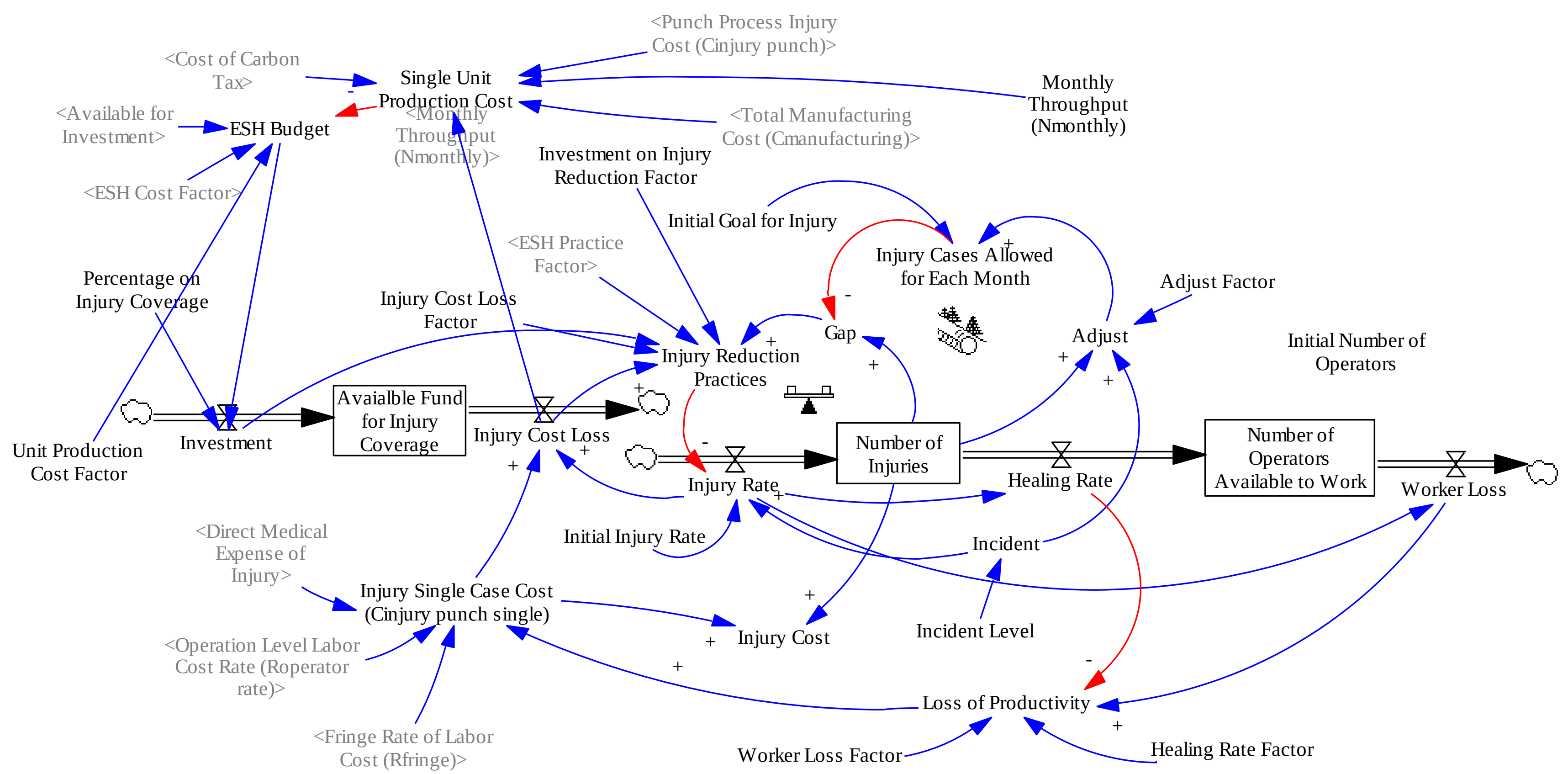
ESH Program Implementation Behavior



Punch Process Setup Time and Injury Behavior



Injury Cost Behavior



Variables

Adjust= DELAY FIXED (
IF THEN ELSE(Incident<0, 0 , Number of Injuries/Adjust Factor) , 3 , 0)
Units: **undefined**

Adjust Factor=
4
Units: **undefined** [0,40]

"Air Compressor Cost Monthly (Caircompressor)"=
"Air Compressor Electricity Use Monthly (Eaircompressor)"*"Electricity Cost Rate (Relec)"
Units: dollar

Air Compressor Efficiency=
0.85
Units: **undefined**

"Air Compressor Electricity Use Monthly (Eaircompressor)"=
"Air Compressor Power (Paircompressor)"*0.746*Air Compressor Operating Hours Per Day *"Working Days Per Month (Ndays/month)"*Air Compressor Efficiency/0.95
Units: kwh
0.95: air compressor motor efficiency

Air Compressor Operating Hours Per Day=
20
Units: hours

"Air Compressor Power (Paircompressor)"=
25
Units: horse power

"Aluminum (Mal)"=
2.96-Aluminum Reduction
Units: kg

"Aluminum Recycled (Mal recycle)"=
1.16
Units: kg

Aluminum Reduction=
0.37
Units: **undefined** [0,2.96]

Aluminum Unit Price=
1.69
Units: dollar/kg

"Argon Price (Cargon rate)"=
105.17
Units: dollar/CL

1CL=250FTS

"Assembly Line Time (Tassembly line)"=
103/60
Units: hours

"Assembly Process Injury Rate (IRassembly)"=
("Effective Risk Exposure Time (Trisk assembly)"*"Working Days Per Month (Ndays/month)"
12)"Recordable Cases at Assembly Process (Nincidents bend)"/"Prior Year's Assembly Time (Tassemblysetup prior year)"
Units: **undefined**

"Assembly Process Injury Single Case Cost (Cinjury assembly single)"=
1000
Units: dollar

"Assembly Process Unit Cost (Cassembly)"=
"Labor Cost (Clabor assembly)"
Units: dollars

Avaialble Fund for Injury Coverage= INTEG (
Investment-Injury Cost Loss,
0)
Units: **undefined**

Available for Investment=
ESH Program Saving*Percentage+Fixed Investment
Units: **undefined**

"Bending Number of Setups (Nsetup bending)"=
21
Units: **undefined**

"Bending Press Unit Setup Time (Tsetup press unit)"=
4.93
Units: minute

"Bending Process Energy Cost (Cenergy bend)"=
"Setup Electricity Use (Eelec setup press)"*"Electricity Cost Rate (Relec)"
Units: dollar

"Bending Process Injury Cost (Cinjury assembly)"=
"Assembly Process Injury Rate (IRassembly)"*"Assembly Process Injury Single Case Cost (Cinjury assembly single)"
/("Monthly Throughput (Nmonthly)"
*12)
Units: dollar

"Bending Process Injury Cost (Cinjury bend)"=
"Bending Process Injury Rate (IRbend)"*"Bending Process Injury Single Case Cost (Cinjury bend single)"
/("Monthly Throughput (Nmonthly)"
*12)

Units: dollar

"Bending Process Injury Rate (IRbend)"=
("Effective Risk Exposure Time (Trisk bend)"*"Working Days Per Month (Ndays/month)"
12)"Recordable Cases at Bending Process (Nincidents bend)"/"Prior Year's Bending Setup Time (Tbendsetup prior year)"
Units: **undefined**

"Bending Process Injury Single Case Cost (Cinjury bend single)"=
1000
Units: dollar

"Bending Process Unit Cost (Cbend)"=
"Bending Process Energy Cost (Cenergy bend)"+"Labor Cost (Clabor bending)"
+"Machine Depreciation (Cmachine press)"
Units: **undefined**

Budget Implementation Delay= DELAY FIXED (
ESH Budget , 1 , 4)
Units: **undefined**

"Carbon Dioxide Equivalent CO2 eq (EIco23 qa)"=
Electricity Reductions CO2 emission factor*"QA Electricity Use (Eelec qa)"
+"QA CO2 Unit Use (Mqa co2)"/1000
Units: **undefined**

"Carbon Dioxide Equivalent CO2 eq (EIco2e bending)"=
Electricity Reductions CO2 emission factor*"Setup Electricity Use (Eelec setup press)"
Units: kg

"Carbon Dioxide Equivalent CO2 eq (EIco2e paint)"=
Electricity Reductions CO2 emission factor*"Painting Electricity Use (Eelec paint)"
Units: metric ton

"Carbon Dioxide Equivalent CO2 eq (EIco2e punch)"=
Electricity Reductions CO2 emission factor*"Operation Electricity Use (Eelec punch)"
Units: kg

"Carbon Dioxide Equivalent CO2 eq (EIco2e weld)"=
Electricity Reductions CO2 emission factor*"Welding Electricity Use (Eelec weld)"
Units: kg

"Carbon Dioxide Equivalent CO2 eq (EIco2e)"=
((Total Process Electricity Use+"Lighting Electricity Consumption Per Day (Elight shopfloor)"
*"Working Days Per Month (Ndays/month)"
/"Monthly Throughput (Nmonthly)")*Electricity Reductions CO2 emission factor
+"Natural Gas Use Per day (Eheating shopfloor)"
*"Working Days Per Month (Ndays/month)"/"Monthly Throughput (Nmonthly)"*Natural Gas CO2 emission factor
+"Air Compressor Electricity Use Monthly (Eaircompressor)"
/"Monthly Throughput (Nmonthly)"*Electricity Reductions CO2 emission factor
+"QA CO2 Unit Use (Mqa co2)"/1000)*"Monthly Throughput (Nmonthly)"

Units: metric ton

Carbon Tax Rate=
20
Units: **undefined**

"CO2 Price (Cco2 rate)"=
40.14
Units: dollar/CL
1CL=250FTS

"Cold Rolled Steel Recycled (Mcr recycle)"=
32.89
Units: kg

Cold Rolled Steel Unit Price=
1.29
Units: dollar/kg

"Cold Rolled Steel Use (Mcr)"=
38.84-ColdRoll Steel Reduction Rate
Units: kg

ColdRoll Steel Reduction Rate=
9
Units: **undefined** [0,38.84]

"Control Panl&Wiring Time (Tassembly control)"=
95/60
Units: hours

Cost of Carbon Tax=
Carbon Tax Rate*"Carbon Dioxide Equivalent CO2 eq (EIco2e)"-EI Benefit/473
Units: dollars
20 is the california carbon tax rate.
http://www.cotce.ca.gov/documents/correspondence/staff_and_commis
sioners/documents/Carbon%20tax.pdf

Direct Medical Expense of Injury=
2500
Units: dollars
Data from
https://www.osha.gov/dcsp/smallbusiness/safetypays/estimator.html
Laceration, 3% profit margin Result: 18140

"Door Assembly Time (Tassembly door)"=
20/60
Units: hours

"Effective Risk Exposure Time (Trisk assembly)"=
"Assembly Line Time (Tassembly line)"+"Control Panl&Wiring Time (Tassembly control)"
+"Door Assembly Time (Tassembly door)"+"Element Assembly Time (Tassembly element)"

+"Number of Control Panle&Wiring operators (Nassembly control)"
Units: hours

"Effective Risk Exposure Time (Trisk bend)"=
"Total Setup Time (Tsetup press)"
Units: hours

"Effective Risk Exposure Time (Trisk pack)"=
"Total Operation Time (Tpackage)"
Units: hours

"Effective Risk Exposure Time (Trisk paint)"=
"Total Operation Time (Tpainting)"
Units: hours

"Effective Risk Exposure Time (Trisk qa)"=
"Total Operation Time (Tqa)"
Units: hours

"Effective Risk Exposure Time (Trisk weld)"=
"Total Operation Time (Tweld)"
Units: hours

EI and SI Benefit=
EI Benefit+SI Benefit
Units: **undefined**

EI Benefit=
IF THEN ELSE(EI Benefit Factor*ESH Practices<EI reduction limit, EI Benefit Factor
*ESH Practices , EI reduction limit)
Units: **undefined**

EI Benefit Factor=
1.837
Units: **undefined** [0,?]

EI reduction limit=
14000
Units: **undefined**
14000

"Electricity Cost Rate (Relec)"=
0.1
Units: dollar/kwh

Electricity Reductions CO2 emission factor=
0.000689551
Units: metric ton CO2/kwh
Reference:
http://www.epa.gov/cleanenergy/energy-resources/refs.html

"Element Assembly Time (Tassembly element)"=

7/60
Units: hours

ESH Budget=
Available for Investment*ESH Cost Factor*Single Unit Production Cost/Unit Production Cost Factor
Units: **undefined**

ESH Cost=
Budget Implementation Delay
Units: **undefined**

ESH Cost Factor=
0.1875
Units: **undefined** [0,1]

ESH Practice Factor=
0.125
Units: **undefined** [0,2]

ESH Practice factor 1=
24
Units: **undefined**

ESH Practices= DELAY FIXED (
ESH Practice factor 1*ESH Cost, 5 , 0)
Units: **undefined**

ESH Program Saving= INTEG (
EI and SI Benefit-ESH Cost,
0)
Units: **undefined**

FINAL TIME = 80
Units: Month
The final time for the simulation.

