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Development of a Methodology to Evaluate Environmental Implications of Lean Implementation

Pamuk Teparakul
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To the Graduate Council:

I am submitting herewith a thesis written by Pamuk Teparakul entitled "Development of a Methodology to Evaluate Environmental Implications of Lean Implementation." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Industrial Engineering.

Rapinder Sawhney, Major Professor

We have read this thesis and recommend its acceptance:

Hampton R. Liggett, Robert M. Counce

Accepted for the Council:
Dixie L. Thompson

Vice Provost and Dean of the Graduate School

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Graduate Studies

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DEVELOPMENT OF A METHODOLOGY TO EVALUATE ENVIRONMENTAL IMPLICATIONS OF LEAN IMPLEMENTATION

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Pamuk Teparakul
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ABSTRACT

While much research has confirmed the effectiveness of lean manufacturing in improving manufacturing productivity, far less work has focused on the impact of lean implementation on the different measures of environmental performance. More notably, there remains much to be understood about the complex relationship between lean manufacturing principles and their overall environmental impacts.

The purpose of this research is to develop a multi-phase methodology to assist practitioners in evaluating overall environmental impacts associated with implementation of various lean manufacturing principles. This knowledge would then allow practitioners to design and analyze manufacturing systems for both productivity and environmental concerns. A case study has also been developed to illustrate the application of this methodology for chip-forming processes using single and/or multi-point cutting tools.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

1.1 Background

Manufacturing based organizations have continuously been under pressure from competition to improve the efficiency and productivity of their manufacturing processes. The mechanisms used towards this charge have changed over time, yet there has been one consistency: all have focused on modifying the manufacturing system and its associated management. A current paradigm commonly applied by industry is Lean manufacturing. Lean manufacturing is an operational strategy oriented toward achieving continual productivity gains while satisfying the customer expectations for quality and on-time delivery. This strategy is credited for radically improving profitability, customer satisfaction, and employee morale (Arbos, 2002; Feld, 2000; EPA, 2003; Warnecke, 1995). Lean implementation may impact the type of equipment required, the number of any given equipment type, layout of the equipment, production demands on the equipment, and capability demands on the equipment.

Similarly, there has been a significant environmental push to reduce the impact of production on the environment. Some of the concepts being applied include green manufacturing, waste minimization, design for environment, life cycle analysis, green supply chain management, etc (Sarkis, 1998). Although these concepts have been around for some time, production decisions impacting the facility are in most cases made in a vacuum without considering the impact of the modification on the environmental considerations of the facility. One reason is the "functional silo" syndrome that exists in almost every manufacturing organization between production functions and the environmental functions.

Figure 1-1 represents a typical production process. Note that production personnel's current paradigm focuses on the production (horizontal) axis. That is to convert the raw material into finished goods in an efficient manner. At the same time the environmental personnel focus on the environmental (vertical) axis and the associated impact to the environment. In many organizations, environmental personnel are not well integrated into operations-based lean implementation efforts, and vice versa. As a result, environmental management activities and lean implementation efforts are conducted in a complete vacuum from the other group (Hanna et al., 2000; EPA, 2003). At one extreme it is possible that the efforts of one group completely negate the efforts of the other group (EPA, 2003).

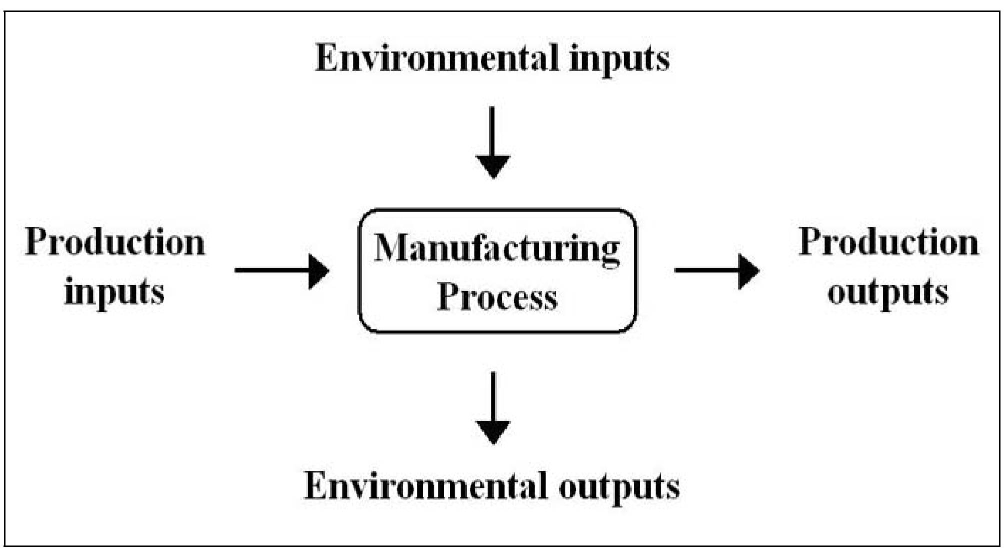

Figure 1-1: Representation of a production process

1.2 Problem Statement

Because of the aforementioned functional silo syndrome, there is a growing need for tools to assess the environmental impacts associated with lean implementation. Unfortunately, there is a lack of research on lean and the environment. Although the lean concept has been applied successfully to improve productivity, there is still much to be understood about the relationship between lean manufacturing and the environmental performance. Previous studies have been limited to exploring the relationship between a single measure of environmental performance (i.e. only energy use or toxic emissions) and one lean manufacturing principle (Bunge et al., 1996; Remmen and Lotrnyzen, 2000; Shen, 1995).

In order to design manufacturing systems for both productivity and environmental concerns, one must truly understand how the applicable production-based modifications would impact both the productivity and the environmental performance. It would therefore be useful for a concept to exist that would assist practitioners in reaching such understandings. For the scope of this research, the production-based modifications considered in this study will only include implementation of lean manufacturing principles identified in Chapter 3.

1.3 Research Objective

The research objective is to develop and illustrate a methodology for evaluating environmental implications of lean implementation. This concept would be referred to as Environmentally Lean (EN-LEAN) manufacturing. The methodology would be multiphase and multiple measures of environmental performance will be considered. The concept will allow production personnel to consider the consequences of lean manufacturing implementation on multiple environmental concerns. It will also provide them with specific ability to articulate this information. Similarly, the concept will provide environmental personnel the mechanism for a better understanding towards production.

To illustrate the application of the methodology, the methodology will be applied for a group of manufacturing processes from the taxonomy in Appendix A (Integrated Manufacturing Technology Initiative, Inc., 2003). The chip forming processes using single-point and/or multiple-point cutting tools (as shown in Appendix A) will be selected as a case study for this research since it is likely that they would have similar environmental impact. This requires the actual evaluation and collection of data from industry that utilizes the processes under consideration.

1.4 Research Organization

This thesis is organized into five chapters. Chapter 2 will review manufacturing management concepts, associated with environmental and safety improvements, available in the literature. The methodology developed for design and analysis of lean and clean manufacturing systems will be outlined in Chapter 3. Chapter 4 will present a case study to demonstrate the use of the methodology introduced in this research. Chapter 5 will provide summary, limitations of the methodology, and recommendations for future research.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In a manufacturing system, resources, such as material, energy, etc., are input and pass through manufacturing processes in which they are transformed into products. At the same time, manufacturing systems consume a great amount of resources and generate a lot of waste. The waste generated during manufacturing processes, which includes gas, liquid and solid waste, are the main source origin of environmental pollution. Therefore, it has become increasingly important to minimize the resource consumption and the environmental impact of manufacturing systems (Liu et al., 2002).

One of the reasons for growing interest in environmental issues is the changing consumer perspective (Ayres et al., 1997). The increasing environmental consciousness of the public has put industries under pressure to develop more environmentally preferable products and processes. As a result, it has become an incentive for the manufacturers to adopt environmentally friendly manufacturing management practices to gain advantage in the marketing platform against their competitors.

The manufacturers are also forced by many environmental laws and legislation to pay more attention to the environmental issues. In many countries, the environmental protection laws, regulations and tax implications are in the works or have already been passed (Gungor and Gupta, 1999). According to Frosch (1995), the development of environmental regulations in the USA has been applied in three stages since Earth Day

1970. The first stage defines restriction on the types of materials that can be discarded, as well as where and how they can be discarded. The Clean Air Act, the Clean Water Act and the Resource Conservation Act are some of the well-known laws under this stage. The second stage focuses on reducing pollution within the industrial processes with the introduction of Pollution Prevention Act of 1990. Finally, in the third stage, the aim is to promote 'clean production' with the coordination of industry and the Environmental Protection Agency (EPA).

As industries are pressured toward more sustainable practices, cost and productivity must also be put into consideration when developing products, processes and production systems. In the past, it is widely believed that improved environmental performance in the manufacturing industry was considered achievable only at the cost of other performance objectives, such as cost and quality. Hence, manufacturing plants face a difficult task of employing manufacturing management strategies that would eventually lead to improved manufacturing performance and improved environmental performance.

This chapter is organized into three remaining sections. In Section 2.2, environmental management tools are reviewed. Section 2.3 provides discussion of lean manufacturing concept. Section 2.4 discusses integrating lean components and environmental management tools, as well as the environmental impacts of lean manufacturing.

2.2 Environmental Management Tools

As a result of increasing public awareness of environmental issues and more stringent environmental regulations, a growing number of manufacturers are adopting environmentally friendly manufacturing management practices. This section examines a number of those relevant concepts, including design for environment, green manufacturing, green supply chain management, life cycle analysis, total quality environmental management, and waste minimization.

2.2.1 Design for Environment

Fiksel and Wapman (1994) defined design for environment as “the systematic consideration, during new production and process development, of design issues associated with environmental safety and health over the full product life-cycle”. The design for environment concept supports the philosophy that environmental factors need to be integrated into the early design of any product or process. The goal of design for the environment is to consider the complete product life cycle. With design for environment concepts, all stages of product life are taken into consideration, including the types of materials that are used in the manufacture of the product, the recyclable and reusable capabilities of the materials, the long term environmental impact of the materials, the efficiency of energy required to manufacture and assemble the product, the capability for easy disassembly for remanufacturing (Gungor and Gupta, 1999; Kuo et al., 2001; Sarkis, 1998).

2.2.2 Green Manufacturing

Green Manufacturing, or Environmentally Conscious Manufacturing, involves the planning, development and implementation of manufacturing processes and technology that focuses on hazardous waste minimization, scrap reduction, safer operations, and design of products that can be recycled, remanufactured or reused (Weissman and

Sekutowski, 1991). Traditionally, industrialists are more concerned about the possible adverse effects of green manufacturing implementation on their profit margins. Nonetheless, experience from Austria, Netherlands, Sweden, and the UK show that manufacturing environmentally-friendly products or services will not necessarily increase operating costs, including process cost, material cost, labor cost, production overhead and administrative expenses. On the contrary, because of more efficient use of resources, a company's operating costs can be reduced (James and Bennett, 1995). Furthermore, the adoption of green manufacturing may provide a competitive edge and other benefits for a company, as it allows a company to use raw materials, energy, or labor in a more effective way, and thereby reduces the operation costs (Hui et al., 2001). By reducing various associated costs, green manufacturing is, hence, good for both the bottom line and the environment (Freeman, 1995; Shen, 1995).

An increasing number of firms recognize that adopting green manufacturing is an integral part of the business strategy as it provides an effective guidance for companies to drive their business practices towards both corporate and environmental goals (Willig, 1994). Expected benefits of green manufacturing include safer and cleaner facilities, reduction in costs for disposal and worker protection, reduction in environmental and health risks, and improved product quality at lower cost and higher productivity.

2.2.3 Green Supply Chain Management

Green supply chain management is an assessment tool for considering the various elements of logistics planning and packaging. The basic components of green supply chain management are inbound logistics, materials management, outbound logistics, packaging, and reverse logistics issues (Sarkis, 1998).

- Inbound logistics and procurement focuses on purchasing and material delivery. The acquisition of materials includes the ability to locate and determine the existence of environmentally friendly materials and vendors.
- Materials management includes minimization of material movement and inventory management.
- Outbound logistics may be the component with the highest potential environmental impact. Outbound logistics is concerned with customer requirements and finished goods, including transportation, warehouse, and distribution planning.
- Packaging consists of primary packaging, secondary packaging, and shipping packaging. Better packaging and loading patterns can reduce materials usage, increase space utilization in the warehouse and in the trailer, and reduction in the amount of handling required.
- Reverse logistics focuses on reintegrating disposed materials and products into the manufacturing system. The major issues are collection, separation, densification, transitional processing, delivery and integration.

2.2.4 Life Cycle Analysis

Life cycle analysis is a methodology that can be used as an objective tool to identify and evaluate opportunities to reduce the environmental impacts associated with a specific product from initial raw materials extraction to final product disposal (Culaba and Purvis, 1999; Gungor and Gupta, 1999)). Society of Environmental Toxicology and

Chemistry (SETAC, 1991) has defined life cycle analysis as “an objective process to evaluate the environmental burdens associated with a product or activity by identifying and quantifying energy and materials used and releases to the environment”. Traditional applications of life-cycle assessment approaches have focused not only on the types and quantities of process inputs such as energy, raw materials, and water, but also on process outputs, such as atmospheric emissions, solid and waterborne wastes, and end product. The 4 major steps in life cycle analysis, which are commonly repeated in the literature, consist of inventory analysis, impact analysis, life-cycle costing and environmental auditing (Keoleian and Menerey, 1994; Miettinen and Hamalainen, 1997; Sarkis, 1998).

- Inventory Analysis helps identify and quantify resource use, energy use, and the environmental effects to natural resources throughout a product’s life.
- Impact Analysis helps assess the environmental consequences and risks associated with waste. It evaluates various alternatives and identifies the activities with greater and lesser environmental consequences.
- Life-Cycle Costing is a methodology in which all costs are identified for a product throughout its lifetime, from raw materials acquisition to disposal.
- Environmental Auditing is the evaluation and implementation of opportunities for environmental improvements. Environmental auditing systematically documents periodic reviews of a facility’s operations, ensuring waste minimization and pollution prevention.

The basic argument for life-cycle assessment methodologies from a manufacturing point of view is that each individual manufacturing process in an effective industrial ecosystem contributes to the optimal function of the entire system. While every process is required to minimize non-recyclable waste generation as well as to minimize material and energy consumption, individual manufacturing processes cannot be considered in isolation. A process that produces relatively large quantities of waste that may be used in other processes may be preferable to one that produces smaller amounts of waste for which there is no use. For example, a car may be made lighter for improved energy use, but the material that makes the automobile lighter is more expensive to recycle that the older material (Frosch and Gallopoulos, 1989).

2.2.5 Total Quality Environmental Management

Total quality environmental management is closely related to the elements of total quality management. Total quality management is a holistic approach to quality management, including continuous improvement, proper training and employee empowerment, appropriate incentives, quality management systems, and extensive use of statistical quality control techniques to support all this. The underlying philosophy of total quality environmental management is that many concepts used in total quality management should also apply to environmental improvement, too (Angell and Klassen, 1999).

The elements of total quality management, as suggested in Malcolm Baldrige Award, include leadership, customer focus, information and analysis, strategic planning, human resource development and quality assurance (Narashimhan and Carter, 1998). The success of total quality management programs has prompted many organizations to apply those principles to the area of environmental management. For example, Xerox was able to reduce 10,000 tons of waste, resulting in savings of $15 million annually, by instituting reuse of packaging and pallets based on a standardized design. AT&T was able to save $3 million annually by redesigning its circuit-board cleaning process that involved an elimination of chemical uses (Narashimhan and Carter, 1998).

2.2.6 Waste Minimization

Waste minimization is a policy that has specifically been mandated by the US Congress in the 1994 Hazardous and Solid Wastes Amendments of the Resource Recovery Act (RCRA), as well as Regulations from the Comprehensive Environmental Response, Compensation and Liabilities Act (CERCLA or the superfund) (Sarkis, 1995). The major emphasis in waste minimization is on pollution prevention or source reduction. Federal Pollution Prevention Act defines pollution prevention to include approaches (products, processes and technology) that will decrease in-process waste streams. It does not include any approaches that are considered 'end-of-pipe', such as waste management, recycling/reuse, and remanufacturing approaches. Practices that can be considered pollution prevention activities include material substitutions, operational improvement, alternative production processes, product reformulation, inventory control, and organization activities such as training (Sarkis, 1995).