Fixed Investment=
8500
Units: **undefined**

Fixed Redesign Maintenance Cost=
100
Units: **undefined**

"Fossil Depletion (EIfossil depletion weld)"=
"Welding Argon Unit Use (Mweld argon)"*0.0648
Units: kg

"Fossil Depletion (EIfossil depletion)"=
"Aluminum (Mal)"/8+"Cold Rolled Steel Use (Mcr)"/9.404+"Stainless Steel Use (Msst))"
/10.0234+"Welding Argon Unit Use (Mweld argon)"/0.0648
Units: dollar

"Fringe Rate of Labor Cost (Rfringe)"=
1.35
Units: **undefined**

Gap=
IF THEN ELSE(Number of Injuries<Injury Cases Allowed for Each Month, 0 , Number of Injuries -Injury Cases Allowed for Each Month)
Units: **undefined**

Healing Rate=
DELAY FIXED(Injury Rate, 2 , 0.3)
Units: **undefined**

Healing Rate Factor=
1
Units: **undefined** [0,2]

"Heater Power (Pheater)"=
150000
Units: **undefined**

"Heaters on Time Per Day (Theat shopfloor)"=
10
Units: **undefined**

Incident=
Incident Level*PULSE TRAIN(30 , 1 , 10 , 40)
Units: **undefined**

Incident Level=
3.063
Units: **undefined**

Initial Goal for Injury=
2
Units: **undefined**

Initial Injury Rate=
INTEGER(RANDOM POISSON(0, 6 , 0.72 , 1.02 , 1.02 , 3))
Units: **undefined** [0,5]

Initial Number of Operators=
100
Units: **undefined**

INITIAL TIME = 0
Units: Month
The initial time for the simulation.

Injury Cases Allowed for Each Month= DELAY FIXED (
Initial Goal for Injury+Adjust, 2 , Initial Goal for Injury)

Units: **undefined**

Injury Cost=
Number of Injuries*"Injury Single Case Cost (Cinjury punch single)"
Units: dollars

Injury Cost Factor=
21
Units: **undefined** [0,?]

Injury Cost Loss=
Injury Rate*"Injury Single Case Cost (Cinjury punch single)"
Units: **undefined**

Injury Cost Loss Factor=
47500
Units: **undefined** [0,50000]

Injury Rate= DELAY FIXED (
Initial Injury Rate-Injury Reduction Practices+Incident
, 2 , 0.3)
Units: **undefined**

Injury Rate Factor=
100
Units: **undefined** [0,?]

Injury Reduction Practices= DELAY FIXED (
IF THEN ELSE(Gap>0, INTEGER(Gap*ESH Practice Factor+Injury Cost Loss/Injury Cost Loss Factor
+Investment/Investment on Injury Reduction Factor) , 0), 1, 0)
Units: **undefined**

"Injury Single Case Cost (Cinjury punch single)"=
Direct Medical Expense of Injury+"Operation Level Labor Cost Rate (Roperator rate)"
*(1+"Fringe Rate of Labor Cost (Rfringe)"
)*Loss of Productivity
Units: dollar

Investment=
ESH Budget*Percentage on Injury Coverage
Units: **undefined**

Investment on Injury Reduction Factor=
8500
Units: **undefined** [0,10000]
8500

"Kanban Machine Power (Ppunch kanban)"=
460*17.8
Units: watt

"Kanban Time (Tpunch kanban)"=

1105.1
Units: seconds

"Labor Cost (Clabor assembly)"=
("Door Assembly Time (Tassembly door)"*1+"Control Panl&Wiring Time (Tassembly control)"
*"Number of Control Panle&Wiring operators (Nassembly control)"
+"Element Assembly Time (Tassembly element)"*"Number of Element Operators (Nassembly element)"
+"Number of Assembly Line (Tassembly line"*"Assembly Line Time (Tassembly line)"
)*"Fringe Rate of Labor Cost (Rfringe)"*"Operation Level Labor Cost Rate (Roperator rate)"
Units: dollar

"Labor Cost (Clabor bending)"=
"Total Setup Time (Tsetup press)"*"Fringe Rate of Labor Cost (Rfringe)"*"Operation Level Labor Cost Rate (Roperator rate)"
Units: dollar

"Labor Cost (Clabor package)"=
"Total Operation Time (Tpackage)"*"Operation Level Labor Cost Rate (Roperator rate)"
"Fringe Rate of Labor Cost (Rfringe)""Number of Packaging Operators (Npackage)"
Units: dollar

"Labor Cost (Clabor paint)"=
"Total Operation Time (Tpainting)"*"Operation Level Labor Cost Rate (Roperator rate)"
"Fringe Rate of Labor Cost (Rfringe)""Number of operators (Noperator paint)"
Units: dollar

"Labor Cost (Clabor punch)"=
"Total Operation Time of Punch Process (Tlabor punch)"*"Fringe Rate of Labor Cost (Rfringe)"
*"Operation Level Labor Cost Rate (Roperator rate)"
Units: dollar

"Labor Cost (Clabor qa)"=
"Total Operation Time (Tqa)"*"Operation Level Labor Cost Rate (Roperator rate)"
"Fringe Rate of Labor Cost (Rfringe)""Number of QA Operators (Nqa)"
Units: dollar

"Labor Cost (Clabor weld)"=
"Total Operation Time (Tweld)"*"Operation Level Labor Cost Rate (Roperator rate)"
*"Fringe Rate of Labor Cost (Rfringe)"
Units: dollar

Lean Practice Factor=
0.625
Units: **undefined** [0.375,10]

Lean Practices= DELAY FIXED (
Lean Practice Factor , 5 , 0)
Units: **undefined**

"Light Power (Plight shopfloor)"=
54
Units: watt

"Light Working Length During a Day (Tlight shopfloor)"=
20
Units: hours

"Lighting Electricity Consumption Per Day (Elight shopfloor)"=
"Light Power (Plight shopfloor)"*"Light Working Length During a Day (Tlight shopfloor)" *"Number of light bulbs in the shop (Nlight shopfloor)"/1000
Units: **undefined**

Loss of Productivity=
10-Healing Rate/Healing Rate Factor+Worker Loss/Worker Loss Factor
Units: hours

Loss of Productivity Factor=
4
Units: **undefined**

"Machine Depreciation (Cmachine press)"=
("Machine Initial Cost (Imachine press)"-"Machine Salvage Value (Smachine press)")*"Machine Use (Umachine press)"
Units: dollar

"Machine Depreciation (Cmachine punch)"=
"Machine Depreciation (Cmachine punch1)"+"Machine Depreciation (Cmachine punch2)"
Units: dollar

"Machine Depreciation (Cmachine punch1)"=
("Machine Initial Cost (Imachine punch1)"-"Machine Salvage Value (Smachine punch1)")*"Machine Use (Umachine punch1)"
Units: dollar

"Machine Depreciation (Cmachine punch2)"=
("Machine Initial Cost (Imachine punch2)"-"Machine Salvage Value (Smachine punch2)")*"Machine Use (Umachine punch2)"
Units: dollar

"Machine Initial Cost (Imachine press)"=
190000
Units: dollar

"Machine Initial Cost (Imachine punch1)"=
880000
Units: dollar

"Machine Initial Cost (Imachine punch2)"=
250000
Units: dollar

"Machine Operation Power (Poperation punch)"=
460*28.6
Units: watt

"Machine Salvage Value (Smachine press)"=
13000
Units: dollar

"Machine Salvage Value (Smachine punch1)"=
130000
Units: dollar

"Machine Salvage Value (Smachine punch2)"=
100000
Units: dollar

"Machine Setup Power (Psetup press)"=
460*0.27
Units: watt

"Machine Setup Power (Psetup punch)"=
460*16.5
Units: watt

"Machine Total Service Time (Tmachine press)"=
62400
Units: hours

"Machine Total Service Time (Tmachine punch1)"=
41600
Units: hours

"Machine Total Service Time (Tmachine punch2)"=
41600
Units: hours

"Machine Use (Umachine press)"=
"Total Setup Time (Tsetup press)"/"Machine Total Service Time (Tmachine press)"
Units: **undefined**

"Machine Use (Umachine punch1)"=
("Normal Production Machining Time (Tpunch)"/3600+Punch Process Setup Time
)/"Machine Total Service Time (Tmachine punch1)"
Units: **undefined**

"Machine Use (Umachine punch2)"=
"Kanban Time (Tpunch kanban)"/3600/"Machine Total Service Time (Tmachine punch2)"
Units: **undefined**

Marine Ecotoxicity=
"N2 Use (Mn2)"*1.77e+010
Units: kg

"Marine Ecotoxicity (EI marine ecotoxity)1"= INTEG (
"N2 Use (Mn2)"/1.77e+010,

0)
Units: **undefined**

"Metal Depletion (EI metal depletion weld)"=
"Welding Argon Unit Use (Mweld argon)"*0.00165
Units: kg

"Metal Depletion (EI metal depletion)"=
"Welding Argon Unit Use (Mweld argon)"*0.00165+"Stainless Steel Use (Msst))"
/18.0972+"Aluminum (Mal)"/137.037
Units: **undefined**

Minimum Reuse Rate=
0.3
Units: **undefined** [0,1]

Minimum Setup Time=
0.23
Units: **undefined**

"Monthly Ancillary Material Cost (Cancillary)"=
2481.84
Units: **undefined**

"Monthly Building Maintenance Cost (Cbuilding maintenance)"=
297.59
Units: **undefined**

"Monthly Safety Device Cost (Csafety device)"=
709.3
Units: **undefined**

"Monthly Throughput (Nmonthly)"=
473
Units: **undefined** [360,530]

"N2 Use (Mn2)"=
76.02/30.42
Units: kg
76.02 FTS = 76.02 Cubic feet at 70F and 1 atm = 30.42kg

Natural Gas CO2 emission factor=
0.005302
Units: metric ton CO2/therm
reference:
http://www.epa.gov/cleanenergy/energy-resources/refs.html

"Natural Gas Cost Rate (Rgas)"=
0.74
Units: **undefined**

"Natural Gas Use Per day (Eheating shopfloor)"=

"Heater Power (Pheater)"*"Heaters on Time Per Day (Theat shopfloor)"*"Number of Heaters (Nheater shopfloor)"
/100000
Units: therm

"Normal Production Machining Time (Tpunch)"=
1698
Units: seconds

"Number of Assembly Line (Tassembly line"=
4
Units: **undefined**

"Number of Control Panle&Wiring operators (Nassembly control)"=
5
Units: **undefined**

"Number of Element Operators (Nassembly element)"=
2
Units: **undefined**

"Number of Heaters (Nheater shopfloor)"=
11
Units: **undefined**

Number of Injuries= INTEG (
Injury Rate-Healing Rate ,
4)
Units: Operators

"Number of light bulbs in the shop (Nlight shopfloor)"=
790
Units: **undefined**

"Number of operators (Noperator paint)"=
3
Units: **undefined**

Number of Operators Available to Work= INTEG (
Healing Rate-Worker Loss,
Initial Number of Operators)
Units: **undefined**

"Number of Packaging Operators (Npackage)"=
4
Units: **undefined**

"Number of QA Operators (Nqa)"=
1.5
Units: **undefined**

"Operation Electricity Cost (Celec punch)"=

"Electricity Cost Rate (Relec)"*"Operation Electricity Use (Eelec punch)"
Units: dollar

"Operation Electricity Use (Eelec punch)"=
"Operation Electricity Use (Eelec working punch)"+"Setup Electricity Use (Eelec setup punch)"
Units: kwh

"Operation Electricity Use (Eelec working punch)"=
"Normal Production Machining Time (Tpunch)"/3600*"Machine Operation Power (Poperation punch)"
/1000+"Kanban Machine Power (Ppunch kanban)"
/1000*"Kanban Time (Tpunch kanban)"/3600+Process Setup Time/3600*16.5*460
Units: kwh
normal production eneregy + kanban parts production

"Operation Level Labor Cost Rate (Roperator rate)"=
17.55
Units: dollar

Original Recycle Rate=
0.7
Units: **undefined** [0,1]

Packaging Material Cost=
"Paper Board Unit Price (Cpaperboard rate)"+"Plastic Bag Unit Price (Cplasticbag rate)"
+"Plastic Unit Price (Cplastic rate)"
Units: dollars

"Packaging Process Injury Cost (Cinjury pack)"=
"Packaging Process Injury Rate (IRpack)"*"Packaging Process Injury Single Case Cost (Cinjury pack single)"
/("Monthly Throughput (Nmonthly)"
*12)
Units: dollar

"Packaging Process Injury Rate (IRpack)"=
("Effective Risk Exposure Time (Trisk pack)"*"Working Days Per Month (Ndays/month)"
12)"Recordable Cases at Packaging Process (Nincidents pack)"/"Prior Year's Packaging Setup Time (Tpackaging prior year) 0"
Units: **undefined**

"Packaging Process Injury Single Case Cost (Cinjury pack single)"=
1000
Units: dollar

"Packaging Process Unit Cost (Cpackage)"=
"Labor Cost (Clabor package)"+Packaging Material Cost
Units: dollar

"Paint Cost (Cpainting paint)"=
"Paint Unit Use (Mpainting paint)"*"Paint Price (Cpaint rate)"
Units: dollar

"Paint Line Oven Power (Ppaint oven)"=
    460*1.45
Units: **undefined**

"Paint Line Power (Ppaint)"=
    460*12.46
Units: watt

"Paint Price (Cpaint rate)"=
    4.99
Units: dollar/lb
1CL=250FTS

"Paint Unit Use (Mpainting paint)"=
    3.53
Units: lb

"Painting Electricity Cost (Celec paint)"=
    "Electricity Cost Rate (Relec)"*"Painting Electricity Use (Eelec paint)"
Units: **undefined**

"Painting Electricity Use (Eelec paint)"=
    "Total Operation Time (Tpainting)"*"Paint Line Power (Ppaint)"/1000+25/60*
"Paint Line Oven Power (Ppaint oven)"/1000
Units: kwh
Oven time: 25min

"Painting Process Injury Cost (Cinjury paint)"=
    "Painting Process Injury Rate (IRpaint)"*"Painting Process Injury Single Case Cost (Cinjury paint single)"
/("Monthly Throughput (Nmonthly)"
*12)
Units: dollar

"Painting Process Injury Rate (IRpaint)"=
    ("Effective Risk Exposure Time (Trisk paint)"*"Working Days Per Month (Ndays/month)"
12)"Recordable Cases at Painting Process (Nincidents paint)"/"Prior Year's Painting Time (Tpaint prior year)"
Units: **undefined**

"Painting Process Injury Single Case Cost (Cinjury paint single)"=
    1000
Units: dollar

"Painting Process Unit Cost (Cpainting)"=
    "Labor Cost (Clabor paint)"+"Paint Cost (Cpainting paint)"+"Painting Electricity Cost (Celec paint)"
+"Paintline Depreciation (Cpaintline)"
Units: **undefined**

"Paintline Depreciation ((Cpaintline)"=
    ("Paintline Initial Cost (Ipaintline)"-"Paintline Salvage Value (Spaintline)"
)/12/"Monthly Throughput (Nmonthly)"/15
Units: dollar
15 years of service life

"Paintline Depreciation (Cpaintline)"=
"Paintline Sidework Depreciation (Cpaintline sidework)"+"Paintline Depreciation ((Cpaintline)"
Units: dollar

"Paintline Initial Cost (Ipaintline)"=
800000
Units: dollar

"Paintline Salvage Value (Spaintline)"=
200000
Units: dollar

"Paintline Sidework Depreciation (Cpaintline sidework)"=
("Paintline Sidework Initial Cost (Ipaintline sidework)"-"Paintline Sidework Salvage Value (Spaintline sidework)"
)/"Monthly Throughput (Nmonthly)"
/12/20
Units: dollar
20 years of service life

"Paintline Sidework Initial Cost (Ipaintline sidework)"=
300000
Units: dollar

"Paintline Sidework Salvage Value (Spaintline sidework)"=
200000
Units: dollar

"Paper Board Unit Price (Cpaperboard rate)"=
0.36
Units: dollars

Percentage=
0.1375
Units: **undefined** [0,1]

Percentage on Injury Coverage=
0.4875
Units: **undefined** [0,1]

"Plastic Bag Unit Price (Cplasticbag rate)"=
0.13
Units: dollars

"Plastic Unit Price (Cplastic rate)"=
0.06
Units: dollars

"Prior Year Assembly Time (Tsetup assembly prioryear)"=
0.75
Units: hours

"Prior Year Bending Setup Time (Tsetup bend prioryear)"=
0.75
Units: hours

"Prior Year Packaging Setup Time (Tsetup pack prioryear)"=
0.75
Units: hours

"Prior Year Painting Time (Tsetup paint prioryear)"=
0.75
Units: hours

"Prior Year QA Setup Time (Tsetup qa prioryear)"=
0.75
Units: hours

"Prior Year Welding Setup Time (Tsetup weld prioryear)"=
0.75
Units: hours

"Prior Year's Assembly Time (Tassemblysetup prior year)"=
"Prior Year Assembly Time (Tsetup assembly prioryear)"*"Working Days Per Month (Ndays/month)"
*12
Units: **undefined**

"Prior Year's Bending Setup Time (Tbendsetup prior year)"=
"Prior Year Bending Setup Time (Tsetup bend prioryear)"*"Working Days Per Month (Ndays/month)"
*12
Units: **undefined**

"Prior Year's Packaging Setup Time (Tpackaging prior year) 0"=
"Prior Year Packaging Setup Time (Tsetup pack prioryear)"*"Working Days Per Month (Ndays/month)"
*12
Units: **undefined**

"Prior Year's Painting Time (Tpaint prior year)"=
"Prior Year Painting Time (Tsetup paint prioryear)"*"Working Days Per Month (Ndays/month)"
*12
Units: **undefined**

"Prior Year's QA Time (Tqa prior year)"=
"Prior Year QA Setup Time (Tsetup qa prioryear)"*"Working Days Per Month (Ndays/month)"
*12
Units: **undefined**

"Prior Year's Welding Setup Time (Tweldsetup prior year)"=
"Prior Year Welding Setup Time (Tsetup weld prioryear)"*"Working Days Per Month (Ndays/month)"
*12
Units: **undefined**

Process Setup Time=

2400
Units: seconds

Product Cost Reduction= DELAY FIXED (
Raw Material Cost Reduction*Production Rate, 5 , 0)
Units: **undefined**

Product Redesign Benefit= INTEG (
Product Cost Reduction-Fixed Redesign Maintenance Cost,
-Redesign One Time Investment)
Units: **undefined**

Production Rate=
15
Units: **undefined**

"Punch Process Injury Cost (Cinjury punch)"=
Punch Process Injury Rate*"Injury Single Case Cost (Cinjury punch single)"
/("Monthly Throughput (Nmonthly)"
*12)
Units: dollar

Punch Process Injury Rate= DELAY FIXED (
(1/Setup Time Factor+Lean Practices/Injury Rate Factor)/Punch Process Setup Time
, 2 , 0)
Units: **undefined**

Punch Process Setup Time= INTEG (
IF THEN ELSE(Punch Process Setup Time<Minimum Setup Time, Minimum Setup Time
, Safety Practices/1000-0.06*Lean Practices),
0.67)
Units: **undefined**

"Punch Process Unit Cost (Cpunch)"=
"Labor Cost (Clabor punch)"+"Machine Depreciation (Cmachine punch)"+"Operation Electricity Cost (Celec punch)"
Units: dollar

"QA CO2 Cost (Cqa co2)"=
"QA CO2 Unit Use (Mqa co2)"/8.76*"CO2 Price (Cco2 rate)"/100
Units: dollar

"QA CO2 Unit Use (Mqa co2)"=
0.32
Units: Cubic feet

"QA Electricity Cost (Celec qa)"=
"Electricity Cost Rate (Relec)"*"QA Electricity Use (Eelec qa)"
Units: **undefined**

"QA Electricity Use (Eelec qa)"=
12*"QA Power (Pqa)"/1000

Units: kwh

"QA Power (Pqa)"=
    120
Units: watt

"QA Process Injury Cost (Cinjury qa)"=
    "QA Process Injury Rate (IRqa)"*"QA Process Injury Single Case Cost (Cinjury qa single)"
/("Monthly Throughput (Nmonthly)"
*12)
Units: dollar

"QA Process Injury Rate (IRqa)"=
    ("Effective Risk Exposure Time (Trisk qa)"*"Working Days Per Month (Ndays/month)"
12)"Recordable Cases at QA Process (Nincidents qa)"/"Prior Year's QA Time (Tqa prior year)"
Units: **undefined**

"QA Process Injury Single Case Cost (Cinjury qa single)"=
    1000
Units: dollar

"QA Process Unit Cost (Pqa)"=
    "Labor Cost (Clabor qa)"+"QA CO2 Cost (Cqa co2)"+"QA Electricity Cost (Celec qa)"
Units: dollar

"Raw Material Cost (Cmaterial)"=
    1429.21+"Stainless Steel Use (Msst))"*Stainless Steel Unit Price+"Cold Rolled Steel Use (Mcr)"
*Cold Rolled Steel Unit Price
    +"Aluminum (Mal)"*Aluminum Unit Price-Raw Material Cost Reduction
Units: **undefined**
BOM cost: 1766.93, subtract SST, CR, and Al cost,

Raw Material Cost Reduction=
    RANDOM UNIFORM((Aluminum Reduction*Aluminum Unit Price+Cold Rolled Steel Unit Price
*ColdRoll Steel Reduction Rate
    +Stainless Steel Unit Price
    +Stainless Steel Reduction)*0.9, (Aluminum Reduction*Aluminum Unit Price+Cold Rolled Steel Unit
Price
*ColdRoll Steel Reduction Rate
    +Stainless Steel Unit Price
    +Stainless Steel Reduction)*1.1 , Aluminum Reduction*Aluminum Unit Price+Cold Rolled Steel Unit
Price
*ColdRoll Steel Reduction Rate
    +Stainless Steel Unit Price
    +Stainless Steel Reduction)
Units: **undefined**

"Recordable Cases at Assembly Process (Nincidents bend)"=
    2
Units: **undefined**

"Recordable Cases at Bending Process (Nincidents bend)"=

2
Units: **undefined**

"Recordable Cases at Packaging Process (Nincidents pack)"=
2
Units: **undefined**

"Recordable Cases at Painting Process (Nincidents paint)"=
2
Units: **undefined**

"Recordable Cases at Punch Process (Nincidents punch)"=
2
Units: **undefined**

"Recordable Cases at QA Process (Nincidents qa)"=
2
Units: **undefined**

"Recordable Cases at Welding Process (Nincidents weld)"=
2
Units: **undefined**

Recycle=
Recycle Rate*Stainless Steel Scrap
Units: **undefined** [0,?]

Recycle Benefit1=
Recycle*Recycle Price
Units: **undefined**

Recycle Price=
1
Units: **undefined** [0,1.52]

Recycle Rate=
IF THEN ELSE(Recycle Price<Reuse Price, Original Recycle Rate-Redesign/(Redesign
+Recycle Rate factor) , Original Recycle Rate
+Redesign/(Redesign+Recycle rate factor 2))
Units: **undefined** [0,1]

Recycle Rate factor=
1700
Units: **undefined** [0,4000]

Recycle rate factor 2=
4000
Units: **undefined**

Redesign=
DELAY FIXED(Stainless Steel Scrap Money Loss, 4 , 0)
Units: **undefined** [0,?]

Redesign One Time Investment=
2000
Units: **undefined**

Reuse=
Stainless Steel Scrap*Reuse Rate
Units: **undefined** [0,?]

Reuse benefit=
Reuse*Reuse Price
Units: **undefined**

Reuse Price=
1.52
Units: **undefined** [0,1.52]

Reuse Rate=
IF THEN ELSE(Recycle Rate<Minimum Reuse Rate, Minimum Reuse Rate, 1-Recycle Rate
)
Units: **undefined** [0,0.7]

Safety Practices=
Punch Process Injury Rate*ESH Practice Factor+"Punch Process Injury Cost (Cinjury punch)"
*Injury Cost Factor
Units: **undefined**

SAVEPER =
TIME STEP
Units: Month [0,?]
The frequency with which output is stored.

Scrap Cost=
Stainless Steel Scrap*Stainless Steel Unit Price
Units: **undefined**

"Setup Electricity Use (Eelec setup press)"=
"Total Setup Time (Tsetup press)"*"Machine Setup Power (Psetup press)"/1000
Units: **undefined**

"Setup Electricity Use (Eelec setup punch)"=
Punch Process Setup Time*"Machine Setup Power (Psetup punch)"/1000
Units: kwh

Setup Time Factor=
4
Units: **undefined** [0,?]

"Shopfloor Energy Cost (Cenergy shopfloor)"=
"Shopfloor Heating Cost (Cheating shopfloor)"+"Shopfloor Lighting Cost (Clight shopfloor)"
Units: dollars

"Shopfloor Heating Cost (Cheating shopfloor)"=
"Natural Gas Cost Rate (Rgas)"*"Natural Gas Use Per day (Eheating shopfloor)"
Units: dollars/Day

"Shopfloor Lighting Cost (Clight shopfloor)"=
"Lighting Electricity Consumption Per Day (Elight shopfloor)"*"Electricity Cost Rate (Relec)"
Units: **undefined**

SI Benefit=
IF THEN ELSE(SI Benefit Factor*ESH Practices<SI Reduction Limit, ESH Practices
*SI Benefit Factor , SI Reduction Limit)
Units: **undefined**

SI Benefit Factor=
0.825
Units: **undefined**

SI Reduction Limit=
4625
Units: **undefined**

Single Unit Production Cost=
Cost of Carbon Tax/"Monthly Throughput (Nmonthly)"+"Punch Process Injury Cost (Cinjury punch)"
+"Total Manufacturing Cost (Cmanufacturing)"-Injury Cost Loss/"Monthly Throughput (Nmonthly)"
Units: **undefined**

"Stainless Steel Recycled (Msst recycle)"=
37.48
Units: kg

Stainless Steel Reduction=
12
Units: **undefined** [0,85.64]

Stainless Steel Scrap=
82.6
Units: **undefined** [0,82.6]

Stainless Steel Scrap Money Loss= INTEG (
Scrap Cost-Recycle Benefit1-Reuse benefit,
0)
Units: **undefined** [0,?]