Reduction of wastes in the waste stream is one strategy that links closely with the process and philosophies associated with some of lean manufacturing principles (Willig, 1994). The elimination of wastes and continuous improvement are basic tenets of the lean manufacturing philosophy. Mistake proofing, one of lean manufacturing principles, can help reduce scrap and defects. Reduction in scrap has a direct relationship with minimizing the waste of a system; reduction in defects, which require rework, is a more indirect relationship. That is, less rework means less energy consumption. Another overlapping principle is employee involvement. Like lean manufacturing, the participation of employee is the key to waste minimization. The greater incentives employees are given to involve in waste minimization program, the greater the chances of successful program. There are a number of lean manufacturing principles that can be used at various levels of analysis that help in the minimization of waste. Empirical studies that study the relationship between waste minimization success and lean manufacturing implementation need to be carried out.

2.3 Lean Manufacturing

In the manufacturing arena, there was the revelation of the improved performance achievable through manufacturing management concept called lean manufacturing. Studies regarding advanced manufacturing systems indicated a shift around the globe toward lean manufacturing practice, many of which centered on reducing waste in the manufacturing process (Ahlstrom, 1998; Feld, 2000). These studies suggest that lean manufacturing, which consists of a complex combination of human resource practices and technology, enables practitioners to achieve superior productivity and quality performance. There are numerous principles that organizations use to implement lean production systems. Companies typically tailor these principles to address their own unique needs and circumstances, although the principles generally remain similar. In doing so, they may develop their own terminology around the various principles (EPA, 2003). For the present study, 9 core lean principles are identified in the literature review.

Brief descriptions of these 9 lean principles are provided below (Askin and Goldberg, 2002; Feld, 2000; Irani, 1999; Ron, 1998; EPA, 2003; and Warnecke, 1995).

- **Cellular manufacturing:** An approach in which manufacturing work centers (cells) have the total capabilities needed to produce an item or group of similar items; contrasts to setting up work centers on the basis of similar equipment or capabilities, in which case items must move among multiple work centers before they are completed; the term group technology is sometimes used to distinguish cells that produce a relatively large group of similar items
- **Employee involvement and empowerment:** Lean implementation cannot be successful without employee involvement and empowerment. All innovations and improvements start with everyone in the organization becoming aware of the need for change and the role each will play in the realization of that change. The most important step is to begin by catching people's attention and raising their awareness. Employees should be assigned the responsibility for ensuring the process runs smoothly and for improving it over time. Coinciding with responsibility for achieving quality and productivity improvement goals, employees must be empowered to make changes. This includes minor investment and procedural changes to support continuous improvement, but also the authority to stop and correct a production system that is not operating properly.
- **Mistake proofing:** Mistake proofing is an effective quality assurance approach that prevents defects by catching errors and other nonstandard conditions before they actually turn into defects. The idea is to ensure zero defects by inspecting the

processing conditions for 100 percent of the work. Defects should be identified as close to the source of the defect as possible. Upon detecting a defect, production should be halted immediately and corrective action should be taken to avoid repeating that defect. Several useful mistake-proofing techniques include checklists and worker source inspection, successive check system, mistake-proof part and fixture design, integrated machine gauging, etc.

- **Product mix/variability:** The capability to produce a variety of models, that in fact differ in labor and material content, on the same production line; allows for efficient utilization of resources while providing rapid response to marketplace demands.
- **Pull Systems:** A process for production by reducing inventories; a manufacturing planning system based on communication of actual real-time needs from downstream operations ultimately final assembly or the equivalent - as opposed to a push system which schedules upstream operations according to theoretical downstream results based on a plan which may not be current.
- **Quick changeover:** A process for improving production by reducing time required to changeover a machine or process from one item or operation to the next item or operation.
- **Small lot production:** Small lot production is a technique used to manufacture products in small-lot size. The idea is to reduce lead-time and defects. Using small lot production, production problems can be discovered and addressed more quickly.

- **Supplier development:** A program in which supplier and customer share technology, risk, benefit, accountability, and collaborate fully in pursuing success.
- **Total productive maintenance:** A maintenance program that focuses on reducing variance in processor availability. The program works by taking a proactive approach to identifying key machines, and developing inspection and maintenance schedules to prevent breakdowns. The benefits of preventive maintenance are increased efficiency and longevity of equipments, reduction in frequency and duration of downtime resulting from failures, and less waste from rejected, off-specification products.

2.4 Integrating Lean Manufacturing and Environmental Management Tools

The main focus of lean manufacturing is on continually improving the productivity. Nonetheless, there are evidences that there is similarity between lean manufacturing and environmental management activities. For example, lean manufacturing systems aim at achieving zero defects, which reduced the wastes associated with reworks and scraps. Mistake proofing and employee's involvement and empowerment are essential tools to achieve this goal. These two principles are also needed in environmental management activities (Roberts and Gehrke, 1996). Although there are common tools utilized in lean manufacturing and environmental management activities, there still remains friction between lean implementation and environmental management tools.

In many organizations, environmental personnel are not well integrated into production-based lean implementation efforts. As a result, environmental personnel are not always aware of a company's lean initiatives. Similarly, operations personnel are less likely to focus on environmental benefits. Lean implementers often think of waste somewhat differently from the way environmental personnel think of waste. Consequently, lean efforts are being implemented in parallel to environmental management activities (Hanna et al., 2000; EPA, 2003).

In 1999, the National Institute of Standards and Technology's Manufacturing Extension Partnership (NIST/MEP), in collaboration with the National Environmental Policy Institute (NEPI), launched an initiative to encourage the integration of environmental management principles with lean manufacturing approaches. Key recommendations included (NEPI, 2000):

1. Increase investment in pollution prevention technical assistance and compliance assistance programs,
2. Develop partnerships between environmental agencies and manufacturing extension programs,
3. Supply chain relationships can be leveraged to encourage behavior change,
4. And the financial services sector should be engaged to increase incentives and/or responsiveness to good environmental performance.

2.4.1 Lean Manufacturing and the Environment

There has been a lack of empirical studies that investigate the relationship of lean manufacturing practice and environmental performance. Most of the available evidence on the benefits of lean production systems comes in the form of case studies and anecdotes assembled by various companies and organizations (EPA, 2003). For example, Gordon (2001) claimed that environmental management and high performance manufacturing required similar skills and resources. Therefore, plants that operate under lean manufacturing principles will have a greater ability to reduce pollution. Case studies provided by National Institute of Standards and Technology (2002) suggested environmental improvements as a result of lean implementation in several companies. Lean implementation at Hyde Manufacturing resulted in reduced hazardous waste generation by 93 percent and solid waste generation by 85 percent. At the Naugatuck Glass Company, lean implementation led to 50 percent reduction in material scrap, a 40 percent decrease in water use, and a 19 percent reduction in energy use. Howard Plating lowered volatile organic compound (VOC) emissions by 90 percent, water use by 40 percent, and energy use by 25 percent, through implementing lean.

A limitation in existing studies was that only an aspect of lean single measure of environmental performance were taken into consideration. For instance, a study in 1995 looked at the relationship between worker participation, one of the lean manufacturing principles, and reductions in reported Toxic Release Inventory [TRI] emissions (Bunge et al., 1996). This study reported that manufacturers using a certain combination of three formal employee participation practices had triple the reductions in emissions of manufacturers using none of these practices. In a study of five Danish firms, where measures of environmental performance were not utilized, within different industrial sectors, Remmen and Lorentzen (2000) found that employee participation can have a strong effect on changing work routines, affecting behavior and increasing environmental consciousness, which ultimately lead to improvement of the firms’ environmental performance. In another study, Majima (1992) argued that lean systems exhibited low inventory, relatively small production lots, and minimal buffers allowing instant feedback of problem conditions during production. As a result of fewer inconsistencies, managing waste is easier to do

On the other hand, a number of researches suggested a negative relationship between environmental performance and manufacturing performance. Bartel and Thomas (1987) argued that initial efforts to reduce pollution very often would result in some savings. Nevertheless, as environmental regulations become more stringent, costs such as new equipment investment also increase. Firms can become less economically productive as a result. Shen (1995) discussed the potential environmental impact of small lot production, one of the lean principles. He suggested that small lot production could result in more wastewater generated from the painting process, as well as more energy usage due to frequent start-over.

It should also be noted that environmental wastes (e.g., solid waste, hazardous wastes, air emissions, wastewater discharges) are not as same as the wastes identified in lean systems, such as time spent waiting, unnecessary processing, overproduction, wasted movement, inefficient use of raw materials and energy, etc. Hence, companies rarely implemented lean for environmental improvement reasons. In addition, lean implementation in environmentally sensitive manufacturing processes can be difficult and may increase environmental risk. These processes typically cause a disruption in the cellular manufacturing layout, as product components must leave the one-piece flow production cells to go in batches through the monument process (e.g., painting and coating, chemical treatment, metal finishing, etc.), before returning to the cells for continued processing (EPA, 2003).

Worker participation in environmental improvements might not be as same as participation in other performance areas. Environmental staff members were the most likely group to initiate environmental improvement projects. Because environmental outcomes could have conflicts with other performance outcome, such as cost, environmental concern might not prove sufficient motivation for employee activity. Hence, depending on the employees' knowledge and concern regarding environmental issues, worker participation might not result in better environmental performance (Hanna, 2000; Rothenburg, 1999). Moreover, Rothenburg (1999) suggested that lean manufacturing avoided the use of non-value-added abatement equipment, which might be crucial in order to decrease emissions. Hence, lean implementation would not necessary improve environmental performances.

These studies offer some evidence that environmental performance may be related to the practices of lean manufacturing principles and the superior performance associated with them. The nature of this relationship, nonetheless, remains inconclusive. Little work has been done to help explain the conflicting findings researchers have obtained. There is still much to be understood about the complex relationship between lean manufacturing system and environmental performance. One limit of the existing studies is that their measures of environmental performance are usually one dimensional in nature (i.e. only energy use or toxic emissions). In order to fully understand the relationship between lean manufacturing system and environmental performance, one must look at a variety of environmental performance metrics. This relationship could be clarified by more detailed case studies, as well as by exploration of direct links between lean production practices and different measures of environmental performance.

CHAPTER 3

METHODOLOGY

The purpose of this chapter is to present the development of the methodology for evaluating environmental implications of lean implementation. As shown in Figure 3-1 below, the methodology is decomposed into four distinct phases: basic EN-LEAN structure development, EN-LEAN matrix development, analysis of matrix, and automation. Each of these four phases is further discussed in detail below.

3.1 Basic Structure Development

The focus of this phase is to investigate the impact of lean manufacturing principles on multiple environmental issues. In order to develop the basic structure, it is necessary to first identify lean manufacturing principles and environmental issues of

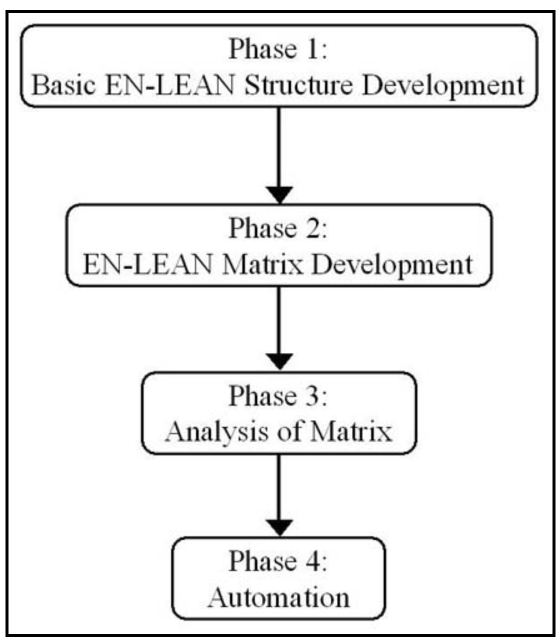

Figure 3-1: Methodology roadmap

concern. Afterward, the next step is to investigate the relationship between them. These tasks are described below.

3.1.1 Identifying Lean Manufacturing Principles

As provided in Chapter 2, a literature review was conducted to identify critical lean manufacturing principle. These lean principles would represent the vertical axis of the basic EN-LEAN structure. The list was then presented to a group of lean manufacturing experts from the Tennessee Manufacturing Extension Program (TMEP) at the University of Tennessee for verification.

3.1.2 Identifying Environmental Issues

A literature search was conducted to identify common environmental issues from a manufacturing facility, which would represent the horizontal axis of the basic structure. The results were presented to a core group of environmental practitioners and experts from TMEP for modifications and verification. Brief descriptions of each environmental issue are provided below (EPA, 1997).

- **Air pollution:** The presence of contaminants or pollutant substances in the air that interfere with human health or welfare, or produce other harmful environmental effects.
- **Energy:** Energy used in the production process.
- **Employee's health:** Contamination of the air inside production plants by noxious gases and particles of solid and liquid matter (particulate) in concentrations that endanger employee's health.

- **Employee's safety:** Risk of employee getting injured while performing their duties.
- **EPCRA:** The Emergency Planning & Community Right-To-Know Act (EPCRA) was passed to increase public knowledge of and access to information on the presence of toxic chemicals in communities, releases of toxic chemicals into the environment, and waste management activities involving toxic chemicals.
- **Hazardous waste:** Industrial waste that can pose a substantial or potential hazard to human health or the environment when improperly managed, possesses at least one of four characteristics (ignitability, corrosivity, reactivity, or toxicity), or appears on special lists created by U.S. Environmental Protection Agency.
- **LCA:** (Life Cycle Assessment) Holistic analytical technique for assessing the environmental effects associated with a product, process or activity.
- **Non hazardous waste:** Non-liquid, non-soluble industrial waste that has no hazardous characteristics or is not listed as hazardous waste by U.S. Environmental Protection Agency.
- **PBT:** Persistent, Bioaccumulative, and Toxic (PBT) Pollutants.
- **Special waste:** High volume production related waste.
- **Storm water and runoff:** Runoff from a storm event, snow melts runoff, surface runoff and drainage.
- **Toxic chemical:** Chemical that may present an unreasonable risk to the environment.
- **Universal waste:** Recyclable hazardous waste.

- **Wastewater:** The presence in water of enough harmful or objectionable material to damage the water's quality.

3.1.3 Investigating Lean and the Environment Relationship

For the present study, a set of meetings with a group of lean experts and environmental experts from TMEP was utilized as a structure to develop a fundamental initial relationship between the lean manufacturing principles and the environmental issues. The structure of the meeting was for the lean experts to present a series of scenarios around a given lean manufacturing principle. Subsequently, the environmental experts discussed the scenarios and developed a consensus on the impact of the lean manufacturing principle to each environmental category. The initial lean and the environment relationship (as presented in Appendix B) would be utilized to develop basic EN-LEAN structure in the next step.