Stainless Steel Unit Price=
1.52
Units: dollar/kg [1,2]

"Stainless Steel Use (Msst))"=
85.64
Units: kg [0,?]

TIME STEP = 1

Units: Month [0,?]
The time step for the simulation.

"Total Manufacturing Cost (Cmanufacturing)"=
("Monthly Ancillary Material Cost (Cancillary)"+"Monthly Building Maintenance Cost (Cbuilding maintenance)"
+"Monthly Safety Device Cost (Csafety device)"
)/"Monthly Throughput (Nmonthly)"
+"Raw Material Cost (Cmaterial)"+"Assembly Process Unit Cost (Cassembly)"+
"Bending Process Unit Cost (Cbend)"+"Packaging Process Unit Cost (Cpackage)"
+"Painting Process Unit Cost (Cpainting)"+"Punch Process Unit Cost (Cpunch)"
+"QA Process Unit Cost (Pqa)"+"Welding Process Unit Cost (Cweld)"
+"Shopfloor Lighting Cost (Clight shopfloor)"+"Air Compressor Cost Monthly (Caircompressor)"
/"Monthly Throughput (Nmonthly)"
+"Shopfloor Heating Cost (Cheating shopfloor)"*"Working Days Per Month (Ndays/month)"
/"Monthly Throughput (Nmonthly)"+Reuse benefit+Recycle Benefit1
Units: dollar/CL

"Total Operation Time (Tpackage)"=
50/60
Units: hours

"Total Operation Time (Tpainting)"=
3
Units: hours

"Total Operation Time (Tqa)"=
0.45
Units: hours

"Total Operation Time (Tweld)"=
158.1/60
Units: hours

"Total Operation Time of Punch Process (Tlabor punch)"=
"Kanban Time (Tpunch kanban)"/3600+"Normal Production Machining Time (Tpunch)"
/3600+Loss of Productivity/Loss of Productivity Factor+Process Setup Time/3600
Units: hours

Total Process Electricity Use=
"Operation Electricity Use (Eelec punch)"+"Painting Electricity Use (Eelec paint)"
+"QA Electricity Use (Eelec qa)"+"Setup Electricity Use (Eelec setup press)"
+"Welding Electricity Use (Eelec weld)"
Units: **undefined**

"Total Setup Time (Tsetup press)"=
"Bending Number of Setups (Nsetup bending)"*"Bending Press Unit Setup Time (Tsetup press unit)"
/60
Units: hours

Unit Production Cost Factor=
3500

Units: **undefined** [0,4000]

"Welding Argon Cost (Cweld argon)"=
"Welding Argon Unit Use (Mweld argon)"/250*"Argon Price (Cargon rate)"
Units: dollar

"Welding Argon Unit Use (Mweld argon)"=
"Welding Argon Yearly Use (Margon yeartly)"/"Monthly Throughput (Nmonthly)"
/12
Units: FTS

"Welding Argon Yearly Use (Margon yeartly)"=
220627
Units: FTS

"Welding Electricity Cost (Celec weld)"=
"Electricity Cost Rate (Relec)"*"Welding Electricity Use (Eelec weld)"
Units: **undefined**

"Welding Electricity Use (Eelec weld)"=
"Total Operation Time (Tweld)"*"Welding Power (Pweld)"/1000
Units: kwh

"Welding Power (Pweld)"=
460*1.45
Units: watt

"Welding Process Injury Cost (Cinjury weld)"=
"Welding Process Injury Rate (IRweld)"*"Welding Process Injury Single Case Cost (Cinjury weld single)"
/("Monthly Throughput (Nmonthly)"
*12)
Units: dollar

"Welding Process Injury Rate (IRweld)"=
("Effective Risk Exposure Time (Trisk weld)"*"Working Days Per Month (Ndays/month)"
12)"Recordable Cases at Welding Process (Nincidents weld)"/"Prior Year's Welding Setup Time (Tweldsetup prior year)"
Units: **undefined**

"Welding Process Injury Single Case Cost (Cinjury weld single)"=
1000
Units: dollar

"Welding Process Unit Cost (Cweld)"=
"Labor Cost (Clabor weld)"+"Welding Argon Cost (Cweld argon)"+"Welding Electricity Cost (Celec weld)"
Units: **undefined**

"Welding Yearly Tool Cost (Ctool weld)"=
19125.5/"Monthly Throughput (Nmonthly)"/12
Units: **undefined**

Worker Loss=
Injury Rate
Units: **undefined**

Worker Loss Factor=
1
Units: **undefined**

"Working Days Per Month (Ndays/month)"=
17
Units: days

Adjust= DELAY FIXED (
IF THEN ELSE(Incident<0, 0 , Number of Injuries/Adjust Factor) , 3 , 0)
Units: **undefined**

Adjust Factor=
4
Units: **undefined** [0,40]

"Air Compressor Cost Monthly (Caircompressor)"=
"Air Compressor Electricity Use Monthly (Eaircompressor)"*"Electricity Cost Rate (Relec)"
Units: dollar

Air Compressor Efficiency=
0.85
Units: **undefined**

"Air Compressor Electricity Use Monthly (Eaircompressor)"=
"Air Compressor Power (Paircompressor)"*0.746*Air Compressor Operating Hours Per Day *"Working Days Per Month (Ndays/month)"*Air Compressor Efficiency/0.95
Units: kwh
0.95: air compressor motor efficiency

Air Compressor Operating Hours Per Day=
20
Units: hours

"Air Compressor Power (Paircompressor)"=
25
Units: horse power

"Aluminum (Mal)"=
2.96-Aluminum Reduction
Units: kg

Aluminum Reduction=
0.37
Units: **undefined** [0,2.96]

Aluminum Unit Price=
1.69

Units: dollar/kg

"Argon Price (Cargon rate)"=
105.17
Units: dollar/CL
1CL=250FTS

"Assembly Line Time (Tassembly line)"=
103/60
Units: hours

"Assembly Process Injury Rate (IRassembly)"=
("Effective Risk Exposure Time (Trisk assembly)"*"Working Days Per Month (Ndays/month)"
12)"Recordable Cases at Assembly Process (Nincidents bend)"/"Prior Year's Assembly Time (Tassemblysetup prior year)"
Units: **undefined**

"Assembly Process Injury Single Case Cost (Cinjury assembly single)"=
1000
Units: dollar

"Assembly Process Unit Cost (Cassembly)"=
"Labor Cost (Clabor assembly)"
Units: dollars

Avaialble Fund for Injury Coverage= INTEG (
Investment-Injury Cost Loss,
0)
Units: **undefined**

Available for Investment=
ESH Program Saving*Percentage+Fixed Investment
Units: **undefined**

"Bending Number of Setups (Nsetup bending)"=
21
Units: **undefined**

"Bending Press Unit Setup Time (Tsetup press unit)"=
4.93
Units: minute

"Bending Process Energy Cost (Cenergy bend)"=
"Setup Electricity Use (Eelec setup press)"*"Electricity Cost Rate (Relec)"
Units: dollar

"Bending Process Injury Cost (Cinjury assembly)"=
"Assembly Process Injury Rate (IRassembly)"*"Assembly Process Injury Single Case Cost (Cinjury assembly single)"
/("Monthly Throughput (Nmonthly)"
*12)
Units: dollar

"Bending Process Injury Cost (Cinjury bend)"=
"Bending Process Injury Rate (IRbend)"*"Bending Process Injury Single Case Cost (Cinjury bend single)"
/("Monthly Throughput (Nmonthly)"
*12)
Units: dollar

"Bending Process Injury Rate (IRbend)"=
("Effective Risk Exposure Time (Trisk bend)"*"Working Days Per Month (Ndays/month)"
12)"Recordable Cases at Bending Process (Nincidents bend)"/"Prior Year's Bending Setup Time (Tbendsetup prior year)"
Units: **undefined**

"Bending Process Injury Single Case Cost (Cinjury bend single)"=
1000
Units: dollar

"Bending Process Unit Cost (Cbend)"=
"Bending Process Energy Cost (Cenergy bend)"+"Labor Cost (Clabor bending)"
+"Machine Depreciation (Cmachine press)"
Units: **undefined**

Budget Implementation Delay= DELAY FIXED (
ESH Budget , 1 , 4)
Units: **undefined**

"Carbon Dioxide Equivalent CO2 eq (EIco23 qa)"=
Electricity Reductions CO2 emission factor*"QA Electricity Use (Eelec qa)"
+"QA CO2 Unit Use (Mqa co2)"/1000
Units: **undefined**

"Carbon Dioxide Equivalent CO2 eq (EIco2e bending)"=
Electricity Reductions CO2 emission factor*"Setup Electricity Use (Eelec setup press)"
Units: kg

"Carbon Dioxide Equivalent CO2 eq (EIco2e paint)"=
Electricity Reductions CO2 emission factor*"Painting Electricity Use (Eelec paint)"
Units: metric ton

"Carbon Dioxide Equivalent CO2 eq (EIco2e punch)"=
Electricity Reductions CO2 emission factor*"Operation Electricity Use (Eelec punch)"
Units: kg

"Carbon Dioxide Equivalent CO2 eq (EIco2e weld)"=
Electricity Reductions CO2 emission factor*"Welding Electricity Use (Eelec weld)"
Units: kg

"Carbon Dioxide Equivalent CO2 eq (EIco2e)"=
((Total Process Electricity Use+"Lighting Electricity Consumption Per Day (Elight shopfloor)"
*"Working Days Per Month (Ndays/month)"
/"Monthly Throughput (Nmonthly)")*Electricity Reductions CO2 emission factor
+"Natural Gas Use Per day (Eheating shopfloor)"

*"Working Days Per Month (Ndays/month)"/"Monthly Throughput (Nmonthly)"*Natural Gas CO2 emission factor
+"Air Compressor Electricity Use Monthly (Eaircompressor)"
/"Monthly Throughput (Nmonthly)"*Electricity Reductions CO2 emission factor
+"QA CO2 Unit Use (Mqa co2)"/1000)*"Monthly Throughput (Nmonthly)"
Units: metric ton

Carbon Tax Rate=
20
Units: **undefined**

"CO2 Price (Cco2 rate)"=
40.14
Units: dollar/CL
1CL=250FTS

Cold Rolled Steel Unit Price=
1.29
Units: dollar/kg

"Cold Rolled Steel Use (Mcr)"=
38.84-ColdRoll Steel Reduction Rate
Units: kg

ColdRoll Steel Reduction Rate=
9
Units: **undefined** [0,38.84]

"Control Panl&Wiring Time (Tassembly control)"=
95/60
Units: hours

Cost of Carbon Tax=
Carbon Tax Rate*"Carbon Dioxide Equivalent CO2 eq (EIco2e)"-EI Benefit/473
Units: dollars
20 is the california carbon tax rate.
http://www.cotce.ca.gov/documents/correspondence/staff_and_commis
sioners/documents/Carbon%20tax.pdf

Direct Medical Expense of Injury=
2500
Units: dollars
Data from
https://www.osha.gov/dcsp/smallbusiness/safetypays/estimator.html
Laceration, 3% profit margin Result: 18140

"Door Assembly Time (Tassembly door)"=
20/60
Units: hours

"Effective Risk Exposure Time (Trisk assembly)"=
"Assembly Line Time (Tassembly line)"+"Control Panl&Wiring Time (Tassembly control)"

+"Door Assembly Time (Tassembly door)"+"Element Assembly Time (Tassembly element)"
+"Number of Control Panle&Wiring operators (Nassembly control)"
Units: hours

"Effective Risk Exposure Time (Trisk bend)"=
"Total Setup Time (Tsetup press)"
Units: hours

"Effective Risk Exposure Time (Trisk pack)"=
"Total Operation Time (Tpackage)"
Units: hours

"Effective Risk Exposure Time (Trisk paint)"=
"Total Operation Time (Tpainting)"
Units: hours

"Effective Risk Exposure Time (Trisk qa)"=
"Total Operation Time (Tqa)"
Units: hours

"Effective Risk Exposure Time (Trisk weld)"=
"Total Operation Time (Tweld)"
Units: hours

EI and SI Benefit=
EI Benefit+SI Benefit
Units: **undefined**

EI Benefit=
IF THEN ELSE(EI Benefit Factor*ESH Practices<EI reduction limit, EI Benefit Factor
*ESH Practices , EI reduction limit)
Units: **undefined**

EI Benefit Factor=
1.837
Units: **undefined** [0,?]