3.1.4 Developing Basic EN-LEAN Structure

The next step was to develop the basic EN-LEAN structure from the initial lean and the environment relationship identified in the previous step. Four levels of ratings were used to record the impact: (1) positive, (2) negative, (3) either positive or negative, depending on the specifics of the application, and (4) no impact. The end product of this step is the basic EN-LEAN structure, illustrated in Table 3-1, which provides the needed conceptual understanding between lean manufacturing principles and environmental issues. This initial database serves as the knowledge base for integrating both productivity and environmental concerns in designing manufacturing facilities

Table 3-1: Basic EN-LEAN structure

Lean Manufacturing Principles	Environmental and Safety Issues												
	Air Pollution	Employee's		Energy Use	LCA	Solid Waste				Toxic Chemical		Water Pollution	
		Health	Safety			Hazardous	Non-hazardous	Special	Universal	PBT	EPCRA	Wastewater	Storm Water Runoff
Cellular Manufacturing	P	P	P	P	-	P	P	P	P	P	P	P	P
Employee's Involvement and empowerment	P/N	P/N	P/N	P/N	P/N	P/N	P/N	P/N	P/N	P/N	P/N	P/N	P/N
Mistake Proofing	P	P	P	P	-	P	P	P	P	P	P	P	P
Product Mix/ Variability	P/N	-	N	-	P	P/N	P/N	P/N	P/N	-	-	-	-
Pull Systems	P	P	P	P	P	P	P	P	P	P	P	P	P
Quick Changeover	-	P	P	P	-	P	P	P	P	P	P	P	-
Small Lot Production	N	N	-	P/N	-	P/N	P/N	P/N	P/N	P	P	N	N
Supplier Development	P/N	P/N	P/N	P/N	P/N	P/N	P/N	P/N	P/N	P/N	P/N	P/N	P/N
Total Productive Maintenance	P	P/N	P	P/N	P	P/N	P/N	P	P/N	P/N	P/N	N	P/N

Note: P = Positive impact
N = Negative impact
- = No impact
P/N= Positive or negative impact

3.2 EN-LEAN Matrix Development

The initial lean and the environment relationship at this stage is generally agreed upon by experts with an understanding that some of these relationships can change based upon the particular situation. However, it is deemed necessary to develop the basic EN-LEAN structure as a foundation for further work. For the methodology to be practical, the basic structure must be customized into EN-LEAN matrix for each specific production process group with similar environmental impacts. There are two major steps in the customization process. The first step is data collection. The second step is to develop the EN-LEAN matrix. Each of these steps is detailed below.

3.2.1 Data Collection

After establishing on which manufacturing process an EN-LEAN matrix will be developed for, the data collection process can then begin.

Although there are several data collection methods including, mail and self-administered questionnaire, telephone interview, face-to-face interview, etc. (Neuman, 1997), the recommended survey method for this study is face-to-face interview. This interviewing method is considered to be essential in order to collect data needed from the survey respondents. One of the advantages of this data collection method is that interviewer may control the sequence of questions and use contingency questions effectively. For example, depending on the answer to a first question, the interviewer may go to another question or skip certain questions. Moreover, face-to-face interview helps ensure that the survey respondents will answer all the questions alone.

3.2.1.1 Developing Interview Checklist

An interview checklist was created for guiding the interview process in a smooth, continuous and consistent manner (See the interview checklist in Appendix C). The use of Likert scales is proposed because of its simplicity and ease of use (Neuman, 1997). Each cell entry in the matrix is an integer in the range between −5 to +5, according to the scale shown in Table 3-2. The entry of + 5 indicates that *lean manufacturing principle A* has a strong positive impact on *environmental attribute 1*, for example. The advantage of this type of scoring is that a zero represents neutrality or no impact, while a negative number implies the negative impact. The matrix for each specific manufacturing process type may be completed by rating the impact of each lean manufacturing principle on each of the environmental attributes.

Asking the survey respondents to make a choice about something they know nothing about may result in an answer, but one that is unreliable and meaningless. Hence, a full-filter question should be utilized. A full-filter question is a special type of

Table 3-2: Environmental impact ratings

Rating	Environmental Impact
+ 5	Strong Positive Impact
+ 3	Moderate Positive Impact
+ 1	Weak Positive Impact
0	No Discernable Impact
– 1	Weak Negative Impact
– 3	Moderate Negative Impact
– 5	Strong Negative Impact

contingency question. It first asks if the survey respondents have an opinion, then asks for the opinion of those who state that they do have an opinion.

Using the information obtained from the interview, the EN-LEAN matrix may then be developed for the specific manufacturing process group.

The interviewer would then have a task of locating qualified respondents. The qualified respondents should be those who have knowledge of lean manufacturing as well as environmental issues associated with the manufacturing processes of interest. To identify qualified respondents, it may be necessary to seek assistance from experts from both industry and non-profit entities, who actively involve in promoting, implementing, and studying lean manufacturing systems. More discussion on identifying qualified respondent will be provided for the case study in Chapter 4.

3.2.1.2 Determining Sample Size Required

Each cell entry in the final matrix will be the mean of each cell entry obtained from the data collection process. Because the data can only be collected from a portion of the true population, interest surely focuses on the deviation between the sample mean and the population mean.

Arnold and Groeneveld (1981) proposed a method for calculating the minimum sample size (n) to ensure that the maximum deviation of the sample mean to the population mean does not exceed t in unit of population standard deviation (σ). The equation is provided below.

$$n = \frac{1}{\alpha \times t^2}$$

Where (1-α) % is the probability that the difference between the sample mean and the population mean does not exceed $t\sigma$.

Although very high probability (i.e., very low α value) and very low deviation (i.e., very low t value) are desired when calculating the necessary sample size, this can yield an unrealistically large sample size. With time and resource constraints, the smaller probability and/or an increase in deviation may need to be accepted. Table 3-3 presents the possible sample sizes for various combinations of α and t values.

3.3 Analysis of Matrix

The purpose of this phase is to provide a more rigorous methodology of evaluating and interpreting the EN-LEAN matrix. The implementation of a lean manufacturing principle may have positive impact on some environmental attributes and no impact, or negative impact, on others. The specific impact on each attribute may be dependent upon the type of manufacturing process. Thus, the determination of the overall environmental impact of a lean manufacturing principle is a multi-attribute problem.

Table 3-3: Possible sample size for various α and t values

α	t		
	0.25	0.5	1
0.01	1600	400	100
0.05	320	80	20
0.10	160	40	10
0.15	107	27	7
0.20	80	20	5

3.3.1 Developing Relative Importance Weights for Environmental Attributes

The first step to solve this multi-attribute problem is to develop the relative importance weights for each of the environmental attributes. The direct assessment approach outlined here is used in determining the weights (Canada and Sullivan, 1989).

1. Attributes are rank-ordered from most important to least important.
2. The top-ranked attribute is assigned 100 points.
3. The next highest ranked attribute is assigned points according to its importance relative to the top-ranked attribute.
4. Continue in order of importance until the lowest-ranked attribute has been assigned points.
5. Sum the points for all of the attributes.
6. Divide each attribute's points by the sum of the points for all attributes and multiply the result by 100 to obtain relative importance weights for each of the attributes, such that the sum of the relative importance weights for all attributes is equal to 100.

3.3.2 Determine Overall Environmental Impact Score

The overall environmental impact score of each lean manufacturing principle is determined by applying the weighted evaluation model. Weighted ratings are calculated by multiplying each lean manufacturing principle's impact on each environmental attribute ($R_{i,j}$) by that environmental attribute's relative importance weight (W_j). These products are then summed for each lean initiative, resulting in overall environmental impact scores (Canada and Sullivan, 1989).

$$O_i = \sum_{j=1}^{m} \left(R_{i,j} \times W_j \right)$$

Where,

O_i = Overall environmental impact score of lean manufacturing principle i

$R_{i,j}$= Rating of score of lean manufacturing principle i on environmental attribute j

W_j= Relative importance weight of environmental attribute j

The assumption that governs this equation is that attributes must be independent and non-redundant. If the assumption does not hold, transformation or adjustment to obtain new attributes is required before using the above equation (Keeney and Raifa, 1993). For example, in some surveying cases, some companies might treat sludge in batches as solid waste, while other companies might treat their sludge as wastewater. Hence, transformation to obtain new attributes would be necessary. After transformation, there would be three attributes, i.e., solid waste, wastewater, and sludge.

3.4 Automation

The EN-LEAN matrix, as presented above, requires a tedious effort to complete the analysis process. It is beneficial that computer based technology be utilized to develop an EN-LEAN model with an intelligent automated analysis process. The automated EN-LEAN model will utilize the concepts associated with expert systems to guide the end user efficiently through the analysis. Furthermore, the model will allow a greater dissemination of the knowledge required for designing and analyzing manufacturing systems.

In the present study, the automation may be based on the use of HTML and JavaScript codes. This would allow the automated EN-LEAN model greater accessibility through the Internet. An example of how the automated EN-LEAN model can be developed will be further discussed in Chapter 4.

CHAPTER 4

CASE STUDY

This chapter offers a discussion on the case study designed to provide a detailed example of how to develop the EN-LEAN model, using the methodology introduced in Chapter 3.

4.1 Introduction

As a case study for this research, an EN-LEAN matrix will be developed for a manufacturing process group with similar environmental impacts in Appendix A. This requires the actual evaluation and collection of data from industry that utilizes the processes under consideration.

For the present study, the case study would be developed for the chip forming processes using single-point and/or multiple-point cutting tools, since they are basic processes used in multiple industries.

4.2 Data Collection

Before data collection process could begin, it was necessary to identify companies appropriate for this study. This identification process was based on the recommendation made by TMEP, due to its access to a number of larger companies in East Tennessee with metal cutting operations using single-point and/or multi-point cutting tools. A request letter for permission was then created and sent out to a number of companies deemed suitable for this study by TMEP. Only companies known to have made substantial progress in implementing lean manufacturing principles were invited to participate in the study. The responsible persons in each company and TMEP identified 28 qualified survey respondents. The qualified survey respondents are defined as the individuals who possess some knowledge of lean manufacturing principles in addition to environmental issues associated with single-point and multi-point cutting operations. Each respondent would be participating in interviewing session using the interview checklist in Appendix C.

Using the equation from Section 3.2.1.2, with t value of 0.5 and sample size (n) of 28, this yields the 85.7% confidence that the deviation between the sample mean and the population mean for this study will not exceed 0.5σ, whereas σ is the population standard deviation.

The survey results for single and/or multi-point cutting operation processes are shown in Appendix E. Each cell entry in the EN-LEAN matrix, shown in Table 4-1, is then the mean environmental impacts of each lean principle on each environmental attribute.

4.3 Analysis of Matrix

To determine overall environmental impact score by using equation discussed in Section 3.3.2, it is necessary that the environmental attributes are independent. For this particular case study, information from the data collection process revealed that the environmental attributes could be classified as independent under the scope of the present study. Air emission concern was impacted by cutting fluid mist. Employees' health and safety concern was determined by machine guards, as well as eye and foot injury. Energy usage concern was determined by electricity and oil consumption. Solid waste (non-

Table 4-1: EN-LEAN matrix for single and multi-point cutting operations

	Air emissions	Employee's health & safety	Energy usage	Solid waste (non-hazardous)	Wastewater	Overall environmental impact score
Point assigned	100	100	100	100	100	
Relative importance weights	20	20	20	20	20	
Total productive maintenance	2.6	3.0	3.1	2.9	2.6	284
Mistake proofing	1.1	1.7	1.8	1.6	1.7	158
Employee's involvement and empowerment	1.1	1.8	2.3	1.5	0.9	152
Supplier development	1.2	1.4	1.5	1.9	1.4	148
Cellular manufacturing	0.1	1.3	1.4	0.4	0.4	72
Quick changeover	0.3	1.4	0.4	0.4	0.4	58
Pull systems	0.1	0.5	0.2	0.3	0.4	30
Product mix/variability	-0.1	0.1	0.0	-0.1	0.1	0
Small lot production	-0.2	-0.5	0.0	-0.1	-0.1	-18

hazardous) concern was impacted by sludge and residual product. Finally, wastewater concern was determined by spent machine oils and coolants.

The overall environmental impact score may range from –500 to +500. The implementation of any lean component, whose score is –500, would have a severely negative impact on the environmental performance of the processes. On the other hand, the implementation of lean components with the score of +500 would have a highly positive impact on the environmental performance of the processes. For those lean components that received a score of zero, their implementation would have no impact on the environmental performance of the process.

For the present case study, each of the five environmental attributes was considered to be equally important. Therefore, all five were assigned equal relative importance weights of 100 points as shown in Table 4-1. Under this circumstance, 7 out of 9 lean components received positive overall environmental impact score. Total productive maintenance received the highest overall environmental impact score of 284. Thus, implementation of total production maintenance for this case study may result in moderately better environmental performance. The implementation of three other lean components may have relatively half of the positive environmental performance impact of total production maintenance. Those three were mistake proofing, employee's health and safety, and supplier development, with the score of 158, 152, and 148, respectively. Implementation of cellular manufacturing, quick changeover, and pull systems may have relatively low positive impact on the environmental performance. These three received the score of 72, 58, and 30, respectively. Product mix/variability was the only component that received the score of zero, which implies that the implementation of the component may have no impact on the environmental performance of the processes under study. Only one lean component, which was small lot production, received negative overall environmental impact score of –18. Hence, the implementation of small lot production may have very low negative impact on the environmental performance.

The overall environmental impact scores associated with lower and upper 90 % confidence interval are shown in Figure D-1 and D-2 in Appendix D. The confidence interval values for the median were calculated using the following equations (Ott and Longnecker, 2001).

$$100(1-\alpha)\%\ \text{confidence interval} = (y_{(L_{\alpha/2})}, y_{(U_{\alpha/2})})$$
$$L_{\alpha/2} = C_{\alpha(2),n}$$
$$U_{\alpha/2} = n - C_{\alpha(2),n} + 1$$

Where,

$C_{\alpha(2),n}$ = Percentile in Table 4 from Ott and Longnecker (2001)

$L_{\alpha/2}$ = Lower 100(1-α)% confidence interval

$U_{\alpha/2}$ = Upper 100(1-α)% confidence interval

4.3.1 Sensitivity Analysis

The most critical environmental attribute can be calculated using the following equations (Triantaphyllou, 2000);

$$\mathrm{Sens}(k) = \frac{1}{\min\left\{\left|\delta'_{k,i,j}\right|\right\}}$$

$$\delta_{k,i,j} < \frac{(O_j - O_i)}{(a_{jk} - a_{ik})}, \quad \text{if}(a_{jk} > a_{ik})$$

$$\delta'_{k,i,j} = \delta_{k,i,j} \times \frac{100}{w_k}$$

Where,

Sens(k) = Sensitivity coefficient of environmental attribute k

O_j = Overall environmental impact score of lean principle j

a_{jk} = Impact score of lean principle j on environmental attribute k

$\delta_{k,i,j}$ = Minimum changes in the current importance weights of environmental attribute k such that ranking of lean principle i and j will be reversed.

$\delta'_{k,i,j}$ = Minimum changes in relative terms.

Table 4-2 and Table 4-3 present all possible $\delta_{k,i,j}$ and $\delta'_{k,i,j}$ values calculated for this case study. It should be noted that negative changes in Table 4-2 indicate increase, while positive changes indicate decreases. For example, an increase of the current weight of energy usage by 60.0% will make employee's involvement and empowerment to be ranked higher than mistake proofing. In some cases, there may not be feasible values of $\delta_{k,i,j}$ and $\delta'_{k,i,j}$. In other words, it may be impossible to reverse the existing ranking of the two alternative lean principles by making changes in the current importance weight of environmental attribute k.

The sensitivity coefficients of the five environmental attributes (air emission, employee's health and safety, energy usage, solid waste (non-hazardous), wastewater) are

Table 4-2: All possible $\delta_{k, i, j}$ values

Pair of lean principles	$\delta_{k, i, j}$				
	AE	EHS	EU	SW	WW
TPM-MP	N/F	N/F	N/F	N/F	N/F
TPM-EI	N/F	N/F	N/F	N/F	N/F
TPM-SD	N/F	N/F	N/F	N/F	N/F
TPM-CM	N/F	N/F	N/F	N/F	N/F
TPM-QC	N/F	N/F	N/F	N/F	N/F
TPM-PS	N/F	N/F	N/F	N/F	N/F
TPM-PMV	N/F	N/F	N/F	N/F	N/F
TPM-SLP	N/F	N/F	N/F	N/F	N/F
MP-EI	N/F	-60.0	-12.0	N/F	7.5
MP-SD	-100.0	N/F	N/F	-33.3	N/F
MP-CM	N/F	N/F	N/F	N/F	N/F
MP-QC	N/F	N/F	N/F	N/F	N/F
MP-PS	N/F	N/F	N/F	N/F	N/F
MP-PMV	N/F	N/F	N/F	N/F	N/F
MP-SLP	N/F	N/F	N/F	N/F	N/F
EI-SD	-40.0	10.0	5.0	-10.0	-8.0
EI-CM	N/F	N/F	N/F	N/F	N/F
EI-QC	N/F	N/F	N/F	N/F	N/F
EI-PS	N/F	N/F	N/F	N/F	N/F
EI-PMV	N/F	N/F	N/F	N/F	N/F
EI-SLP	N/F	N/F	N/F	N/F	N/F
SD-CM	N/F	N/F	N/F	N/F	N/F
SD-QC	N/F	N/F	N/F	N/F	N/F
SD-PS	N/F	N/F	N/F	N/F	N/F
SD-PMV	N/F	N/F	N/F	N/F	N/F
SD-SLP	N/F	N/F	N/F	N/F	N/F
CM-QC	-14.2	-14.1	-13.0	-14.0	-14.0
CM-PS	-42.0	-41.2	-40.8	-41.9	-42.0
CM-PMV	-71.8	-70.8	-70.6	-71.5	-71.7
CM-SLP	-89.7	-88.2	-88.6	-89.5	-89.5
QC-PS	-27.8	-27.1	-27.8	-27.9	-28.0
QC-PMV	-57.6	-56.7	-57.6	-57.5	-57.7
QC-SLP	-75.5	-74.1	-75.6	-75.5	-75.5
PS-PMV	-29.8	-29.6	-29.8	-29.6	-29.7
PS-SLP	-47.7	-47.0	-47.8	-47.6	-47.5
PMV-SLP	N/F	N/F	N/F	N/F	N/F

Note: N/F = Non-Feasible; AE = Air emissions; EHS = Employees' health and safety; EU = Energy usage; SW = Solid waste (non-hazardous); WW = Wastewater; TPM = Total productive maintenance; MP = Mistake proofing; EI = Employee's involvement and empowerment; SD = Supplier development; CM = Cellular manufacturing; QC = Quick changeover; PS = Pull systems; PMV = Product mix/variability; SLP = Small lot production

Table 4-3: All possible $\delta'_{k,i,j}$ values

Pair of lean principles	$\delta'_{k,i,j}$				
	AE	EHS	EU	SW	WW
TPM-MP	N/F	N/F	N/F	N/F	N/F
TPM-EI	N/F	N/F	N/F	N/F	N/F
TPM-SD	N/F	N/F	N/F	N/F	N/F
TPM-CM	N/F	N/F	N/F	N/F	N/F
TPM-QC	N/F	N/F	N/F	N/F	N/F
TPM-PS	N/F	N/F	N/F	N/F	N/F
TPM-PMV	N/F	N/F	N/F	N/F	N/F
TPM-SLP	N/F	N/F	N/F	N/F	N/F
MP-EI	N/F	-300.0	-60.0	N/F	37.5
MP-SD	-500.0	N/F	N/F	-166.7	N/F
MP-CM	N/F	N/F	N/F	N/F	N/F
MP-QC	N/F	N/F	N/F	N/F	N/F
MP-PS	N/F	N/F	N/F	N/F	N/F
MP-PMV	N/F	N/F	N/F	N/F	N/F
MP-SLP	N/F	N/F	N/F	N/F	N/F
EI-SD	-200.0	50.0	25.0	-50.0	-40.0
EI-CM	N/F	N/F	N/F	N/F	N/F
EI-QC	N/F	N/F	N/F	N/F	N/F
EI-PS	N/F	N/F	N/F	N/F	N/F
EI-PMV	N/F	N/F	N/F	N/F	N/F
EI-SLP	N/F	N/F	N/F	N/F	N/F
SD-CM	N/F	N/F	N/F	N/F	N/F
SD-QC	N/F	N/F	N/F	N/F	N/F
SD-PS	N/F	N/F	N/F	N/F	N/F
SD-PMV	N/F	N/F	N/F	N/F	N/F
SD-SLP	N/F	N/F	N/F	N/F	N/F
CM-QC	-71.0	-70.5	-650	-70.0	-70.0
CM-PS	-210.0	-206.0	-204.0	-209.5	-210.0
CM-PMV	-359.0	-354.0	-353.0	-357.5	-358.5
CM-SLP	-448.5	-441.0	-443.0	-447.5	-447.5
QC-PS	-139.0	-135.5	-139.0	-139.5	-140.0
QC-PMV	-288.0	-283.5	-288.0	-287.5	-288.5
QC-SLP	-377.5	-370.5	-378.0	-377.5	-377.5
PS-PMV	-149.0	-148.0	-149.0	-148.0	-148.5
PS-SLP	-238.5	-235.0	-239.0	-238.0	-237.5
PMV-SLP	N/F	N/F	N/F	N/F	N/F

Note: N/F = Non-Feasible; AE = Air emissions; EHS = Employees' health and safety; EU = Energy usage; SW = Solid waste (non-hazardous); WW = Wastewater; TPM = Total productive maintenance; MP = Mistake proofing; EI = Employee's involvement and empowerment; SD = Supplier development; CM = Cellular manufacturing; QC = Quick changeover; PS = Pull systems; PMV = Product mix/variability; SLP = Small lot production

0.0141, 0.02, 0.04, 0.02, and 0.0267 respectively. According to the calculated sensitivity coefficients, energy usage is the most sensitive environmental attribute, followed by wastewater, employee's health and safety, solid waste, and air emission. That is any change in the weight of energy usage will likely have the most effect on the existing ranking of the overall environmental scores of these 9 lean principles.

4.3.1.1 Example calculation for sensitivity analysis

Let O_j = Overall environmental impact score of employee's involvement

O_i = Overall environmental impact score of mistake proofing

a_{jk} = Impact score of employee's involvement and empowerment on wastewater

a_{ik} = Impact score of mistake proofing on wastewater

$$\delta_{k,i,j} < \frac{(152-158)}{(0.9-1.7)}$$
$$< 7.5$$
$$\delta'_{k,i,j} < 7.5 \times \frac{100}{20}$$
$$< 37.5$$

From Table 4-3, 37.5 is the minimum $\{|\delta'_{k,i,j}|\}$. Therefore,

$$\text{Sens(wastewater)} = \frac{1}{37.5}$$
$$= 0.0267$$

4.4 Automation

To make the EN-LEAN matrix developed in this case study user-friendly, computer based technology was utilized to automate the analysis process. The EN-LEAN model was developed using HTML and JavaScript codes (see Appendix E). The model can be run with Microsoft Internet Explorer or any other Internet browsers. However, the model screen is best viewed with Microsoft Internet Explorer 6.0 and with the screen resolution set at 1024*768 and above.

Figure 4-1 displays the screenshot of the automate EN-LEAN model as viewed in Microsoft Internet Explorer. Initially, all the input data fields remain empty. By clicking the default button, the default input data will then appear in the automated EN-LEAN model (see Figure 4-2).

Because practitioners may have different priority on their environmental concern, each would have to ability to assign the relative importance weights for each environmental attribute according to their interest. The users can conveniently change the relative importance weights in the ranges of 0 to 100 by clicking in the appropriated box and typing in the desired value. The new overall environmental impact score will then be calculated after clicking any other data fields in the screen. If necessary, the other cell entries in the model may also be modified in the range between –5 to +5.

4.5 Summary

In summary, for the chip-forming processes utilizing single and/or multi- point cutting tools, the result indicated that 7 out of 9 lean manufacturing principles would have low to moderate positive impact on the overall environmental concern. The most environmentally friendly of this group was total productive maintenance. Implementation of product mix/variability was considered to have no impact on the overall environmental

Figure 4-1: Screenshot of automated EN-LEAN model

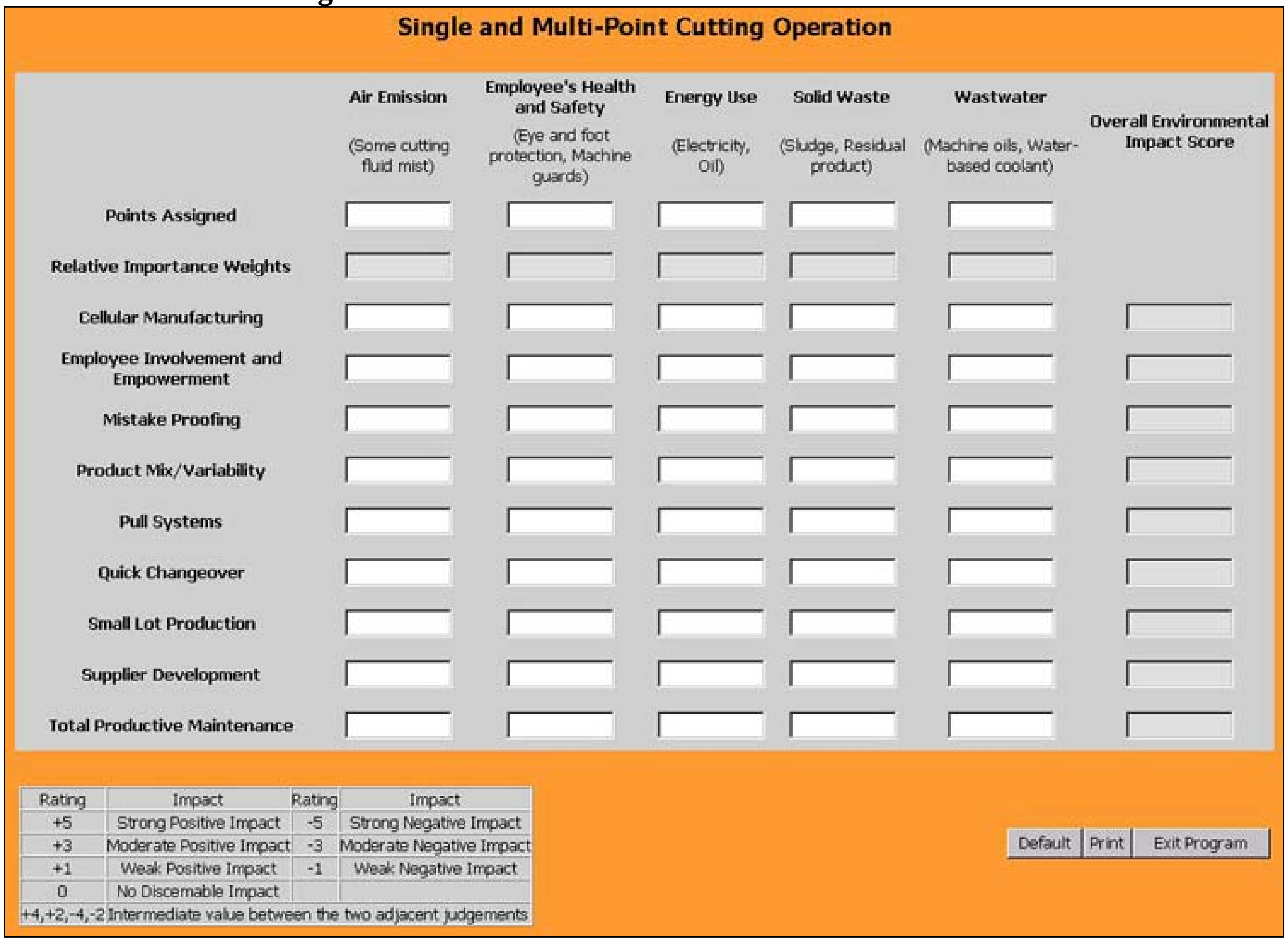

Figure 4-2: Screenshot of automated EN-LEAN model with default input data

Single and Multi-Point Cutting Operation

	Air Emission (Some cutting fluid mist)	Employee's Health and Safety (Eye and foot protection, Machine guards)	Energy Use (Electricity, Oil)	Solid Waste (Sludge, Residual product)	Wastwater (Machine oils, Water-based coolant)	Overall Environmental Impact Score
Points Assigned	100	100	100	100	100	
Relative Importance Weights	20.00	20.00	20.00	20.00	20.00	
Cellular Manufacturing	0.1	1.3	1.4	0.4	0.4	72
Employee Involvement and Empowerment	1.1	1.8	2.3	1.5	0.9	152
Mistake Proofing	1.1	1.7	1.8	1.6	1.7	158
Product Mix/Variability	-0.1	0.1	0	-0.1	0.1	0
Pull Systems	0.1	0.5	0.2	0.3	0.4	30
Quick Changeover	0.3	1.4	0.4	0.4	0.4	58
Small Lot Production	-0.2	-0.5	0	-0.1	-0.1	-18
Supplier Development	1.2	1.4	1.5	1.9	1.4	148
Total Productive Maintenance	2.6	3	3.1	2.9	2.6	284

Rating	Impact	Rating	Impact
+5	Strong Positive Impact	-5	Strong Negative Impact
+3	Moderate Positive Impact	-3	Moderate Negative Impact
+1	Weak Positive Impact	-1	Weak Negative Impact
0	No Discernable Impact		
+4,+2,-4,-2	Intermediate value between the two adjacent judgements		

Default | Print | Exit Program

concern. Only small lot production was considered to have negative impact on the overall environmental concern, albeit very low. This case study raises a point that there still remain tradeoffs between small lot production and some measures of environmental performance for the participating companies. This knowledge would have allowed practitioners to more effectively evaluate the possible environmental implications of lean implementation in their manufacturing systems.

CHAPTER 5

CONCLUSIONS

5.1 Summary

The importance of the natural environment in manufacturing practices is at a level that is unparalleled since the start of the industrial revolution. Organizations are now more aware of the natural environment as a result of regulations, legislations, competitive pressures, and a growing consumer demand for environmentally friendly products and manufacturing processes. One of the tools being applied by industry is lean manufacturing. Although the concept has been applied successfully to improve productivity, there is still much to be understood about the relationship between lean manufacturing and the environmental performance. Previous studies have been limited to exploring the relationship between a single measure of environmental performance (i.e. only energy use or toxic emissions) and one lean manufacturing principle.

This study introduced a methodology that can be used to develop the automated EN-LEAN model to aid in evaluating and analyzing environmental impacts associated with various lean manufacturing decision alternatives. Unlike previous research, the proposed methodology takes into account multiple measures of environmental performance and lean manufacturing principles. In addition, a case study was developed to illustrate the application of the proposed methodology for the chip-forming processes utilizing single and/or multi-point cutting tools.

5.2 Conclusions

The result from the case study suggests that, not all lean manufacturing principles would help improve the environmental performance for the firms participating in the present study. More specifically, this case study raises a point that there still remain tradeoffs between small lot production and some measures of environmental performance for the participating companies. The survey results showed that small lot production implementation would have weak negative impact on air emission, employee's health and safety, solid waste (non-hazardous), and wastewater. However, such implementation would have no discernable impact on energy usage. This knowledge would have allowed engineer to more effectively design and analyze their manufacturing systems for both productivity and environmental concerns.

As demonstrated in the case study, the methodology can be utilized to assess the potential environmental impacts prior to actual lean implementation. The methodology provides a useful platform for evaluating environmental implications of lean implementation that has not been delineated elsewhere. Yet, there are still many limitations of the methodology and also possible extensions.

5.3 Limitations

Using the methodology introduced in this research, an EN-LEAN matrix may only be developed for manufacturing processes, in which there is access to input data from qualified survey respondents. In a case where there is no access to reliable input data, the methodology may not be applicable.

Identifying qualified survey respondents is a challenging process since it is almost impossible to require respondents to take qualifying exam. For the case study developed in Chapter 4, the identifying process was relied on the recommendation by TMEP.

The Likert scale, used in this study, may introduce a potential danger of the response set, which is the tendency of some people to answer a large number of items in the same way out of laziness or a psychological predisposition (Neuman, 1997).

5.4 Recommendation for Further Research

Development of software and a comprehensive knowledge base may greatly enhance the use of the proposed methodology. Computer-assisted interviewing system may be utilized to expedite interview process. The system is especially valuable for contingency questions because the computer can show the questions appropriate for a participant without interviewers having to turn pages looking for the next question. The knowledge base may also include information from various case studies.

Research is also needed to develop classifications of manufacturing processes from various industries based on commonality of environmental impacts. This would allow further applications of the proposed methodology for other groups of manufacturing processes from different industries. After certain lean manufacturing components have been applied to the production processes, follow-up investigation should also be made to discover the consequential environmental performances.

The ratings of environmental impacts of lean implementation in the present study are accomplished based on subjective judgments by research participants. Therefore, incorporating methods for quantifying the environmental impact would further enhance the methodology. Allen and Shonnard (2002) described metrics for evaluating the releases of emissions and wastes from manufacturing processes.