EI reduction limit=
14000
Units: **undefined**
14000

"Electricity Cost Rate (Relec)"=
0.1
Units: dollar/kwh

Electricity Reductions CO2 emission factor=
0.000689551
Units: metric ton CO2/kwh
Reference:
http://www.epa.gov/cleanenergy/energy-resources/refs.html

"Element Assembly Time (Tassembly element)"=
7/60
Units: hours

ESH Budget=
Available for Investment*ESH Cost Factor*Single Unit Production Cost/Unit Production Cost Factor
Units: **undefined**

ESH Cost=
Budget Implementation Delay
Units: **undefined**

ESH Cost Factor=
0.1875
Units: **undefined** [0,1]

ESH Practice Factor=
0.125
Units: **undefined** [0,2]

ESH Practice factor 1=
24
Units: **undefined**

ESH Practices= DELAY FIXED (
ESH Practice factor 1*ESH Cost, 5 , 0)
Units: **undefined**

ESH Program Saving= INTEG (
EI and SI Benefit-ESH Cost,
0)
Units: **undefined**

FINAL TIME = 80
Units: Month
The final time for the simulation.

Fixed Investment=
8500
Units: **undefined**

Fixed Redesign Maintenance Cost=
100
Units: **undefined**

"Fossil Depletion (EIfossil depletion weld)"=
"Welding Argon Unit Use (Mweld argon)"*0.0648
Units: kg

"Fossil Depletion (EIfossil depletion)"=
"Aluminum (Mal)"/8+"Cold Rolled Steel Use (Mcr)"/9.404+"Stainless Steel Use (Msst))"
/10.0234+"Welding Argon Unit Use (Mweld argon)"/0.0648

Units: dollar

"Fringe Rate of Labor Cost (Rfringe)"=
1.35
Units: **undefined**

Gap=
IF THEN ELSE(Number of Injuries<Injury Cases Allowed for Each Month, 0 , Number of Injuries -Injury Cases Allowed for Each Month)
Units: **undefined**

Healing Rate=
DELAY FIXED(Injury Rate, 2 , 0.3)
Units: **undefined**

Healing Rate Factor=
1
Units: **undefined** [0,2]

"Heater Power (Pheater)"=
150000
Units: **undefined**

"Heaters on Time Per Day (Theat shopfloor)"=
10
Units: **undefined**

Incident=
Incident Level*PULSE TRAIN(30 , 1 , 10 , 40)
Units: **undefined**

Incident Level=
3.063
Units: **undefined**

Initial Goal for Injury=
2
Units: **undefined**

Initial Injury Rate=
INTEGER(RANDOM POISSON(0, 6 , 0.72 , 1.02 , 1.02 , 3))
Units: **undefined** [0,5]

Initial Number of Operators=
100
Units: **undefined**

INITIAL TIME = 0
Units: Month
The initial time for the simulation.

Injury Cases Allowed for Each Month= DELAY FIXED (

Initial Goal for Injury+Adjust, 2 , Initial Goal for Injury)
Units: **undefined**

Injury Cost=
Number of Injuries*"Injury Single Case Cost (Cinjury punch single)"
Units: dollars

Injury Cost Factor=
21
Units: **undefined** [0,?]

Injury Cost Loss=
Injury Rate*"Injury Single Case Cost (Cinjury punch single)"
Units: **undefined**

Injury Cost Loss Factor=
47500
Units: **undefined** [0,50000]

Injury Rate= DELAY FIXED (
Initial Injury Rate-Injury Reduction Practices+Incident
, 2 , 0.3)
Units: **undefined**

Injury Rate Factor=
100
Units: **undefined** [0,?]

Injury Reduction Practices= DELAY FIXED (
IF THEN ELSE(Gap>0, INTEGER(Gap*ESH Practice Factor+Injury Cost Loss/Injury Cost Loss Factor
+Investment/Investment on Injury Reduction Factor) , 0), 1, 0)
Units: **undefined**

"Injury Single Case Cost (Cinjury punch single)"=
Direct Medical Expense of Injury+"Operation Level Labor Cost Rate (Roperator rate)"
*(1+"Fringe Rate of Labor Cost (Rfringe)"
)*Loss of Productivity
Units: dollar

Investment=
ESH Budget*Percentage on Injury Coverage
Units: **undefined**

Investment on Injury Reduction Factor=
8500
Units: **undefined** [0,10000]
8500

"Kanban Machine Power (Ppunch kanban)"=
460*17.8
Units: watt

"Kanban Time (Tpunch kanban)"=
1105.1
Units: seconds

"Labor Cost (Clabor assembly)"=
("Door Assembly Time (Tassembly door)"*1+"Control Panl&Wiring Time (Tassembly control)"
*"Number of Control Panle&Wiring operators (Nassembly control)"
+"Element Assembly Time (Tassembly element)"*"Number of Element Operators (Nassembly element)"
+"Number of Assembly Line (Tassembly line"*"Assembly Line Time (Tassembly line)"
)*"Fringe Rate of Labor Cost (Rfringe)"*"Operation Level Labor Cost Rate (Roperator rate)"
Units: dollar

"Labor Cost (Clabor bending)"=
"Total Setup Time (Tsetup press)"*"Fringe Rate of Labor Cost (Rfringe)"*"Operation Level Labor Cost Rate (Roperator rate)"
Units: dollar

"Labor Cost (Clabor package)"=
"Total Operation Time (Tpackage)"*"Operation Level Labor Cost Rate (Roperator rate)"
"Fringe Rate of Labor Cost (Rfringe)""Number of Packaging Operators (Npackage)"
Units: dollar

"Labor Cost (Clabor paint)"=
"Total Operation Time (Tpainting)"*"Operation Level Labor Cost Rate (Roperator rate)"
"Fringe Rate of Labor Cost (Rfringe)""Number of operators (Noperator paint)"
Units: dollar

"Labor Cost (Clabor punch)"=
"Total Operation Time of Punch Process (Tlabor punch)"*"Fringe Rate of Labor Cost (Rfringe)"
*"Operation Level Labor Cost Rate (Roperator rate)"
Units: dollar

"Labor Cost (Clabor qa)"=
"Total Operation Time (Tqa)"*"Operation Level Labor Cost Rate (Roperator rate)"
"Fringe Rate of Labor Cost (Rfringe)""Number of QA Operators (Nqa)"
Units: dollar

"Labor Cost (Clabor weld)"=
"Total Operation Time (Tweld)"*"Operation Level Labor Cost Rate (Roperator rate)"
*"Fringe Rate of Labor Cost (Rfringe)"
Units: dollar

Lean Practice Factor=
0.625
Units: **undefined** [0.375,10]

Lean Practices= DELAY FIXED (
Lean Practice Factor , 5 , 0)
Units: **undefined**

"Light Power (Plight shopfloor)"=
54

Units: watt

"Light Working Length During a Day (Tlight shopfloor)"=
20
Units: hours

"Lighting Electricity Consumption Per Day (Elight shopfloor)"=
"Light Power (Plight shopfloor)"*"Light Working Length During a Day (Tlight shopfloor)" *"Number of light bulbs in the shop (Nlight shopfloor)"/1000
Units: **undefined**

Loss of Productivity=
10-Healing Rate/Healing Rate Factor+Worker Loss/Worker Loss Factor
Units: hours

Loss of Productivity Factor=
4
Units: **undefined**

"Machine Depreciation (Cmachine press)"=
("Machine Initial Cost (Imachine press)"-"Machine Salvage Value (Smachine press)")*"Machine Use (Umachine press)"
Units: dollar

"Machine Depreciation (Cmachine punch)"=
"Machine Depreciation (Cmachine punch1)"+"Machine Depreciation (Cmachine punch2)"
Units: dollar

"Machine Depreciation (Cmachine punch1)"=
("Machine Initial Cost (Imachine punch1)"-"Machine Salvage Value (Smachine punch1)")*"Machine Use (Umachine punch1)"
Units: dollar

"Machine Depreciation (Cmachine punch2)"=
("Machine Initial Cost (Imachine punch2)"-"Machine Salvage Value (Smachine punch2)")*"Machine Use (Umachine punch2)"
Units: dollar

"Machine Initial Cost (Imachine press)"=
190000
Units: dollar

"Machine Initial Cost (Imachine punch1)"=
880000
Units: dollar

"Machine Initial Cost (Imachine punch2)"=
250000
Units: dollar

"Machine Operation Power (Poperation punch)"=
460*28.6

Units: watt

"Machine Salvage Value (Smachine press)"=
13000
Units: dollar

"Machine Salvage Value (Smachine punch1)"=
130000
Units: dollar

"Machine Salvage Value (Smachine punch2)"=
100000
Units: dollar

"Machine Setup Power (Psetup press)"=
460*0.27
Units: watt

"Machine Setup Power (Psetup punch)"=
460*16.5
Units: watt

"Machine Total Service Time (Tmachine press)"=
62400
Units: hours

"Machine Total Service Time (Tmachine punch1)"=
41600
Units: hours

"Machine Total Service Time (Tmachine punch2)"=
41600
Units: hours

"Machine Use (Umachine press)"=
"Total Setup Time (Tsetup press)"/"Machine Total Service Time (Tmachine press)"
Units: **undefined**

"Machine Use (Umachine punch1)"=
("Normal Production Machining Time (Tpunch)"/3600+Punch Process Setup Time
)/"Machine Total Service Time (Tmachine punch1)"
Units: **undefined**

"Machine Use (Umachine punch2)"=
"Kanban Time (Tpunch kanban)"/3600/"Machine Total Service Time (Tmachine punch2)"
Units: **undefined**

Marine Ecotoxicity=
"N2 Use (Mn2)"*1.77e+010
Units: kg

"Marine Ecotoxicity (EI marine ecotoxity)1"= INTEG (

"N2 Use (Mn2)"/1.77e+010,
0)
Units: **undefined**

"Metal Depletion (EI metal depletion weld)"=
"Welding Argon Unit Use (Mweld argon)"*0.00165
Units: kg

"Metal Depletion (EI metal depletion)"=
"Welding Argon Unit Use (Mweld argon)"*0.00165+"Stainless Steel Use (Msst))"
/18.0972+"Aluminum (Mal)"/137.037
Units: **undefined**

Minimum Reuse Rate=
0.3
Units: **undefined** [0,1]

Minimum Setup Time=
0.23
Units: **undefined**

"Monthly Ancillary Material Cost (Cancillary)"=
2481.84
Units: **undefined**

"Monthly Building Maintenance Cost (Cbuilding maintenance)"=
297.59
Units: **undefined**

"Monthly Safety Device Cost (Csafety device)"=
709.3
Units: **undefined**

"Monthly Throughput (Nmonthly)"=
473
Units: **undefined** [360,530]

"N2 Use (Mn2)"=
76.02/30.42
Units: kg
76.02 FTS = 76.02 Cubic feet at 70F and 1 atm = 30.42kg

Natural Gas CO2 emission factor=
0.005302
Units: metric ton CO2/therm
reference:
http://www.epa.gov/cleanenergy/energy-resources/refs.html

"Natural Gas Cost Rate (Rgas)"=
0.74
Units: **undefined**

"Natural Gas Use Per day (Eheating shopfloor)"=
"Heater Power (Pheater)"*"Heaters on Time Per Day (Theat shopfloor)"*"Number of Heaters (Nheater shopfloor)"
/100000
Units: therm

"Normal Production Machining Time (Tpunch)"=
1698
Units: seconds

"Number of Assembly Line (Tassembly line"=
4
Units: **undefined**

"Number of Control Panle&Wiring operators (Nassembly control)"=
5
Units: **undefined**

"Number of Element Operators (Nassembly element)"=
2
Units: **undefined**

"Number of Heaters (Nheater shopfloor)"=
11
Units: **undefined**

Number of Injuries= INTEG (
Injury Rate-Healing Rate ,
4)
Units: Operators

"Number of light bulbs in the shop (Nlight shopfloor)"=
790
Units: **undefined**

"Number of operators (Noperator paint)"=
3
Units: **undefined**

Number of Operators Available to Work= INTEG (
Healing Rate-Worker Loss,
Initial Number of Operators)
Units: **undefined**

"Number of Packaging Operators (Npackage)"=
4
Units: **undefined**

"Number of QA Operators (Nqa)"=
1.5
Units: **undefined**

"Operation Electricity Cost (Celec punch)"=
"Electricity Cost Rate (Relec)"*"Operation Electricity Use (Eelec punch)"
Units: dollar

"Operation Electricity Use (Eelec punch)"=
"Operation Electricity Use (Eelec working punch)"+"Setup Electricity Use (Eelec setup punch)"
Units: kwh

"Operation Electricity Use (Eelec working punch)"=
"Normal Production Machining Time (Tpunch)"/3600*"Machine Operation Power (Poperation punch)"
/1000+"Kanban Machine Power (Ppunch kanban)"
/1000*"Kanban Time (Tpunch kanban)"/3600+Process Setup Time/3600*16.5*460
Units: kwh
normal production eneregy + kanban parts production

"Operation Level Labor Cost Rate (Roperator rate)"=
17.55
Units: dollar

Original Recycle Rate=
0.7
Units: **undefined** [0,1]