Finally, further research is also needed to develop similar methodology that would allow engineer to understand the impact of environmentally friendly manufacturing management concepts on the productivity.

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APPENDICES

APPENDIX A: Process Taxonomy

Note: This process taxonomy is based on Integrated Manufacturing Technology Initiative, Inc. (2003). *21st Century Manufacturing Taxonomy: A Framework for Manufacturing Technology Knowledge Management*. United States of America.

1 MATERIAL PRE/POST PROCESSING

- 1.1 Liquid/Granular Separation
  - 1.1.1 Sorting
  - 1.1.2 Screening
  - 1.1.3 Sieving
- 1.2 Liquid/Granular Mixing
  - 1.2.1 Blending
  - 1.2.2 Shaking
  - 1.2.3 Turbulent Mixing
- 1.3 Thermal Processing
  - 1.3.1 Sterilization
  - 1.3.2 Radiation
  - 1.3.3 Freezing
- 1.4 Chemical Processing
  - 1.4.1 Bleaching
  - 1.4.2 Dye-Setting
  - 1.4.3 Cleansing
  - 1.4.4 Wrinkle-Proofing
- 1.5 Mechanical Processing
  - 1.5.1 Chopping/Shredding
  - 1.5.2 Beating
- 1.6 Surface Processing
  - 1.6.1 Surface Preparation
    - 1.6.1.1 Descaling
      - 1.6.1.1.1 Mechanical Descaling
        - 1.6.1.1.1.1 Abrasive Blasting
          - 1.6.1.1.1.1.1 Co2 Pellet Blasting
          - 1.6.1.1.1.1.2 Argon Pellet Blasting
          - 1.6.1.1.1.1.3 Sand Blasting
        - 1.6.1.1.1.2 Belt Sanding
        - 1.6.1.1.1.3 Shot Peen Preparation
        - 1.6.1.1.1.4 Wire Brushing
        - 1.6.1.1.1.5 Grinding
      - 1.6.1.1.2 Thermal Descaling
        - 1.6.1.1.2.1 Flame Cleaning
        - 1.6.1.1.2.2 Freezing
      - 1.6.1.1.3 Chemical Descaling
        - 1.6.1.1.3.1 Pickling
    - 1.6.1.2 Deburring
      - 1.6.1.2.1 Mechanical Deburring
        - 1.6.1.2.1.1 Abrasive-Jet Deburring

1.6.1.2.1.2 Abrasive-Flow Deburring
1.6.1.2.1.3 Barrel Tumbling
1.6.1.2.1.4 Brush Deburring
1.6.1.2.1.5 Burnish Deburring
1.6.1.2.1.6 Edge Rolling
1.6.1.2.1.7 Liquid Hone Deburring
1.6.1.2.1.8 Skiving
1.6.1.2.1.9 Spindle Finishing
1.6.1.2.1.10 Ultrasonic Deburring
1.6.1.2.1.11 Vibratory Finishing
1.6.1.2.1.12 Water-Jet Deburring
1.6.1.2.2 Knife Deburring
1.6.1.2.3 Thermal Deburring
1.6.1.2.3.1 Thermalchemical Deburring
1.6.1.2.4 Chemical Deburring
1.6.1.2.4.1 Electrochemical Deburring
1.6.1.2.4.2 Electropolish Deburring
1.6.1.2.4.3 Plasma Glow Deburring
1.6.1.3 Degreasing
1.6.1.3.1 Mechanical Degreasing
1.6.1.3.1.1 Ultrasonic Degreasing
1.6.1.3.2 Chemical Degreasing
1.6.1.3.2.1 Vapor Degreasing
1.6.1.3.2.2 Solvent Degreasing
1.6.1.3.2.3 Alkali Degreasing
1.6.2 Surface Coating
1.6.2.1 Mechanical Coating
1.6.2.1.1 Spray Coating
1.6.2.1.1.1 Air Gun Spraying
1.6.2.1.1.2 Electrostatic Coating
1.6.2.1.1.3 Flocking
1.6.2.1.2 Dip/Flow Coating
1.6.2.1.2.1 Cold Dip Coating
1.6.2.1.2.2 Hot Dip Coating
1.6.2.1.2.3 Electrocoating
1.6.2.1.2.4 Fluidized Bed Coating
1.6.2.1.2.5 Curtain Coating
1.6.2.1.2.6 Glazing
1.6.2.1.2.7 Frosting
1.6.2.1.3 Slashing
1.6.2.1.4 Dust Coating
1.6.2.1.5 Roll Coating
1.6.2.1.5.1 Calendering
1.6.2.1.5.2 Roller Coating

1.6.2.2 Thermal Coating
1.6.2.2.1 Flame Spraying
1.6.2.2.1.1 Combination Flame Spraying
1.6.2.2.1.2 Plasma Arc Spraying
1.6.2.2.1.3 Detonation Gun Spraying
1.6.2.2.2 Ion Spraying/Plating
1.6.2.2.2.1 Vacuum Metallizing
1.6.2.2.2.2 Sputtering
1.6.2.2.2.3 Chemical Vapor Phase Deposition
1.6.2.2.3 Heat Tinting
1.6.2.2.4 Glazing
1.6.2.3 Chemical Coating
1.6.2.3.1 Electroplating
1.6.2.3.2 Chemical Conversion
1.6.2.3.2.1 Anodizing
1.6.2.3.2.2 Alkaline Oxide Treatment
1.6.2.3.2.3 Fused Nitrate Treatment
1.6.2.3.2.4 Phosphate Treatment
1.6.2.3.2.5 Chromate Treatment
1.6.3 Surface Modification
1.6.3.1 Burnishing
1.6.3.2 Peening
1.6.3.2.1 Shot Peening
1.6.3.2.2 Hammer Peening
1.6.3.3 Texturing
1.6.3.4 Wire Brush Finishing
1.6.3.5 Buffing
1.6.3.6 Polishing
1.6.3.7 Corona Discharge

2 MATERIAL PRODUCT PROCESSING

2.1 Mechanical Material Reduction
2.1.1 Single Point Cutting
2.1.1.1 Single Point Thread Cutting
2.1.1.2 Turning
2.1.1.3 Facing
2.1.1.4 Boring
2.1.1.4.1 Horizontal Boring
2.1.1.4.2 Jig Boring
2.1.1.4.3 Lathe Boring
2.1.1.4.4 Precision Boring
2.1.1.4.5 Vertical Boring
2.1.1.5 Shaping
2.1.1.6 Planing
2.1.1.7 Parting

- 2.1.1.8 Grooving
- 2.1.1.9 Threading

2.1.2 Multipoint Cutting
- 2.1.2.1 Drilling
- 2.1.2.2 Reaming
- 2.1.2.3 Milling
  - 2.1.2.3.1 Arbor Milling
  - 2.1.2.3.2 End Milling
- 2.1.2.4 Routing
- 2.1.2.5 Hammer Milling
- 2.1.2.6 Broaching
- 2.1.2.7 Multipoint Threading
  - 2.1.2.7.1 Tapping
  - 2.1.2.7.2 Die Threading
  - 2.1.2.7.3 Thread Milling
- 2.1.2.8 Filing
  - 2.1.2.8.1 Band Filing
  - 2.1.2.8.2 Reciprocating Filing
- 2.1.2.9 Gear Cutting
  - 2.1.2.9.1 Gear Hobbing
  - 2.1.2.9.2 Gear Milling
- 2.1.2.10 Gear Shaping
  - 2.1.2.10.1 Band Sawing
  - 2.1.2.10.2 Circular Sawing
  - 2.1.2.10.3 Reciprocating Sawing

2.1.3 Abrasive Machining
- 2.1.3.1 Grinding
  - 2.1.3.1.1 Centerless Grinding
  - 2.1.3.1.2 Cylindrical Grinding
  - 2.1.3.1.3 Internal Grinding
  - 2.1.3.1.4 Surface Grinding
- 2.1.3.2 Crushing
  - 2.1.3.2.1 Jaw Crushers
  - 2.1.3.2.2 Gyratory Crushers
  - 2.1.3.2.3 Roll Crusher
  - 2.1.3.2.4 Impact Breakers
  - 2.1.3.2.5 Pan Crushers
  - 2.1.3.2.6 Tumbling Mills
  - 2.1.3.2.7 Nonrotary Ball or Bead Mills
  - 2.1.3.2.8 Hammer Mills
  - 2.1.3.2.9 Ring Roller Mills
  - 2.1.3.2.10 Disk Attrition Mills
  - 2.1.3.2.11 Dispersion and Colloid Mills
  - 2.1.3.2.12 Fluid-Energy or Jet Mills

            - 2.1.3.3 Honing
            - 2.1.3.4 Lapping
            - 2.1.3.5 Superfinishing
            - 2.1.3.6 Abrasive Jet Machining
            - 2.1.3.7 Abrasive Finishing
                - 2.1.3.7.1 Sandblasting
                - 2.1.3.7.2 Vibratory Finishing
        - 2.1.4 Solid Separating
            - 2.1.4.1 Slitting
            - 2.1.4.2 Nibbling
            - 2.1.4.3 Blanking
                - 2.1.4.3.1 Conventional Blanking
                - 2.1.4.3.2 Steel-Rule Die Blanking
                - 2.1.4.3.3 Fine Blanking
            - 2.1.4.4 Piercing
                - 2.1.4.4.1 Punching
                - 2.1.4.4.2 Perforating
                - 2.1.4.4.3 Lancing
                - 2.1.4.4.4 Notching
- 2.2 Thermal Reduction
    - 2.2.1 Boiling/Distillation
    - 2.2.2 Electrical Discharge Machining (EDM)
        - 2.2.2.1 Cavity-Type EDM
        - 2.2.2.2 EDM Grinding
        - 2.2.2.3 EDM Cutting
    - 2.2.3 Torch Cutting
        - 2.2.3.1 Air Carbon Arc Cutting
        - 2.2.3.2 Gas Cutting
        - 2.2.3.3 Plasma Arc Cutting
    - 2.2.4 High Energy Beam Machining
        - 2.2.4.1 Electron Beam Cutting
        - 2.2.4.2 Laser Beam Cutting
        - 2.2.4.3 Ion Beam Cutting
- 2.3 Chemical Reduction
    - 2.3.1 Chemical Milling
        - 2.3.1.1 Immersion Milling/Blanking
        - 2.3.1.2 Spray Milling
    - 2.3.2 Electrochemical Milling (ECM)
        - 2.3.2.1 Cavity-Type ECM
        - 2.3.2.2 Grinder Type ECM
    - 2.3.3 Photochemical Milling
        - 2.3.3.1 Photo Etching
        - 2.3.3.2 Photo Milling
- 2.4 Forming

- 2.4.1 Casting
    - 2.4.1.1 Nonreusable Mold
        - 2.4.1.1.1 Ceramic Mold Casting
            - 2.4.1.1.1.1 Investment Casting
            - 2.4.1.1.1.2 Plaster Mold Casting
        - 2.4.1.1.2 Sand Mold Casting
            - 2.4.1.1.2.1 Cored Sand Casting
            - 2.4.1.1.2.2 Green Sand Casting
            - 2.4.1.1.2.3 No-Bake Mold Casting
            - 2.4.1.1.2.4 Shell Mold Casting
    - 2.4.1.2 Reusable Mold
        - 2.4.1.2.1 Die Casting
        - 2.4.1.2.2 Permanent Mold Casting
        - 2.4.1.2.3 Flexible Mold Casting
        - 2.4.1.2.4 Continuous Casting
- 2.4.2 Molding
    - 2.4.2.1 Ceramic Molding
        - 2.4.2.1.1 Wet Forming
        - 2.4.2.1.2 Dry Forming
    - 2.4.2.2 Polymer Molding
        - 2.4.2.2.1 Injection Molding
        - 2.4.2.2.2 Blow Molding
        - 2.4.2.2.3 Transfer Molding
        - 2.4.2.2.4 Compression Molding
        - 2.4.2.2.5 Extrusion Molding
        - 2.4.2.2.6 Thermoform Molding
        - 2.4.2.2.7 Rotational Molding
    - 2.4.2.3 Continuous Compacting
        - 2.4.2.3.1 Powder Metallurgy Extrusion
        - 2.4.2.3.2 Powder Metallurgy Rolling
    - 2.4.2.4 Noncontinuous Compacting
        - 2.4.2.4.1 Pressing
        - 2.4.2.4.2 Centrifugal Compacting
        - 2.4.2.4.3 Explosive Compacting
        - 2.4.2.4.4 Isostatic Pressing
        - 2.4.2.4.5 Slip Casting
    - 2.4.2.5 Fiber Spinning
    - 2.4.2.6 Rotary Molding
- 2.4.3 Deposition
    - 2.4.3.1 Air Laying (Polymer Fibers)
    - 2.4.3.2 Wet Laying (Pulp Fibers)
    - 2.4.3.3 Electroforming
    - 2.4.3.4 Laminating
        - 2.4.3.4.1 Filament Winding

- 2.4.3.4.2 Sheet Laminating
- 2.4.3.4.3 Sheet Coextrusion
- 2.4.3.4.4 Bulk Laminating
  - 2.4.3.4.4.1 Spray Lay-Up
  - 2.4.3.4.4.2 Hand Lay-Up
  - 2.4.3.4.4.3 Fiber Extrusion
  - 2.4.3.4.4.4 Fiber Coextrusion
  - 2.4.3.4.4.5 Fiber Laydown (Non-Wovens)
- 2.4.3.4.5 Pultrusion

2.4.4 Compounding
- 2.4.4.1 Reacting

2.4.5 Agglomeration

2.4.6 Deformation
- 2.4.6.1 Bending
  - 2.4.6.1.1 Straight Angle Bending
  - 2.4.6.1.2 Corrugation Bending
  - 2.4.6.1.3 Joggle Bending
  - 2.4.6.1.4 Curling
  - 2.4.6.1.5 Seaming
  - 2.4.6.1.6 Tube Bending
  - 2.4.6.1.7 Roll Forming
    - 2.4.6.1.7.1 Plate Roll Bending
  - 2.4.6.1.8 Swaging
- 2.4.6.2 Upsetting
- 2.4.6.3 Folding
- 2.4.6.4 Sheet Forming
  - 2.4.6.4.1 Progressive Roll Forming
  - 2.4.6.4.2 Stretch Draw Forming
  - 2.4.6.4.3 Tube Forming
- 2.4.6.5 High Energy Rate Forming
  - 2.4.6.5.1 Explosive Forming
  - 2.4.6.5.2 Electromagnetic Forming
  - 2.4.6.5.3 Electrohydraulic Forming
- 2.4.6.6 Pulping
- 2.4.6.7 Forging
  - 2.4.6.7.1 Hot Forging
    - 2.4.6.7.1.1 Drop Forging
    - 2.4.6.7.1.2 Upset Forging
    - 2.4.6.7.1.3 Hot Press Forging
  - 2.4.6.7.2 Cold Forging
- 2.4.6.8 Extruding
  - 2.4.6.8.1 Direct Extrusion
  - 2.4.6.8.2 Indirect Extrusion
  - 2.4.6.8.3 Impact Extrusion

        - 2.4.6.8.4 Extrusion Casting (Films)
        - 2.4.6.8.5 Co-Extrusion
      - 2.4.6.9 Drawing/Pulling
        - 2.4.6.9.1 Deep Drawing
        - 2.4.6.9.2 Progressive Die Pulling
        - 2.4.6.9.3 Wire Drawing
        - 2.4.6.9.4 Tube Drawing
      - 2.4.6.10 Rolling
        - 2.4.6.10.1 Sheet Rolling
        - 2.4.6.10.2 Foil Rolling
        - 2.4.6.10.3 Structural Rolling
        - 2.4.6.10.4 Pierce Rolling
        - 2.4.6.10.5 Calendering
      - 2.4.6.11 Shear Pinning
      - 2.4.6.12 Coining/Sizing/Hobbing
        - 2.4.6.12.1 Coining
        - 2.4.6.12.2 Sizing
        - 2.4.6.12.3 Hobbing
      - 2.4.6.13 Thread Rolling
      - 2.4.6.14 Knurling
      - 2.4.6.15 Embossing
      - 2.4.6.16 Foaming
        - 2.4.6.16.1 Blowing
        - 2.4.6.16.2 Shaking
        - 2.4.6.16.3 Polymerization
        - 2.4.6.16.4 Curing
        - 2.4.6.16.5 Emulsification
        - 2.4.6.16.6 Closed Cell
        - 2.4.6.16.7 Open Cell
- 2.5 Material Rearrangement
  - 2.5.1 Spinning
  - 2.5.2 Folding
  - 2.5.3 Weaving
  - 2.5.4 Knitting
  - 2.5.5 Non-Woven/Disordered Structures
    - 2.5.5.1 Melt-Blown Fiber-Making, Non-Wovens
    - 2.5.5.2 Spun-Bond
    - 2.5.5.3 Carded
    - 2.5.5.4 Consolidation
- 2.6 Material Conveyance
  - 2.6.1 Pumping
    - 2.6.1.1 Centrifugal Pumps
    - 2.6.1.2 Propeller Pumps
    - 2.6.1.3 Turbine Pumps

2.8.4.3 Ultrafiltration
2.8.5 Field-Based Separation
2.8.5.1 Electrophoresis
2.8.5.2 Electrodialysis
2.8.5.3 Dielectrophoresis
2.8.6 Solid/Liquid Separation
2.8.6.1 Cross-Flow Filtration
2.8.6.2 Cross-Flow-Electrofiltration
2.8.6.3 Surface-Based Solid-Liquid Separations Involving Second Liquid
2.8.7 Absorptive Bubble
2.8.8 Diffusional Separation
2.8.8.1 Gaseous Diffusion
2.8.8.2 Thermal Diffusion
2.8.8.3 Pressure Diffusion
2.8.8.4 Mass Diffusion
2.9 Extraction
2.9.1 Liquid/Liquid
2.9.1.1 Mixer-Settler
2.9.1.2 Single Drop Immersion
2.9.1.3 Continuous/ Differential Contacting
2.9.1.3.1 Axial Dispersion
2.9.1.3.2 Spray Towers
2.9.1.3.3 Packed Towers
2.9.1.3.4 Perforated Plate (Sieve Plate) Towers
2.9.1.3.5 Mechanically Agitated Gravity Assist
2.9.1.3.6 Centrifugal Extractors
2.9.2 Solid/Solid
2.9.2.1 Mixing
2.9.2.2 Sampling
2.9.2.2.1 Dry Sampling
2.9.2.2.2 Slurry Sampling
2.9.2.3 Screening
2.9.2.4 Wet Classification
2.9.2.4.1 Non-Mechanical Classifiers
2.9.2.4.1.1 Cone Classifiers
2.9.2.4.1.2 Liquid Cyclone Classifiers
2.9.2.4.2 Mechanical Classifiers
2.9.2.4.2.1 Drag Classifiers
2.9.2.4.2.2 Rake and Spiral Classifiers
2.9.2.4.2.3 Bowl Classifiers
2.9.2.4.2.4 Bowl Desilter
2.9.2.4.2.5 Hydroseparation
2.9.2.4.2.6 Solid-Bowl Centrifuges
2.9.2.4.2.7 Countercurrent Classifiers

        2.9.2.4.3 Hydraulic Classifiers
    2.9.2.5 Jigging
    2.9.2.6 Tabling
    2.9.2.7 Spiral Concentration
    2.9.2.8 Dense Media Separation
    2.9.2.9 Magnetic Separation
    2.9.2.10 Electrostatic Separation
    2.9.2.11 Flotation
    2.9.2.12 Ultrafine Solid Separation
        2.9.2.12.1 Ultraflotation
        2.9.2.12.2 Selective Flocculation
        2.9.2.12.3 Immiscible Liquid Separation
        2.9.2.12.4 Dialectric Separation
        2.9.2.12.5 Eletrophoretic Separation
    2.9.2.13 Automatic Sorting
        2.9.2.13.1 Optical Sorting
        2.9.2.13.2 Electrical Conductivity Sorting
2.9.3 Liquid/Solid
    2.9.3.1 Agitation
    2.9.3.2 Mixing
    2.9.3.3 Crystallization
    2.9.3.4 Ion Exchange
    2.9.3.5 Sorption
    2.9.3.6 Gravity Sedimentation
    2.9.3.7 Filtration
    2.9.3.8 Centrifuge
2.9.4 Gas/Solid
    2.9.4.1 Fluidized Bed
    2.9.4.2 Gravity Settling
    2.9.4.3 Impingement Separation
    2.9.4.4 Cyclone Separation
    2.9.4.5 Mechanical Centrifugal Separation
    2.9.4.6 Particulate Scrubbing
    2.9.4.7 Granular Bed Filtering
    2.9.4.8 Filtering
    2.9.4.9 Electrical Precipitation
2.9.5 Gas/Liquid
    2.9.5.1 Gas-Liquid Contacting
    2.9.5.2 Phase Dispersion
    2.9.5.3 Phase Separation
2.9.6 Absorption
2.9.7 Adsorption
2.9.8 Ion Exchange
2.9.9 Particle Diffusion

- 2.10 Thermal Processing
  - 2.10.1 Annealing
    - 2.10.1.1 Recovery
      - 2.10.1.1.1 Stress Relieving
      - 2.10.1.1.2 Tempering
    - 2.10.1.2 Recrystallization
      - 2.10.1.2.1 Full Annealing
    - 2.10.1.2.2 Process Annealing
      - 2.10.1.2.3 Short Cycle Annealing
  - 2.10.2 Hardening
    - 2.10.2.1 Surface Hardening
      - 2.10.2.1.1 Carburizing
      - 2.10.2.1.2 Chromizing
      - 2.10.2.1.3 Carbonitriding
      - 2.10.2.1.4 Cyaniding
      - 2.10.2.1.5 Diffusion Hardening
      - 2.10.2.1.6 Flame Hardening
      - 2.10.2.1.7 Induction Hardening
      - 2.10.2.1.8 Peening
    - 2.10.2.2 Through Hardening
      - 2.10.2.2.1 Water Quench Hardening
      - 2.10.2.2.2 Oil Quench Hardening
      - 2.10.2.2.3 Air Quench Hardening
      - 2.10.2.2.4 Martempering
      - 2.10.2.2.5 Austempering
      - 2.10.2.2.6 Age Hardening
  - 2.10.3 Sintering
    - 2.10.3.1 Solid Phase Sintering
    - 2.10.3.2 Liquid Phase Sintering
  - 2.10.4 Heat removal
    - 2.10.4.1 Chilling
    - 2.10.4.2 Freeze drying
    - 2.10.4.3 Freeze concentration
    - 2.10.4.4 Frosting
  - 2.10.5 Firing
  - 2.10.6 Heated Chamber Processing
    - 2.10.6.1 Curing
    - 2.10.6.2 Baking
    - 2.10.6.3 Roasting
    - 2.10.6.4 Broiling
  - 2.10.7 Frying
    - 2.10.7.1 Deep Frying
    - 2.10.7.2 Surface Frying
  - 2.10.8 Liquid Bath Processing

- 2.10.8.1 Blanching
- 2.10.8.2 Boiling
- 2.10.8.3 Steaming

2.10.9 Sanitization and Sterilization
2.10.10 Heat Exchange
2.10.11 Evaporation

2.11 Material Transformation

- 2.11.1 Drying
- 2.11.2 Crystallization
- 2.11.3 Distillation
- 2.11.4 Leaching
- 2.11.5 Fractionation
- 2.11.6 Catalytic Processing
  - 2.11.6.1 Homogeneous Catalysis
  - 2.11.6.2 Heterogeneous Catalysis
- 2.11.7 Chemical transformations
- 2.11.8 Photochemical Processing
  - 2.11.8.1 Photolithography
- 2.11.9 Electrochemical Processing
- 2.11.10 Biochemical Processing
  - 2.11.10.1 Fermentation
  - 2.11.10.2 Enzymatic Reactions
  - 2.11.10.3 Photosynthesis
- 2.11.11 Phase Transformation
- 2.11.12 Hydrogenation
- 2.11.13 Homogenization
- 2.11.14 Hardening/Hydrogenation/Saturating
- 2.11.15 Distillation
  - 2.11.15.1 Extractive Distillation
  - 2.11.15.2 Azeotropic Distillation
  - 2.11.15.3 Batch Distillation
  - 2.11.15.4 Dynamic Distillation
- 2.11.16 Water Purification
  - 2.11.16.1 Reverse Osmosis
  - 2.11.16.2 Ion Exchange
- 2.11.17 Fluid Bed Reactors
- 2.11.18 Chromatographic Separation
- 2.11.19 Falling Film Reactors
- 2.11.20 Wiped Film Evaporators
- 2.11.21 Refrigeration and Freezing
- 2.11.22 Tempering
- 2.11.23 Curing
- 2.11.24 Degassing
- 2.11.25 Quenching

- 2.11.26 Oxidation
- 2.11.27 Hydrobromination
- 2.11.28 Cryogenic Collection
- 2.11.29 Sublimation
- 2.11.30 Supercritical Separation Processing
- 2.11.31 Neutralization
- 2.11.32 Processing of Non-Newtonian Fluids or Non-Ideal Materials
- 2.11.33 Viscoplastic and Viscoelastic Solids
- 2.11.34 Embossing
- 2.11.35 Activation

2.12 Biomechanical Processing
- 2.12.1 DNA Tools
- 2.12.2 Viral/Bacterial Tools

2.13 Electronics
- 2.13.1 Materials and Substrates
  - 2.13.1.1 Metal Disposition
  - 2.13.1.2 Sequential Disposition
  - 2.13.1.3 Sputtering Thin Film Disposition
  - 2.13.1.4 Conformal Coatings
  - 2.13.1.5 Chemical Techniques
    - 2.13.1.5.1 Plating
    - 2.13.1.5.2 Etching
- 2.13.2 Semiconductors
  - 2.13.2.1 Via Formation
  - 2.13.2.2 Fine Line Formation
  - 2.13.2.3 Lithography
  - 2.13.2.4 Micro-Machined
  - 2.13.2.5 Micro-Vacuum
  - 2.13.2.6 Multiplayer Mask Technology
  - 2.13.2.7 Shallow Junction Processes
    - 2.13.2.7.1 Ion Implantation
    - 2.13.2.7.2 Plasma Doping
    - 2.13.2.7.3 P Gild
  - 2.13.2.8 Non-Hazardous Water Cleaning
  - 2.13.2.9 Cyanide-Free Plating
- 2.13.3 Electronic Packaging and Interconnections
  - 2.13.3.1 Plasma
  - 2.13.3.2 Adhesives
  - 2.13.3.3 Embedded Discretes
  - 2.13.3.4 Super Plastic Forming
  - 2.13.3.5 Metallic Fired Glass Fritz
  - 2.13.3.6 Hole Formation
    - 2.13.3.6.1 Drilling
    - 2.13.3.6.2 Punching

2.13.3.6.3 Lasers
2.13.3.6.4 Etching
2.13.4 Optics
2.13.4.1 Precision Electronically Steerable Light Sources
2.13.4.2 Solid-State Lasers
2.13.4.2.1 Red
2.13.4.2.2 Blue
2.13.4.2.3 Green
2.13.4.3 Lasers
2.13.4.3.1 Fixed
2.13.4.3.2 Scan
2.13.4.3.3 Point to Point
2.13.5 Displays
2.13.5.1 Metal Disposition
2.13.5.2 Etching
2.13.5.3 Cleaning
2.13.5.4 Polymer Coating
2.13.5.5 Photo Lithography
2.13.5.6 High-Resolution Printing
2.13.5.7 Glass Plate Alignment and Sealing
2.13.5.8 Spacer Application
2.13.5.9 Vacuum Sealing
2.13.5.10 Alignment Rubbing
2.13.5.11 Glass Scribe and Separation
2.13.5.12 Liquid Crystal Filling
2.13.5.13 Polarizer Laminates
2.13.5.14 Thermo Curing

3 ASSEMBLY

3.1 High-Speed Assembly
3.1.1 Cutting
3.1.2 Perforation
3.1.3 Bonding
3.1.4 Combining
3.2 Mechanical Joining
3.2.1 Sewing
3.2.2 Folding-Joining
3.2.2.1 Folding-Gluing
3.2.2.2 Stitched Joining
3.2.2.3 Gluing
3.2.2.4 Flexo Folder Gluing
3.2.3 Press/Snap Fit
3.2.3.1 Fastening
3.2.3.2 Riveting
3.2.3.3 Staking

3.2.3.4 Wiring/Connecting
3.2.4 Pressure (Cold) Welding
3.2.5 Friction (Inertial) Welding
3.2.6 Ultrasonic Welding
3.2.7 Ultrasonic Bonding of Films/Solids
3.2.8 RF bonding
3.2.9 Explosive Welding
3.3 Thermal Joining
3.3.1 Thermal Welding
3.3.1.1 Electric Arc Welding
3.3.1.1.1 Shielded Metal Arc Welding
3.3.1.1.2 Gas Metal Arc Welding
3.3.1.1.3 Gas Tungsten Arc Welding
3.3.1.1.4 Submerged Arc Welding
3.3.1.1.5 Carbon Arc Welding
3.3.1.1.6 Stud Arc Welding
3.3.1.2 Electrical Resistance Welding
3.3.1.2.1 Spot Welding
3.3.1.2.2 Seam Welding
3.3.1.2.3 Projection Welding
3.3.1.2.4 Butt Welding
3.3.1.2.5 Percussion Welding
3.3.1.2.6 Electroslag Welding
3.3.1.3 Gas/Chemical Welding
3.3.1.3.1 Combustible Gas Welding
3.3.1.4 Atomic Hydrogen Welding
3.3.1.5 Braze Welding
3.3.1.5.1 Gas Brazing
3.3.1.5.2 Carbon Arc Brazing
3.3.1.6 Diffusion Bonding
3.3.1.7 High Energy Beam Welding
3.3.1.7.1 Electron Beam Welding
3.3.1.7.2 Laser Beam Welding
3.3.1.7.3 Plasma Arc Welding
3.3.2 Brazing
3.3.2.1 Infrared Brazing
3.3.2.2 Resistance Brazing
3.3.2.3 Torch Brazing
3.3.2.4 Dip Brazing
3.3.2.5 Furnace Brazing
3.3.2.6 Induction Brazing
3.3.3 Soldering
3.3.3.1 Friction Soldering
3.3.3.1.1 Ultrasonic Soldering

        3.3.3.2 Induction Soldering
        3.3.3.3 Infrared Soldering
        3.3.3.4 Dip Soldering
        3.3.3.5 Iron Soldering
        3.3.3.6 Resistance Soldering
        3.3.3.7 Torch Soldering
        3.3.3.8 Wave Soldering
        3.3.3.9 Laser Soldering
3.4 Chemical Joining
    3.4.1 Adhesive Bonding
        3.4.1.1 Gluing
    3.4.2 Stress Curing
    3.4.3 Wetting
    3.4.4 Mixing
    3.4.5 Crystallization
    3.4.6 Agglomeration
3.5 Filling
    3.5.1 Gravity Fill
    3.5.2 Force Fill
    3.5.3 Foam Fill
3.6 Electronics Assembly
    3.6.1 Electronic Packaging and Interconnections
        3.6.1.1 Chip Packaging
        3.6.1.2 Single-Chip Packaging
        3.6.1.3 Multichip Packaging
        3.6.1.4 On-Chip Interconnect
        3.6.1.5 Chip-to-Package
        3.6.1.6 Package-to-Board
        3.6.1.7 Flip Chip
        3.6.1.8 Wafer Chip Bumping
        3.6.1.9 Ball Gate Array
        3.6.1.10 Laser/Fiber Alignment
    3.6.2 Printed Circuit Board Assembly
        3.6.2.1 Through Hole
        3.6.2.2 Surface Mount
        3.6.2.3 Mixed Technology
        3.6.3 Hybrid Assembly
        3.6.3.1 Wire Bonding
        3.6.4 Wiring
        3.6.4.1 Cables
        3.6.4.2 Harnesses
        3.6.4.3 Point to Point

APPENDIX B: Lean and the Environment Relationship

Table B-1: Environmental impact of cellular manufacturing

Cellular Manufacturing	Positive Impact	Negative Impact
Air Pollution	Higher machine efficiency.	-
Wastewater	Reduction in leaks and spills during material transfer	-
Storm Water Runoff	Reduction in leaks and spills during material transfer between outdoor workstations.	-
Hazardous Waste	Reduction in leaks and spills during material transfer	-
Universal Waste		-
Special Waste		-
Non-hazardous Waste		-
Employee's Heath	Less exposure to leaks and spills during material transfer	-
Employee's Safety	Shorter walking distance. Less injury risk due to better plant layouts.	-
Toxic Chemical	Reduction in leaks and spills during material transfer	-
LCA	-	-
Energy	Higher machine efficiency.	