Packaging Material Cost=
"Paper Board Unit Price (Cpaperboard rate)"+"Plastic Bag Unit Price (Cplasticbag rate)"
+"Plastic Unit Price (Cplastic rate)"
Units: dollars

"Packaging Process Injury Cost (Cinjury pack)"=
"Packaging Process Injury Rate (IRpack)"*"Packaging Process Injury Single Case Cost (Cinjury pack single)"
/("Monthly Throughput (Nmonthly)"
*12)
Units: dollar

"Packaging Process Injury Rate (IRpack)"=
("Effective Risk Exposure Time (Trisk pack)"*"Working Days Per Month (Ndays/month)"
12)"Recordable Cases at Packaging Process (Nincidents pack)"/"Prior Year's Packaging Setup Time (Tpackaging prior year) 0"
Units: **undefined**

"Packaging Process Injury Single Case Cost (Cinjury pack single)"=
1000
Units: dollar

"Packaging Process Unit Cost (Cpackage)"=
"Labor Cost (Clabor package)"+Packaging Material Cost
Units: dollar

"Paint Cost (Cpainting paint)"=
"Paint Unit Use (Mpainting paint)"*"Paint Price (Cpaint rate)"
Units: dollar

"Paint Line Oven Power (Ppaint oven)"=
460*1.45
Units: **undefined**

"Paint Line Power (Ppaint)"=
460*12.46
Units: watt

"Paint Price (Cpaint rate)"=
4.99
Units: dollar/lb
1CL=250FTS

"Paint Unit Use (Mpainting paint)"=
3.53
Units: lb

"Painting Electricity Cost (Celec paint)"=
"Electricity Cost Rate (Relec)"*"Painting Electricity Use (Eelec paint)"
Units: **undefined**

"Painting Electricity Use (Eelec paint)"=
"Total Operation Time (Tpainting)"*"Paint Line Power (Ppaint)"/1000+25/60*
"Paint Line Oven Power (Ppaint oven)"/1000
Units: kwh
Oven time: 25min

"Painting Process Injury Cost (Cinjury paint)"=
"Painting Process Injury Rate (IRpaint)"*"Painting Process Injury Single Case Cost (Cinjury paint single)"
/("Monthly Throughput (Nmonthly)"
*12)
Units: dollar

"Painting Process Injury Rate (IRpaint)"=
("Effective Risk Exposure Time (Trisk paint)"*"Working Days Per Month (Ndays/month)"
12)"Recordable Cases at Painting Process (Nincidents paint)"/"Prior Year's Painting Time (Tpaint prior year)"
Units: **undefined**

"Painting Process Injury Single Case Cost (Cinjury paint single)"=
1000
Units: dollar

"Painting Process Unit Cost (Cpainting)"=
"Labor Cost (Clabor paint)"+"Paint Cost (Cpainting paint)"+"Painting Electricity Cost (Celec paint)"
+"Paintline Depreciation (Cpaintline)"
Units: **undefined**

"Paintline Depreciation ((Cpaintline)"=
("Paintline Initial Cost (Ipaintline)"-"Paintline Salvage Value (Spaintline)"
)/12/"Monthly Throughput (Nmonthly)"/15
Units: dollar

15 years of service life

"Paintline Depreciation (Cpaintline)"=
"Paintline Sidework Depreciation (Cpaintline sidework)"+"Paintline Depreciation ((Cpaintline)"
Units: dollar

"Paintline Initial Cost (Ipaintline)"=
800000
Units: dollar

"Paintline Salvage Value (Spaintline)"=
200000
Units: dollar

"Paintline Sidework Depreciation (Cpaintline sidework)"=
("Paintline Sidework Initial Cost (Ipaintline sidework)"-"Paintline Sidework Salvage Value (Spaintline sidework)"
)/"Monthly Throughput (Nmonthly)"
/12/20
Units: dollar
20 years of service life

"Paintline Sidework Initial Cost (Ipaintline sidework)"=
300000
Units: dollar

"Paintline Sidework Salvage Value (Spaintline sidework)"=
200000
Units: dollar

"Paper Board Unit Price (Cpaperboard rate)"=
0.36
Units: dollars

Percentage=
0.1375
Units: **undefined** [0,1]

Percentage on Injury Coverage=
0.4875
Units: **undefined** [0,1]

"Plastic Bag Unit Price (Cplasticbag rate)"=
0.13
Units: dollars

"Plastic Unit Price (Cplastic rate)"=
0.06
Units: dollars

"Prior Year Assembly Time (Tsetup assembly prioryear)"=
0.75

Units: hours

"Prior Year Bending Setup Time (Tsetup bend prioryear)"=
0.75
Units: hours

"Prior Year Packaging Setup Time (Tsetup pack prioryear)"=
0.75
Units: hours

"Prior Year Painting Time (Tsetup paint prioryear)"=
0.75
Units: hours

"Prior Year QA Setup Time (Tsetup qa prioryear)"=
0.75
Units: hours

"Prior Year Welding Setup Time (Tsetup weld prioryear)"=
0.75
Units: hours

"Prior Year's Assembly Time (Tassemblysetup prior year)"=
"Prior Year Assembly Time (Tsetup assembly prioryear)"*"Working Days Per Month (Ndays/month)"
*12
Units: **undefined**

"Prior Year's Bending Setup Time (Tbendsetup prior year)"=
"Prior Year Bending Setup Time (Tsetup bend prioryear)"*"Working Days Per Month (Ndays/month)"
*12
Units: **undefined**

"Prior Year's Packaging Setup Time (Tpackaging prior year) 0"=
"Prior Year Packaging Setup Time (Tsetup pack prioryear)"*"Working Days Per Month (Ndays/month)"
*12
Units: **undefined**

"Prior Year's Painting Time (Tpaint prior year)"=
"Prior Year Painting Time (Tsetup paint prioryear)"*"Working Days Per Month (Ndays/month)"
*12
Units: **undefined**

"Prior Year's QA Time (Tqa prior year)"=
"Prior Year QA Setup Time (Tsetup qa prioryear)"*"Working Days Per Month (Ndays/month)"
*12
Units: **undefined**

"Prior Year's Welding Setup Time (Tweldsetup prior year)"=
"Prior Year Welding Setup Time (Tsetup weld prioryear)"*"Working Days Per Month (Ndays/month)"
*12
Units: **undefined**

Process Setup Time=
2400
Units: seconds

Product Cost Reduction= DELAY FIXED (
Raw Material Cost Reduction*Production Rate, 5 , 0)
Units: **undefined**

Product Redesign Benefit= INTEG (
Product Cost Reduction-Fixed Redesign Maintenance Cost,
-Redesign One Time Investment)
Units: **undefined**

Production Rate=
15
Units: **undefined**

"Punch Process Injury Cost (Cinjury punch)"=
Punch Process Injury Rate*"Injury Single Case Cost (Cinjury punch single)"
/("Monthly Throughput (Nmonthly)"
*12)
Units: dollar

Punch Process Injury Rate= DELAY FIXED (
(1/Setup Time Factor+Lean Practices/Injury Rate Factor)/Punch Process Setup Time
, 2 , 0)
Units: **undefined**

Punch Process Setup Time= INTEG (
IF THEN ELSE(Punch Process Setup Time<Minimum Setup Time, Minimum Setup Time
, Safety Practices/1000-0.06*Lean Practices),
0.67)
Units: **undefined**

"Punch Process Unit Cost (Cpunch)"=
"Labor Cost (Clabor punch)"+"Machine Depreciation (Cmachine punch)"+"Operation Electricity Cost
(Celec punch)"
Units: dollar

"QA CO2 Cost (Cqa co2)"=
"QA CO2 Unit Use (Mqa co2)"/8.76*"CO2 Price (Cco2 rate)"/100
Units: dollar

"QA CO2 Unit Use (Mqa co2)"=
0.32
Units: Cubic feet

"QA Electricity Cost (Celec qa)"=
"Electricity Cost Rate (Relec)"*"QA Electricity Use (Eelec qa)"
Units: **undefined**

"QA Electricity Use (Eelec qa)"=

12*"QA Power (Pqa)"/1000
Units: kwh

"QA Power (Pqa)"=
120
Units: watt

"QA Process Injury Cost (Cinjury qa)"=
"QA Process Injury Rate (IRqa)"*"QA Process Injury Single Case Cost (Cinjury qa single)"
/("Monthly Throughput (Nmonthly)"
*12)
Units: dollar

"QA Process Injury Rate (IRqa)"=
("Effective Risk Exposure Time (Trisk qa)"*"Working Days Per Month (Ndays/month)"
12)"Recordable Cases at QA Process (Nincidents qa)"/"Prior Year's QA Time (Tqa prior year)"
Units: **undefined**

"QA Process Injury Single Case Cost (Cinjury qa single)"=
1000
Units: dollar

"QA Process Unit Cost (Pqa)"=
"Labor Cost (Clabor qa)"+"QA CO2 Cost (Cqa co2)"+"QA Electricity Cost (Celec qa)"
Units: dollar

"Raw Material Cost (Cmaterial)"=
1429.21+"Stainless Steel Use (Msst))"*Stainless Steel Unit Price+"Cold Rolled Steel Use (Mcr)"
*Cold Rolled Steel Unit Price
+"Aluminum (Mal)"*Aluminum Unit Price-Raw Material Cost Reduction
Units: **undefined**
BOM cost: 1766.93, subtract SST, CR, and Al cost,

Raw Material Cost Reduction=
RANDOM UNIFORM((Aluminum Reduction*Aluminum Unit Price+Cold Rolled Steel Unit Price
*ColdRoll Steel Reduction Rate
+Stainless Steel Unit Price
+Stainless Steel Reduction)*0.9, (Aluminum Reduction*Aluminum Unit Price+Cold Rolled Steel Unit
Price
*ColdRoll Steel Reduction Rate
+Stainless Steel Unit Price
+Stainless Steel Reduction)*1.1 , Aluminum Reduction*Aluminum Unit Price+Cold Rolled Steel Unit
Price
*ColdRoll Steel Reduction Rate
+Stainless Steel Unit Price
+Stainless Steel Reduction)
Units: **undefined**

"Recordable Cases at Assembly Process (Nincidents bend)"=
2
Units: **undefined**

"Recordable Cases at Bending Process (Nincidents bend)"=
2
Units: **undefined**

"Recordable Cases at Packaging Process (Nincidents pack)"=
2
Units: **undefined**

"Recordable Cases at Painting Process (Nincidents paint)"=
2
Units: **undefined**

"Recordable Cases at Punch Process (Nincidents punch)"=
2
Units: **undefined**

"Recordable Cases at QA Process (Nincidents qa)"=
2
Units: **undefined**

"Recordable Cases at Welding Process (Nincidents weld)"=
2
Units: **undefined**

Recycle=
Recycle Rate*Stainless Steel Scrap
Units: **undefined** [0,?]

Recycle Benefit1=
Recycle*Recycle Price
Units: **undefined**

Recycle Price=
1
Units: **undefined** [0,1.52]

Recycle Rate=
IF THEN ELSE(Recycle Price<Reuse Price, Original Recycle Rate-Redesign/(Redesign
+Recycle Rate factor) , Original Recycle Rate
+Redesign/(Redesign+Recycle rate factor 2))
Units: **undefined** [0,1]

Recycle Rate factor=
1700
Units: **undefined** [0,4000]

Recycle rate factor 2=
4000
Units: **undefined**

Redesign=
DELAY FIXED(Stainless Steel Scrap Money Loss, 4 , 0)

Units: **undefined** [0,?]

Redesign One Time Investment=
    2000
Units: **undefined**

Reuse=
    Stainless Steel Scrap*Reuse Rate
Units: **undefined** [0,?]

Reuse benefit=
    Reuse*Reuse Price
Units: **undefined**

Reuse Price=
    1.52
Units: **undefined** [0,1.52]

Reuse Rate=
    IF THEN ELSE(Recycle Rate<Minimum Reuse Rate, Minimum Reuse Rate, 1-Recycle Rate
)
Units: **undefined** [0,0.7]

Safety Practices=
    Punch Process Injury Rate*ESH Practice Factor+"Punch Process Injury Cost (Cinjury punch)"
*Injury Cost Factor
Units: **undefined**

SAVEPER =
    TIME STEP
Units: Month [0,?]
The frequency with which output is stored.

Scrap Cost=
    Stainless Steel Scrap*Stainless Steel Unit Price
Units: **undefined**

"Setup Electricity Use (Eelec setup press)"=
    "Total Setup Time (Tsetup press)"*"Machine Setup Power (Psetup press)"/1000
Units: **undefined**

"Setup Electricity Use (Eelec setup punch)"=
    Punch Process Setup Time*"Machine Setup Power (Psetup punch)"/1000
Units: kwh

Setup Time Factor=
    4
Units: **undefined** [0,?]