Table B-2: Environmental impact of employee's involvement and empowerment

Employee's Involvement	Positive Impact	Negative Impact
Air Pollution	Employee contribute by offering ideas on how to reduce all types of environmental impacts from production processes and getting involve in implementation of those plans.	Employee doesn't know or care about environment.
Wastewater		
Storm Water Runoff		
Hazardous Waste		
Universal Waste		
Special Waste		
Non-hazardous Waste		
Employee's Heath		
Employee's Safety		
Toxic Chemical		
LCA		
Energy		

Table B-3: Environmental impact of mistake proofing

Mistake Proofing	Positive Impact	Negative Impact
Air Pollution	Less machine uptimes.	-
Wastewater		-
Storm Water Runoff		-
Hazardous Waste	Less wastes associated with defects	-
Universal Waste		-
Special Waste		-
Non-hazardous Waste		-
Employee's Heath	Less machine uptimes.	-
Employee's Safety		-
Toxic Chemical	Less wastes associated with defects	-
LCA	Longer machine life	-
Energy	Less machine uptimes.	-

Table B-4: Environmental impact of product mix/variability

Product Mix/Variability	Positive Impact	Negative Impact
Air Pollution	Maybe positive or negative depending on setup	
Wastewater	-	-
Storm Water Runoff	-	-
Hazardous Waste	Maybe positive or negative depending on setup	
Universal Waste		
Special Waste		
Non-hazardous Waste		
Employee's Heath	-	-
Employee's Safety	-	Can't use automation due to product mix.
Toxic Chemical	-	-
LCA	Easier to implement reuse and recycle program.	-
Energy	-	-

Table B-5: Environmental impact of pull systems

Pull Systems	Positive Impact	Negative Impact
Air Pollution	Less air emission due to reduction of excess work-in-progress, reworks and scraps.	-
Wastewater	Less wastewater due reduction of excess work-in-progress, reworks and scraps.	-
Storm Water Runoff	Less runoff due to less reworks and scraps for outside operation.	-
Hazardous Waste	Less waste due to reduction of excess work-in-progress, reworks, and scraps.	-
Universal Waste		-
Special Waste		-
Non-hazardous Waste		-
Employee's Heath	Less exposure to pollution due to reduction of excess work-in-progress, reworks and scraps.	-
Employee's Safety	Less overproduction.	-
Toxic Chemical	Less waste due to reduction of excess work-in-progress, reworks and scraps.	-
LCA	Less obsolete materials and products.	-
Energy	Less inventory cost from heating and cooling	-

Table B-6: Environmental impact of quick changeover

Quick Changeover	Positive Impact	Negative Impact
Air Pollution	-	-
Wastewater	Less waste associated with setup procedures such as spills and leaks.	-
Storm Water Runoff	-	-
Hazardous Waste	Less waste associated with setup procedures such as spills and leaks.	-
Universal Waste		-
Special Waste		-
Non-hazardous Waste		-
Employee's Heath	Less exposure to wastes associated with setup procedures such as spills and leaks.	-
Employee's Safety	Less risk of injury due to shorter and simpler setup procedures.	-
Toxic Chemical	Less waste associated with setup procedures such as spills and leaks.	-
LCA	-	-
Energy	Less energy use for setup.	-

Table B-7: Environmental impact of small lot production

Small Lot Production	Positive Impact	Negative Impact
Air Pollution	-	Possibly, more air pollution due to frequents start-over.
Wastewater	-	More wastewater from the paint process because equipment has to be cleaned out more often between batches.
Storm Water Runoff	-	More runoff from the paint process if equipment cleanings are done outside.
Hazardous Waste	Small lot production reduces reworks and scraps should something goes wrong.	More sludge and residual products from cutting operations.
Universal Waste		
Special Waste		
Non-hazardous Waste		
Employee's Heath	-	More exposure to cleaning solvents from the paint process.
Employee's Safety	-	-
Toxic Chemical	Smaller lot sizing reduces reworks and scraps should something go wrong.	-
LCA	-	-
Energy	Less energy usage due to less reworks and scraps.	More energy usage due to frequent shutdown and startup.

Table B-8: Environmental impact of supplier development

Supplier Development	Positive Impact	Negative Impact
Air Pollution	May be positive or negative depending on materials purchased.	
Wastewater		
Storm Water Runoff		
Hazardous Waste		
Universal Waste		
Special Waste		
Non-hazardous Waste		
Employee's Heath		
Employee's Safety		
Toxic Chemical		
LCA		
Energy		

Table B-9: Environmental impact of total productive maintenance

<table>
<tr><th>Total Productive Maintenance</th><th>Positive Impact</th><th>Negative Impact</th></tr>
<tr><td>Air Pollution</td><td>Reduction in fugitive emission from equipment leaks.</td><td>-</td></tr>
<tr><td>Wastewater</td><td>-</td><td>Wastewater from washing and cleaning.</td></tr>
<tr><td>Storm Water Runoff</td><td>Less unplanned release outside the facility.</td><td>More runoff if equipment is outdoor.</td></tr>
<tr><td>Hazardous Waste</td><td rowspan="2">Less unreacted raw materials or by-products generated in process due to higher efficiency.</td><td>Acid and caustic wastes from metal conditioning, etching, cleaning, and stripping.</td></tr>
<tr><td>Universal Waste</td><td>Waste oils such as hydraulic, compressor, crankcase, coolant, etc.</td></tr>
<tr><td>Special Waste</td><td>Less process materials purged from production lines during unplanned downtimes.</td><td>-</td></tr>
<tr><td>Non-hazardous Waste</td><td>Less unreacted raw materials or by-products generated in process due to higher efficiency.</td><td>General maintenance trash such as packaging materials, plastic wraps, paper, etc.</td></tr>
<tr><td>Employee’s Heath</td><td>Less exposure to emissions from equipment leaks.</td><td>More exposure to cleaning solvents.</td></tr>
<tr><td>Employee’s Safety</td><td>Reduction in possibility of adverse events such as explosion and fire.</td><td>-</td></tr>
<tr><td>Toxic Chemical</td><td>Less toxic chemical use due to higher production efficiency.</td><td>Waste cleaning solvents such as acetone, alcohol, turpentine, etc.</td></tr>
<tr><td>LCA</td><td>Longer machine life.</td><td>-</td></tr>
<tr><td>Energy</td><td>Higher efficiency of machine.</td><td>Energy use for maintenance procedure.</td></tr>
</table>

APPENDIX C: Interview Checklist

Section I: Environmental and Safety Issues Associated with Single-Point and Multi-Point Cutting Operations

1.1 Air pollution

Do you generate any air emissions from these operations?

- If yes, specify and comment
- If no, skip 2.1

1.2 Employee's Health and Safety

Are there any obvious Occupational Health and Safety issues regarding these operations?

- If yes, specify and comment
- If no, skip 2.2

1.3 Energy Use

Please specify types of energy use

1.4 LCA

Are there any LCA issues regarding these operations?

- If yes, comment
- If no, skip 2.4

1.5 Solid Waste

1.5.1 Hazardous

Do you generate any hazardous waste from these operations?

- If yes, specify and comment
- If no, skip 2.5.1

1.5.2 Non-Hazardous

Do you generate any non-hazardous waste from these operations?

- If yes, specify and comment
- If no, skip 2.5.2

1.5.3 Special

Do you generate any special waste from these operations?

- If yes, specify and comment
- If no, skip 2.5.3

1.5.4 Universal

Do you generate any universal waste from these operations?

- If yes, specify and comment
- If no, skip 2.5.4

1.6 Toxic Chemical

1.6.1 EPCRA

Do you generate any toxic chemical associated with EPCRA from these operations?

- If yes, specify and comment
- If no, skip 2.6.1

1.6.2 PBT

Do you generate any PBT pollutants from these operations?

- If yes, specify and comment
- If no, skip 2.6.2

1.7 Water Pollution

1.7.1 Storm Water Runoff

Is there any evidence of or potential for storm water pollution?

- If yes, specify and comment
- If no, skip 2.7.1

1.7.2 Wastewater

Do you generate any wastewater from these operations?

- If yes, specify and comment
- If no, skip 2.7.2

Section II: Impact of Lean Manufacturing Principles on Environmental and Safety Issues

2.1 Air Pollution

Please comment on how air pollution discussed in 1.1 may be impacted by the following lean manufacturing principles.

2.1.1 Cellular Manufacturing

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.1.2 Employee's Involvement and Empowerment

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.1.3 Mistake proofing

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.1.4 Product Mix/Variability

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.1.5 Pull Systems

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.1.6 Quick Changeover

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.1.7 Small Lot Production

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.1.8 Supplier Development

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.1.9 Total Productive Maintenance

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.2 Employee's Health and Safety

Please comment on how employee's health and safety issues discussed in 1.2 may be impacted by the following lean manufacturing principles.

2.2.1 Cellular Manufacturing

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.2.2 Employee's Involvement and Empowerment

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.2.3 Mistake proofing

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.2.4 Product Mix/Variability

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.2.5 Pull Systems

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.2.6 Quick Changeover

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.2.7 Small Lot Production

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.2.8 Supplier Development

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.2.9 Total Productive Maintenance

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.3 Energy Use

Please comment on how energy use discussed in 1.3 may be impacted by the following lean manufacturing principles.

2.3.1 Cellular Manufacturing

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.3.2 Employee's Involvement and Empowerment

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.3.3 Mistake proofing

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.3.4 Product Mix/Variability

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.3.5 Pull Systems
- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.3.6 Quick Changeover
- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.3.7 Small Lot Production
- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.3.8 Supplier Development
- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.3.9 Total Productive Maintenance
- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.4 LCA

Please comment on how LCA issue discussed in 1.4 may be impacted by the following lean manufacturing principles.

2.4.1 Cellular Manufacturing
- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.4.2 Employee's Involvement and Empowerment
- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.4.3 Mistake proofing
- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.4.4 Product Mix/Variability
- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.4.5 Pull Systems
- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.4.6 Quick Changeover
- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.4.7 Small Lot Production
- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.4.8 Supplier Development

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.4.9 Total Productive Maintenance

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.5 Solid Waste

2.5.1 Hazardous

Please comment on how hazardous waste discussed in 1.5.1 may be impacted by the following lean manufacturing principles.

2.5.1.1 Cellular Manufacturing

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.5.1.2 Employee's Involvement and Empowerment

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.5.1.3 Mistake proofing

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.5.1.4 Product Mix/Variability

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.5.1.5 Pull Systems

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.5.1.6 Quick Changeover

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.5.1.7 Small Lot Production

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.5.1.8 Supplier Development

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.5.1.9 Total Productive Maintenance

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.5.2 Non-Hazardous

Please comment on how non-hazardous waste discussed in 1.5.2 may be impacted by the following lean manufacturing principles.

2.5.2.1 Cellular Manufacturing

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.5.2.2 Employee's Involvement and Empowerment

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.5.2.3 Mistake proofing

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.1.2.4 Product Mix/Variability

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.5.2.5 Pull Systems

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.5.2.6 Quick Changeover

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.5.2.7 Small Lot Production

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.5.2.8 Supplier Development

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.5.2.9 Total Productive Maintenance

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.5.3 Special

Please comment on how special waste discussed in 1.5.3 may be impacted by the following lean manufacturing principles.

2.5.3.1 Cellular Manufacturing

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.5.3.2 Employee's Involvement and Empowerment

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.5.3.3 Mistake proofing

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.5.3.4 Product Mix/Variability

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.5.3.5 Pull Systems

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.5.3.6 Quick Changeover

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.5.3.7 Small Lot Production

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.5.3.8 Supplier Development

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.5.3.9 Total Productive Maintenance

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.5.4 Universal

Please comment on how universal waste discussed in 1.5.4 may be impacted by the following lean manufacturing principles.

2.5.4.1 Cellular Manufacturing

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.5.4.2 Employee's Involvement and Empowerment

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.5.4.3 Mistake proofing

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.5.4.4 Product Mix/Variability

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.5.4.5 Pull Systems

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.5.4.6 Quick Changeover

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.5.4.7 Small Lot Production

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.5.4.8 Supplier Development

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.5.4.9 Total Productive Maintenance

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.6 Toxic Chemical
2.6.1 EPCRA
Please comment on how EPCRA toxic chemicals discussed in 1.6.1 may be impacted by the following lean manufacturing principles.
2.6.1.1 Cellular Manufacturing
- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.6.1.2 Employee's Involvement and Empowerment
- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.6.1.3 Mistake proofing
- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.6.1.4 Product Mix/Variability
- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.6.1.5 Pull Systems
- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.6.1.6 Quick Changeover
- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.6.1.7 Small Lot Production
- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.6.1.8 Supplier Development
- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.6.1.9 Total Productive Maintenance
- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.6.2 PBT
Please comment on how PBT pollutants discussed in 1.6.2 may be impacted by the following lean manufacturing principles.
2.6.2.1 Cellular Manufacturing
- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.6.2.2 Employee's Involvement and Empowerment
- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.6.2.3 Mistake proofing
- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.6.2.4 Product Mix/Variability

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.6.2.5 Pull Systems

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.6.2.6 Quick Changeover

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.6.2.7 Small Lot Production

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.6.2.8 Supplier Development

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.6.2.9 Total Productive Maintenance

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.7 Water Pollution

2.7.1 Storm Water Runoff

Please comment on how storm water runoff discussed in 1.7.1 may be impacted by the following lean manufacturing principles.

2.7.1.1 Cellular Manufacturing

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.7.1.2 Employee's Involvement and Empowerment

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.7.1.3 Mistake proofing

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.7.1.4 Product Mix/Variability

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.7.1.5 Pull Systems

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.7.1.6 Quick Changeover

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.7.1.7 Small Lot Production

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.7.1.8 Supplier Development

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.7.1.9 Total Productive Maintenance

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.7.2 Wastewater

Please comment on how wastewater discussed in 1.7.2 may be impacted by the following lean manufacturing principles.

2.7.2.1 Cellular Manufacturing

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.7.2.2 Employee's Involvement and Empowerment

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.7.2.3 Mistake proofing

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.7.2.4 Product Mix/Variability

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.7.2.5 Pull Systems

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.7.2.6 Quick Changeover

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.7.2.7 Small Lot Production

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.7.2.8 Supplier Development

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

2.7.2.9 Total Productive Maintenance

- -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
- Comment

APPENDIX D: Survey Results for Single and/or Multi-Point Cutting Operations

Table D-1: Impacts of lean principles on air pollution

	CM	EI	MP	PM/V	PS	QC	SLP	SD	TPM
1	0	0	0	0	0	0	0	0	3
2	0	0	0	0	0	0	0	0	3
3	2	0	0	0	0	0	0	2	3
4	-1	1	1	0	0	1	-2	2	2
5	-1	2	3	-1	-1	-1	-1	3	4
6	-1	1	1	-1	1	1	2	0	2
7	0	2	2	1	1	1	-1	0	3
8	0	0	0	0	0	0	0	0	1
9	0	0	0	0	0	0	0	1	2
10	1	0	2	0	0	0	0	2	1
11	1	3	1	-1	1	1	1	2	4
12	0	2	2	1	-1	-1	-1	0	2
13	1	2	3	0	0	1	-1	1	3
14	0	1	1	-1	1	0	0	2	2
15	-1	3	0	1	0	1	0	2	3
16	0	0	2	-1	0	0	1	1	3
17	0	2	0	0	0	0	-1	2	3
18	0	1	0	1	0	0	-1	2	2
19	1	3	3	1	-1	1	0	1	3
20	-1	1	1	-1	1	1	0	0	1
21	1	0	0	-1	1	-1	-1	2	2
22	1	1	2	1	0	0	0	1	2
23	0	0	2	0	-1	1	1	3	3
24	-1	0	1	0	1	0	-1	2	3
25	1	2	0	-1	0	-1	0	0	4
26	0	2	1	0	1	1	0	1	2
27	0	0	3	1	0	1	0	2	3
28	0	1	0	-1	0	0	0	0	3
Mean	0.1	1.1	1.1	-0.1	0.1	0.3	-0.2	1.2	2.6
Standard deviation	0.8	1.1	1.1	0.8	0.7	0.7	0.8	1.0	0.8
Max	2	3	3	1	1	1	2	3	4
Min	-1	0	0	-1	-1	-1	-2	0	1
Median	0	1	1	0	0	0	0	1	3
Lower 90% CI	0	0	0	-1	0	0	-1	0	2
Upper 90% CI	0	2	2	0	0	1	0	2	3

Note: Confidence intervals for the median were calculated base on Ott, R.L., & Longnecker, M. (2001). *An introduction to statistical methods and data analysis*, 5th ed.,. 243-245.