"Shopfloor Energy Cost (Cenergy shopfloor)"=
    "Shopfloor Heating Cost (Cheating shopfloor)"+"Shopfloor Lighting Cost (Clight shopfloor)"
Units: dollars

"Shopfloor Heating Cost (Cheating shopfloor)"=
"Natural Gas Cost Rate (Rgas)"*"Natural Gas Use Per day (Eheating shopfloor)"
Units: dollars/Day

"Shopfloor Lighting Cost (Clight shopfloor)"=
"Lighting Electricity Consumption Per Day (Elight shopfloor)"*"Electricity Cost Rate (Relec)"
Units: **undefined**

SI Benefit=
IF THEN ELSE(SI Benefit Factor*ESH Practices<SI Reduction Limit, ESH Practices
*SI Benefit Factor , SI Reduction Limit)
Units: **undefined**

SI Benefit Factor=
0.825
Units: **undefined**

SI Reduction Limit=
4625
Units: **undefined**

Single Unit Production Cost=
Cost of Carbon Tax/"Monthly Throughput (Nmonthly)"+"Punch Process Injury Cost (Cinjury punch)"
+"Total Manufacturing Cost (Cmanufacturing)"-Injury Cost Loss/"Monthly Throughput (Nmonthly)"
Units: **undefined**

Stainless Steel Reduction=
12
Units: **undefined** [0,85.64]

Stainless Steel Scrap=
82.6
Units: **undefined** [0,82.6]

Stainless Steel Scrap Money Loss= INTEG (
Scrap Cost-Recycle Benefit1-Reuse benefit,
0)
Units: **undefined** [0,?]

Stainless Steel Unit Price=
1.52
Units: dollar/kg [1,2]

"Stainless Steel Use (Msst))"=
85.64
Units: kg [0,?]

TIME STEP = 1
Units: Month [0,?]
The time step for the simulation.

"Total Manufacturing Cost (Cmanufacturing)"=
("Monthly Ancillary Material Cost (Cancillary)"+"Monthly Building Maintenance Cost (Cbuilding maintenance)"
+"Monthly Safety Device Cost (Csafety device)"
)/"Monthly Throughput (Nmonthly)"
+"Raw Material Cost (Cmaterial)"+"Assembly Process Unit Cost (Cassembly)"+
"Bending Process Unit Cost (Cbend)"+"Packaging Process Unit Cost (Cpackage)"
+"Painting Process Unit Cost (Cpainting)"+"Punch Process Unit Cost (Cpunch)"
+"QA Process Unit Cost (Pqa)"+"Welding Process Unit Cost (Cweld)"
+"Shopfloor Lighting Cost (Clight shopfloor)"+"Air Compressor Cost Monthly (Caircompressor)"
/"Monthly Throughput (Nmonthly)"
+"Shopfloor Heating Cost (Cheating shopfloor)"*"Working Days Per Month (Ndays/month)"
/"Monthly Throughput (Nmonthly)"+Reuse benefit+Recycle Benefit1
Units: dollar/CL

"Total Operation Time (Tpackage)"=
50/60
Units: hours

"Total Operation Time (Tpainting)"=
3
Units: hours

"Total Operation Time (Tqa)"=
0.45
Units: hours

"Total Operation Time (Tweld)"=
158.1/60
Units: hours

"Total Operation Time of Punch Process (Tlabor punch)"=
"Kanban Time (Tpunch kanban)"/3600+"Normal Production Machining Time (Tpunch)"
/3600+Loss of Productivity/Loss of Productivity Factor+Process Setup Time/3600
Units: hours

Total Process Electricity Use=
"Operation Electricity Use (Eelec punch)"+"Painting Electricity Use (Eelec paint)"
+"QA Electricity Use (Eelec qa)"+"Setup Electricity Use (Eelec setup press)"
+"Welding Electricity Use (Eelec weld)"
Units: **undefined**

"Total Setup Time (Tsetup press)"=
"Bending Number of Setups (Nsetup bending)"*"Bending Press Unit Setup Time (Tsetup press unit)"
/60
Units: hours

Unit Production Cost Factor=
3500
Units: **undefined** [0,4000]

"Welding Argon Cost (Cweld argon)"=

"Welding Argon Unit Use (Mweld argon)"/250*"Argon Price (Cargon rate)"
Units: dollar

"Welding Argon Unit Use (Mweld argon)"=
"Welding Argon Yearly Use (Margon yeartly)"/"Monthly Throughput (Nmonthly)"
/12
Units: FTS

"Welding Argon Yearly Use (Margon yeartly)"=
220627
Units: FTS

"Welding Electricity Cost (Celec weld)"=
"Electricity Cost Rate (Relec)"*"Welding Electricity Use (Eelec weld)"
Units: **undefined**

"Welding Electricity Use (Eelec weld)"=
"Total Operation Time (Tweld)"*"Welding Power (Pweld)"/1000
Units: kwh

"Welding Power (Pweld)"=
460*1.45
Units: watt

"Welding Process Injury Cost (Cinjury weld)"=
"Welding Process Injury Rate (IRweld)"*"Welding Process Injury Single Case Cost (Cinjury weld single)"
/("Monthly Throughput (Nmonthly)"
*12)
Units: dollar

"Welding Process Injury Rate (IRweld)"=
("Effective Risk Exposure Time (Trisk weld)"*"Working Days Per Month (Ndays/month)"
12)"Recordable Cases at Welding Process (Nincidents weld)"/"Prior Year's Welding Setup Time (Tweldsetup prior year)"
Units: **undefined**

"Welding Process Injury Single Case Cost (Cinjury weld single)"=
1000
Units: dollar

"Welding Process Unit Cost (Cweld)"=
"Labor Cost (Clabor weld)"+"Welding Argon Cost (Cweld argon)"+"Welding Electricity Cost (Celec weld)"
Units: **undefined**

"Welding Yearly Tool Cost (Ctool weld)"=
19125.5/"Monthly Throughput (Nmonthly)"/12
Units: **undefined**

Worker Loss=
Injury Rate
Units: **undefined**

Worker Loss Factor=
1
Units: **undefined**

"Working Days Per Month (Ndays/month)"=
17
Units: days

Appendix E. Sustainability Assessment of the Manufacturing System

Case background

The case is based on an Oregon Based laboratory equipment manufacturer which is medium size with about 200 employees. Typical products include lab using ovens, incubators, and fridges. Raw metal sheets are ordered from a steel sheets supplier and steel scraps can be recycled with cash back. The manufacturing system will be introduced in the following text with three structure levels, enterprise level, shopfloor level, and operation level. The manufacturing system consists of office area and production area. At office area, business supporting functions including marketing, purchase, product design and administration are located. At production area, there are two shops, machining shop and assembly shop. The process starts from raw metal sheets which will be firstly cut by a punch machine into a designed shape and then bended to a certain angle at a break press machine. There are three punch machines and three bending press machines with each machine operated by one operator.

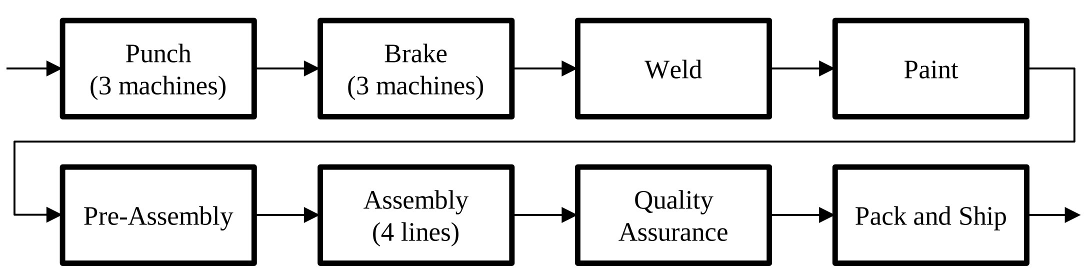


Figure 1. Manufacturing Processes of the Case Study

The Static Model and Sustainability Assessment

Cost Assessment

Operation Level

The primary operations involved in the manufacturing process are punching, bending, welding, painting, assembly, quality assurance, and packaging.

Punch The punch process cuts shaped parts of the product from cold roll or stainless steel sheets. Two series of parts are processed during the punching procedure: standard production and Kanban parts. Standard production parts are processed from raw materials at the enterprise upon receiving an order. Kanban parts are pre-processed and sent directly to punching upon receiving an order. Each part requires specific programs to be punched correctly.

Bending Process The bending process bends processed metal sheets to a certain angle. The bended metal sheets will be conveyed to welding or directly to assembly. There are three bending presses and three operators in the workcell.

Weld Process The welding process joins metal sheets together into a particular part of Model A. The welding work cell consists seven work stations, seven operators, and one supervisor. The welding process includes four sub-processes, weld, PEM, Spot weld, and grind. One operator is also responsible for distributing parts to each sub-process.

Paint Process The painting process has a paint line of 360 feet long and travels at a speed of 4 feet per minute. The operators hang all the parts that need to be painted on the line and get the parts off the line after they go through a full cycle which is usually about 90 minutes. During this process, the part will be painted and then stay in the oven to be dried for 25 minutes. The product models have multiple paint colors, but only two typical colors, white and grey. The paint changeover time is about 25 minutes. There are three operators at this process.

Assembly There are four subprocesses at assembly, pre-assembly, acid wash, door assembly, and assembly. The first three subprocesses can happen simultaneously. In the end, all the parts will be gathered to an assembly line. There are four assembly lines.

Quality Assurance Quality assurance (QA) inspects the product quality and makes sure there is no leak in the chamber and all the functins work well. CO_2 or water might be filled to the chamber depending on the product model. There is only one operator at QA.

Packaging Packaging process is the last process of the whole production process. It packs the tested product to a box, insures the product won't be damaged during shipping, and adds related product document (e.g., manual) into the package. There are four operators in this process.

There are three major cost categories at operation level, energy, labor, material machine and tool. These costs, however, are largely dependent on operation parameters (e.g., process time). Therefore, process time calculation is also provided for each process.

A detailed cost assessment of operation level processes can be found from Appendix. The cost assessment result (Exhibit 4) shows that labor cost takes the largest part of process cost, while energy takes the least portion. This indicates at the bottom level of this manufacturing system, labor cost is much larger than equipment and tools cost. Besides, process time is related to energy and labor cost, and also related to punch and bending press when unit of production depreciation is used as the depreication method. Hence, reducing process time can be a potential improvement on reducing manufacturing cost.

Exhibit 4. Cost Composition of Operation Level Manufacturing Processes.

Punch	**Cost Category**	**Percentage**	**Assembly**	**Cost Category**	**Percentage**
	Energy	2.37%		Energy	0
	Labor	59.00%		Labor	100%
	Material Tool Mcachine	38.63%		Material Tool Mcachine	0
Bend	**Cost Category**	**Percentage**	**QA**	**Cost Category**	**Percentage**
	Energy	0.05%		Energy	0.13%
	Labor	86.99%		Labor	87.32%
	Material Tool Mcachine	12.96%		Material Tool Mcachine	12.55%
Weld	**Cost Category**	**Percentage**	**Packaging**	**Cost Category**	**Percentage**
	Energy	0.21%		Energy	0
	Labor	74.96%		Labor	97.27%
	Material Tool Mcachine	24.83%		Material Tool Mcachine	2.73%
Paint	**Cost Category**	**Percentage**			
	Energy	0.60%			
	Labor	68.39%			
	Material Tool Mcachine	31.01%			

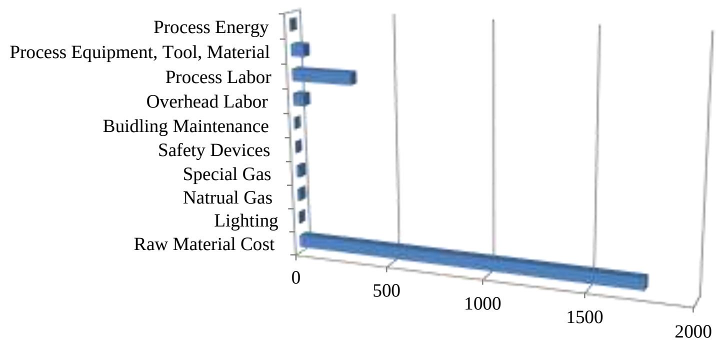
Shopfloor Level

The cost model shopfloor level structure consists raw material cost, lighting, gas consumption, special gas, safety device, building maintenance, overhead labor, process labor, Equipment, process energy. Exhibit 5 shows all the variables for shopfloor cost items.

Exhibit 5. Shopfloor Cost Model Structure Variables.

Cost Items	**Variables**	**Definitons**
Raw Material Cost	$C_{rawmaterial}$	Total raw material cost (from bill of material) for one unit of a product.
Lighting	$C_{lighting}$	Total lighting energy cost at the shopfloor, including both metal shop and assembly shop.
Natrual Gas	$C_{Naturalgas}$	Total natural gas cost
Special Gas	$C_{Specialgas}$	Total special gas cost, including, argon, N2, CO2, Oxygen, etc.
Safety Devices	$C_{Safetydevice}$	Safety device cost, e.g., eyewash, glasses, gloves, respirators, hearting protections.
Buidling Maintenance	$C_{Buildingmaintenance}$	Building maintenance cost, e.g., mat cleaning, sweep
Overhead Labor	$C_{Overheadlabor}$	Overhead labor includes part department workers, shopfloor helpers, one deburing operator, and one grinding operator.
Process Labor	$C_{Processlabor}$	Process labor include all the operators working on a specific process from punch to packaging
Process Equipment, Tool, Material	C_{PETM}	It includes equipment maintenance, process tools, and ancillary materials.
Process Energy	$C_{processenergy}$	Total energy consumption from each operation level process.

Exhibit 6. Model A shopfloor cost composition.



The shopfloor level structure includes some variables the values of which are aggregated by operation level variables. They are process labor ($C_{Processlabor}$), process equipment tool and material (C_{PETM}), and process energy ($C_{processenergy}$). Exhibit 6 shows the shopfloor structure cost composition for one unit of product model A.

The result shows that the total manufacturing (shopfloor) cost mainly comes from raw material which takes 78% of total cost. The labor cost which takes 14% of total cost, is the second largest amount contributing element, followed by process equipment tool and materials which takes about 3% of total cost.

Enterprise Level

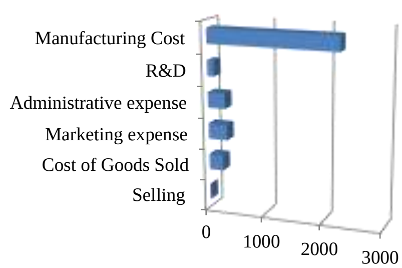
The cost model enterprise level structure consists selling, cost of goods sold, marketing expense, administrative expense, R&D, manufacturing cost, and other. Exhibit 7 shows all the variables for enterprise level structure.

Exhibit 7. Enterprise Level Cost Model Structure Variables.

Cost Items	**Variables**	**Definitons**
Selling	$C_{Selling}$	Selling costs include sales commissions, freight cost, sales tax, etc.
Cost of Goods Sold	$C_{Costofgoods}$	The direct costs attributable to the production of the goods sold by a company
Marketing expense	$C_{Marketing}$	The total cost associated with delivering goods or services to customers.
Administrative expense	$C_{Administration}$	Administrative costs are those state costs that cannot be identified with any single program (block) but are indispensable to the conduct of agency activities and to the organization's survival.
R&D	$C_{R\&D}$	Costs associated with research and design of new product development and technical support.
Manufacturing Cost	$C_{Manufacturing}$	Manufacturing cost is the sum of costs of all resources consumed in the process of making a product.

The manufacturing cost is the sum of shopfloor level costs. Exhibit 8 shows the enterprise level structure cost composition for one unit of product model A.

Exhibit 8. Model A enterprise level cost composition.



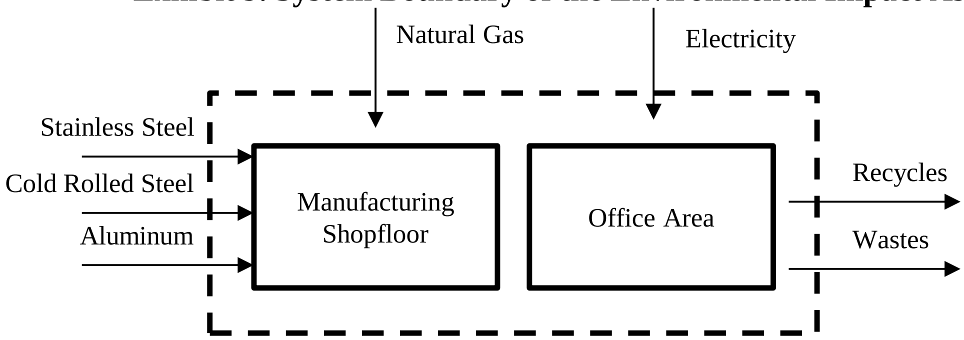
The result shows that manufacturing cost takes 69.01% of total cost of the company, followed by marketing expense, 10.08%, administrative expense 9.23%, cost of goods sold 7.6%, R&D 3.58%, and selling cost 0.41%.

4.2.2 Environmental Impact Assessment

Life cycle assessment methodology is employed to assess the environmental impact of the manufacturing system.

Goal and scope definition: The environmental impact assessment of this manufacturing system focuses on the enterprise level considering both manufacturing shopfloor and office area energy consumption and material use, which is a cradle to gate assessment. The functional unit of this study is one unit of product model A. The environmental impact is mainly from raw material use (e.g., stainless steel, aluminum, and coldrolled steel) and energy consumption from electricity use and natural gas. In this case, production consumables such as tools, screws are assumed non-significance due to their little amount of material compared with raw material use. Energy consumption includes not only both manufacturing area electricity use, natural gas use, but also office area electricity use and natural gas use. The system boundary is outline below in Exhibit 9.

Exhibit 9. System Boundary of the Environmental Impact Assessment



Life cycle inventory: As energy consumption for producing a single unit of product model A is difficult to be accurately allocated. Here we use monthly electricity and natural gas consumption measured from energy monitor as raw data which will be allocated based on monthly throughput from the manufacturing system. For example, for a certain month natural gas consumption is 6203 therm, and in the month 473 units were produced. Then the unit natural gas consumption will be 13.11 therm. Same principle applies to office electricity and shopfloor lighting electricity. Process energy was collected at each single machine when processing the assessed unit. Raw material data was retrieved from product design specifications.

Exhibit 10. Life Cycle Inventory of the Manufacturing System Environmental Impact Assessment

Category	Material	Amount	Unit
Energy	Office Electricity	0.15	kwh
	Shopfloor Electricity	61.82	kwh
	Natural Gas	13.11	therm
Material	Stainless Steel	85.64	kg
	Aluminum	2.96	kg
	Coldrolled Steel	38.84	kg
Recycle	Stainless Steel	37.48	kg

Impact assessment: The selection of indicators for environmental impact depends on the material type and assessment objective. In this case, as carbon tax can be applied to charge energy consumption, carbon dioxide equivalent is used as the indicator for energy consumption impact. Material use, however, according to ReCiPe method, results in metal depletion and fossil depletion, which will be used as indicators for environmental impact in this case.

For energy consumption, as described above, CO2E calculated based on EPA carbon dioxide equivalent calculator. The emission factors are also retrieved from EPA. For material use, Eco-invent 3.1, a widely adopted database for LCA, is used here as the database for evaluating metal depletion and fossil depletion. The impact data was calculated with ReCiPe Hierarchist perspective Endpoint method. The factors and impact values for raw material use are shown in Exhibit 11.

Exhibit 11. Environmental Impact of Energy Consumption and Raw Material Use for Product Model A

Category	Material	Amount	Unit	Impact Category	Factor	Environmental impact	Unit
Energy	Office Electricity	0.15	kwh	GWP CO2E	0.000689551	0.0001	metric tons CO2
	Shopfloor Electricity	61.82	kwh	GWP CO2E	0.000689551	0.0426	metric tons CO2
	Natural Gas	13.11	therm	GWP CO2E	0.005302	0.0695	metric tons CO2
Material	Stainless Steel	85.64	kg	Metal depletion	0.0552	4.7273	kg Fe eq/p/yr
				Fossil depletion	0.0998	8.5469	kg oil eq/p/yr
	Aluminum	2.96	kg	Metal depletion	0.0073	0.0216	kg Fe eq/p/yr
				Fossil depletion	0.1250	0.3700	kg oil eq/p/yr
	Coldrolled Steel	38.84	kg	Fossil depletion	0.1060	4.1170	kg oil eq/p/yr
Recycle	Recycled Stainless Steel	-37.48	kg	Metal depletion	0.0552	-2.0689	kg Fe eq/p/yr
				Fossil depletion	0.0998	-3.7405	kg oil eq/p/yr

Bar graphs for energy consumption CO2E, metal depletion, and fossil depletion are show in Exhibit 12, 13, and 14.

Exhibit 12. CO2E from Office electricity, Shopfloor Electricity, and Natural Gas

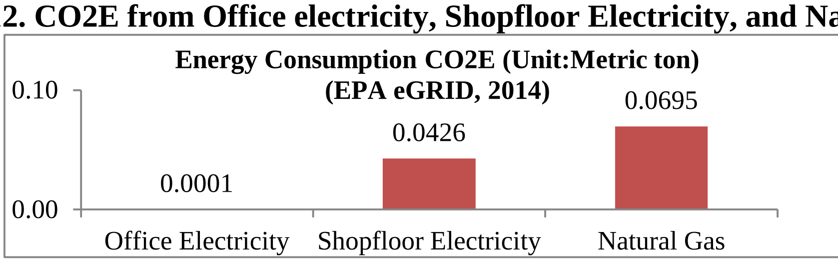


Exhibit 13. Metal Depletion Impact from Stainless Steel Aluminum, and Recycled Stainless Steel.

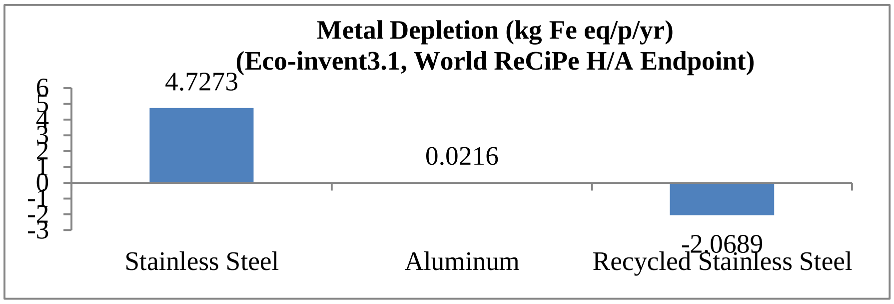
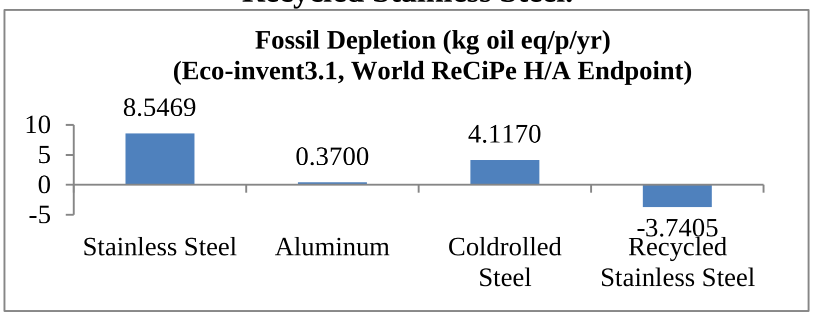


Exhibit 14. Fossil Depletion Impact from Stainless Steel, Aluminum, Coldrolled Steel, and Recycled Stainless Steel.



Interpretation: Due to the limitation of data access and the scope of this assessment, the environmental impact assessment only includes shopfloor and enterprise level total raw material use and energy consumption. Production consumables such as tools, fluids are not considered in this study, which reduces accuracy of this assessment. The result, however, managed to reflect approximate environmental impact of energy consumption and raw material use for the product. The result also shows that for producing one unit of the product, natural gas consumption generates most environmental impact compared to shopfloor electricity. Office energy consumption can be neglected due to its small amount. On metal depletion impact, stainless steel use causes almost all the impact because the amount of Aluminum use is far less than stainless steel. Moreover, the impact factor for Aluminum is also less than stainless steel. Fossil depletion is caused by the extraction process of materials from nature. The impact factor of coldrolled steel is higher than stainless steel, but as its amount is less than stainless steel, the impact value is less. Aluminum, enjoys the highest impact factor, however, it does not generate much environmental impact as a result of its small amount. From above results, stainless steel, which contributes most to the raw material cost and environmental impact should be the focus of improving design for sustainability.

Economic of Environmental impact: The monetary value of environmental impact consists of two parts, the energy consumption carbon tax and the risk cost of metal depletion impact. For the carbon tax, the tax rate is \$20/metric ton of CO2e. The value of $W_{pollution\_co2e}$ is the summation of energy consumption converted to CO2e. Then the carbon tax from consumption for producing one unit of model A is calculated as follows:

$$C_{EI\_carbontax} = W_{pollution\_co2e} * C_{taxrate\_i} = \$2.244$$

The cost of risk for environmental impact in this case does not occur as for this company there is no tax or fine related environmental impact other than CO2 emission. In order to illustrate the calculation of risk cost, a hypothetical scenario is shown based on the case manufacturer. Suppose a fine (C_{fine_ssn} = \$20,000) is given when metal depletion of stainless steel reaches a level of 10 kg oil eq/p/yr. In order to resolve this issue the company has to spend \$10,000, which is the $C_{resolving\_ssn}$. Probability is set largely depending on the case situation. If this issue is under control and is difficult to reach the fine level, the risk factor can be set as a low number (0.1). On the other hand, if this issue is difficult to control and will easily reach the fine level, the risk factor can be set as a high number (0.9). Here we will use 0 as the company does not face critical environmental impact issue. Therefore, according to equation 20, the cost of risk for violating the regulation of stainless steel metal depletion is:

$C_{EI} = C_{resolving\_ssn}$ = \$10,000 when the probability $P_{EI\_ssn} = 0$

As the risk cost for this case is hypothetical, the actual environmental impact cost is \$2.244.