Table D-2: Impacts of lean principles on employee's health and safety

	CM	EI	MP	PM/V	PS	QC	SLP	SD	TPM
1	1	1	1	0	0	1	0	1	3
2	1	1	1	0	0	1	0	1	3
3	1	3	2	0	0	0	-1	2	3
4	2	3	3	0	0	0	0	1	3
5	0	3	3	0	1	1	0	3	3
6	2	2	1	1	0	0	0	1	4
7	2	3	2	0	1	1	0	2	3
8	1	2	3	0	0	0	0	1	3
9	2	3	1	0	0	0	0	1	3
10	1	2	2	0	0	1	0	1	3
11	1	1	1	0	0	0	0	1	3
12	1	2	2	0	0	0	0	1	3
13	2	3	2	0	0	1	0	2	3
14	1	2	1	0	1	1	0	2	3
15	1	2	2	0	1	0	0	2	3
16	2	3	2	0	0	0	0	2	3
17	2	3	3	0	0	0	0	2	4
18	2	2	2	0	0	0	0	2	3
19	1	2	1	0	0	0	0	1	3
20	1	1	1	0	0	1	0	1	3
21	1	2	2	0	0	0	0	1	3
22	2	3	2	0	1	1	0	2	3
23	2	3	2	0	0	1	0	2	3
24	1	2	1	0	0	0	0	1	3
25	1	3	2	0	0	0	0	2	3
26	1	3	2	0	0	0	0	2	3
27	1	2	1	0	0	0	0	1	3
28	2	3	3	0	0	0	0	2	4
Mean	1.4	2.3	1.8	0.0	0.2	0.4	0.0	1.5	3.1
Standard deviation	0.6	0.7	0.7	0.0	0.4	0.5	0.2	0.6	0.3
Max	2	3	3	1	1	1	0	3	4
Min	0	1	1	0	0	0	-1	1	3
Median	1	2	2	0	0	0	0	2	3
Lower 90% CI	1	2	1	0	0	0	0	1	3
Upper 90% CI	2	3	2	0	0	1	0	2	3

Note: Confidence intervals for the median were calculated base on Ott, R.L., & Longnecker, M. (2001). *An introduction to statistical methods and data analysis*, 5th ed.,. 243-245.

Table D-3: Impacts of lean principles on energy use

	CM	EI	MP	PM/V	PS	QC	SLP	SD	TPM
1	1	1	1	0	1	1	0	0	3
2	1	1	1	0	1	1	0	0	3
3	2	2	2	0	0	1	-1	1	3
4	1	4	2	0	1	2	-2	2	3
5	1	2	3	1	1	1	-1	3	3
6	1	1	1	0	-1	1	1	0	3
7	1	2	2	0	0	1	-1	2	3
8	2	1	2	0	0	1	0	2	3
9	1	2	3	-1	1	2	-1	2	2
10	2	2	1	1	1	1	-1	3	3
11	1	2	2	0	-1	2	0	1	3
12	1	2	2	0	1	2	0	2	3
13	1	1	2	0	0	1	-1	0	3
14	1	3	1	0	0	1	-1	1	3
15	1	1	1	0	1	1	0	2	3
16	1	1	2	0	1	2	0	2	3
17	1	2	2	1	1	1	0	1	3
18	2	3	2	1	0	2	1	2	3
19	1	1	2	-1	0	2	-1	1	3
20	1	1	1	0	1	1	-1	1	3
21	1	1	1	0	1	2	0	0	3
22	2	2	3	0	0	2	0	0	3
23	2	1	1	0	1	1	0	1	3
24	1	1	1	1	0	1	-2	1	3
25	1	2	2	-1	0	2	-1	2	3
26	2	2	1	0	1	2	-1	1	3
27	1	2	2	0	1	1	0	0	3
28	2	3	2	0	1	2	-1	1	3
Mean	1.3	1.8	1.7	0.1	0.5	1.4	-0.5	1.4	3.0
Standard deviation	0.5	0.8	0.7	0.5	0.6	0.5	0.7	1.0	0.2
Max	2	4	3	1	1	2	1	3	3
Min	1	1	1	-1	-1	1	-2	0	2
Median	1	2	2	0	1	1	-1	1	3
Lower 90% CI	1	1	1	0	0	1	-1	1	3
Upper 90% CI	1	2	2	0	1	2	0	2	3

Note: Confidence intervals for the median were calculated base on Ott, R.L., & Longnecker, M. (2001). *An introduction to statistical methods and data analysis*, 5^{th} ed.,. 243-245.

Table D-4: Impacts of lean principles on solid waste (non-hazardous)

	CM	EI	MP	PM/V	PS	QC	SLP	SD	TPM
1	1	1	1	0	0	0	0	1	3
2	1	1	1	0	0	0	0	1	3
3	0	1	0	0	0	1	0	1	1
4	1	2	2	0	0	1	1	2	3
5	0	1	1	-1	0	0	-1	3	2
6	0	2	2	-1	0	1	0	2	4
7	0	1	2	0	0	1	0	1	2
8	1	1	1	0	0	0	0	1	2
9	0	1	2	0	0	0	0	2	2
10	1	2	3	0	1	0	0	3	4
11	0	1	2	-1	0	1	-1	2	3
12	0	1	1	0	1	0	0	1	2
13	0	2	2	0	0	0	0	2	2
14	1	2	2	0	0	0	0	2	3
15	0	1	1	0	1	1	0	3	4
16	0	1	1	0	0	0	0	2	3
17	1	2	3	1	1	1	0	3	3
18	1	2	2	1	1	1	0	1	3
19	0	1	1	-1	0	1	-1	2	3
20	0	2	2	0	0	0	0	3	4
21	0	2	2	0	0	0	0	1	3
22	1	2	2	0	0	0	0	2	2
23	0	2	2	0	1	0	0	3	3
24	0	1	1	0	0	0	-1	1	3
25	1	2	2	0	1	1	0	2	4
26	1	2	1	0	1	1	0	2	3
27	0	2	2	0	1	0	0	2	3
28	0	2	2	0	0	0	0	2	3
Mean	0.4	1.5	1.6	-0.1	0.3	0.4	-0.1	1.9	2.9
Standard deviation	0.5	0.5	0.7	0.5	0.5	0.5	0.4	0.7	0.8
Max	1	2	3	1	1	1	1	3	4
Min	0	1	0	-1	0	0	-1	1	1
Median	0	2	2	0	0	0	0	2	3
Lower 90% CI	0	1	1	0	0	0	0	1	3
Upper 90% CI	1	2	2	0	1	1	0	2	3

Note: Confidence intervals for the median were calculated base on Ott, R.L., & Longnecker, M. (2001). *An introduction to statistical methods and data analysis*, 5th ed.,. 243-245.

Table D-5: Impacts of lean principles on wastewater

	CM	EI	MP	PM/V	PS	QC	SLP	SD	TPM
1	0	0	1	0	0	0	0	0	3
2	0	0	1	0	0	0	0	0	3
3	1	1	2	0	1	0	0	1	2
4	1	2	2	0	0	0	1	2	3
5	1	2	2	-1	1	0	-1	2	1
6	0	1	2	-1	0	0	0	2	3
7	1	2	2	1	0	0	0	1	2
8	1	1	1	1	1	1	0	2	3
9	0	0	1	1	0	0	0	1	3
10	1	1	3	1	1	0	0	2	4
11	0	1	1	0	0	1	-1	1	2
12	0	1	1	-1	0	0	0	2	2
13	0	0	2	1	0	0	0	2	2
14	1	1	2	0	0	0	0	2	3
15	0	0	1	0	0	1	0	2	2
16	0	0	1	0	1	0	0	1	2
17	1	2	3	1	0	0	0	3	4
18	1	1	2	0	1	1	0	2	2
19	0	1	1	-1	1	1	-1	1	2
20	0	1	2	0	0	0	0	2	3
21	0	1	2	0	0	0	0	1	2
22	1	1	2	0	0	0	0	2	3
23	0	1	2	0	0	0	0	1	3
24	0	0	1	0	0	0	-1	1	2
25	1	1	2	0	1	1	0	0	3
26	1	1	1	0	1	0	0	0	3
27	0	2	2	0	1	1	0	2	3
28	0	1	2	0	0	1	0	2	3
Mean	0.4	0.9	1.7	0.1	0.4	0.3	-0.1	1.4	2.6
Standard deviation	0.5	0.7	0.6	0.6	0.5	0.5	0.4	0.8	0.7
Max	1	2	3	1	1	1	1	3	4
Min	0	0	1	-1	0	0	-1	0	1
Median	0	1	2	0	0	0	0	2	3
Lower 90% CI	0	1	1	0	0	0	0	1	2
Upper 90% CI	1	1	2	0	1	0	0	2	3

Note: Confidence intervals for the median were calculated base on Ott, R.L., & Longnecker, M. (2001). *An introduction to statistical methods and data analysis*, 5th ed.,. 243-245.

Figure D-1: Screenshot of automated EN-LEAN model with lower 90% confidence interval input data

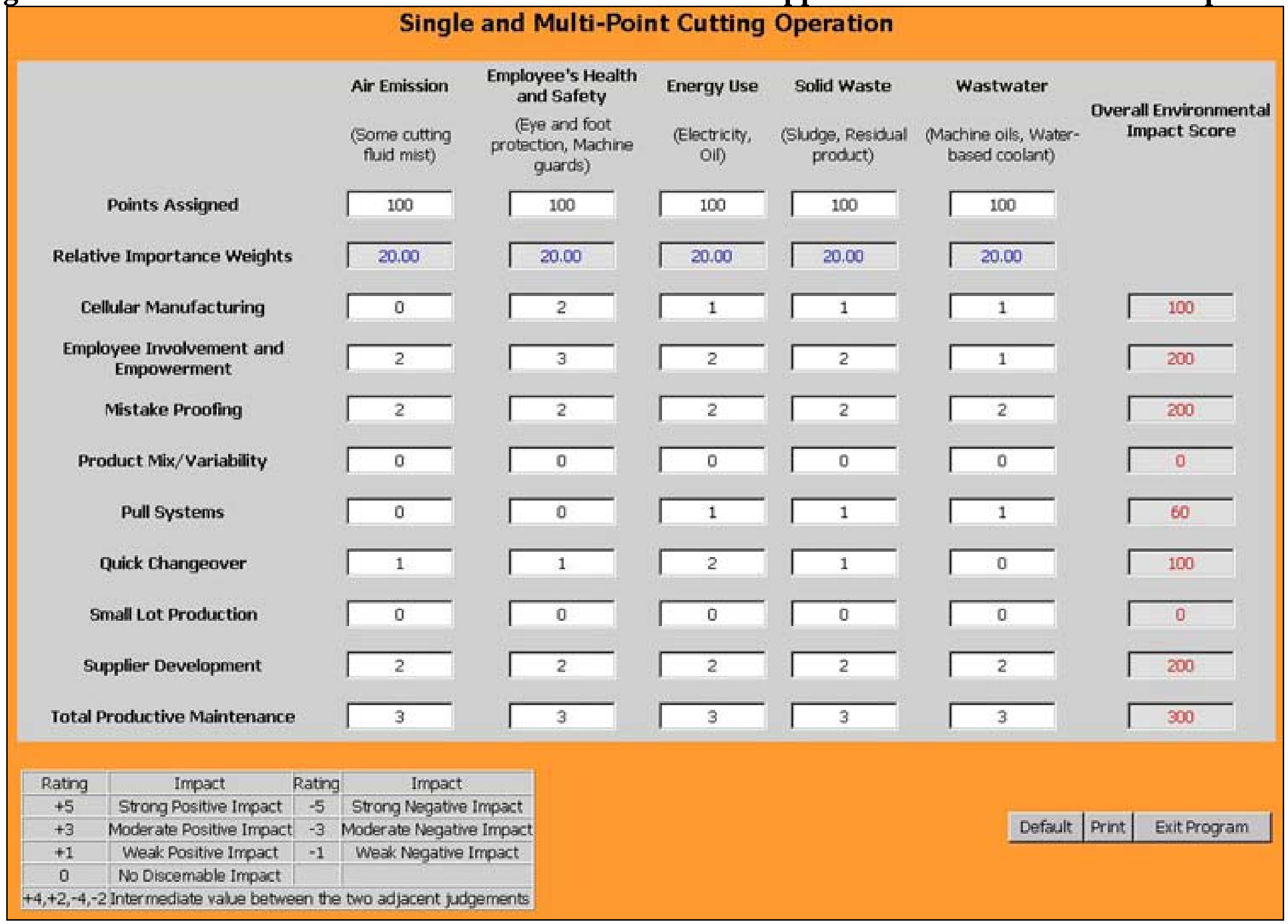
Single and Multi-Point Cutting Operation

	Air Emission (Some cutting fluid mist)	Employee's Health and Safety (Eye and foot protection, Machine guards)	Energy Use (Electricity, Oil)	Solid Waste (Sludge, Residual product)	Wastwater (Machine oils, Water-based coolant)	Overall Environmental Impact Score
Points Assigned	100	100	100	100	100	
Relative Importance Weights	20.00	20.00	20.00	20.00	20.00	
Cellular Manufacturing	0	1	1	0	0	40
Employee Involvement and Empowerment	0	2	1	1	1	100
Mistake Proofing	0	1	1	1	1	80
Product Mix/Variability	-1	0	0	0	0	-20
Pull Systems	0	0	0	0	0	0
Quick Changeover	0	0	1	0	0	20
Small Lot Production	-1	0	-1	0	0	-40
Supplier Development	0	1	1	1	1	80
Total Productive Maintenance	2	3	3	3	2	260

Rating	Impact	Rating	Impact
+5	Strong Positive Impact	-5	Strong Negative Impact
+3	Moderate Positive Impact	-3	Moderate Negative Impact
+1	Weak Positive Impact	-1	Weak Negative Impact
0	No Discernable Impact		
+4,+2,-4,-2	Intermediate value between the two adjacent judgements		

Default | Print | Exit Program

Figure D-2: Screenshot of automated EN-LEAN model with upper 90% confidence interval input data



Single and Multi-Point Cutting Operation

	Air Emission (Some cutting fluid mist)	Employee's Health and Safety (Eye and foot protection, Machine guards)	Energy Use (Electricity, Oil)	Solid Waste (Sludge, Residual product)	Wastewater (Machine oils, Water-based coolant)	Overall Environmental Impact Score
Points Assigned	100	100	100	100	100	
Relative Importance Weights	20.00	20.00	20.00	20.00	20.00	
Cellular Manufacturing	0	2	1	1	1	100
Employee Involvement and Empowerment	2	3	2	2	1	200
Mistake Proofing	2	2	2	2	2	200
Product Mix/Variability	0	0	0	0	0	0
Pull Systems	0	0	1	1	1	60
Quick Changeover	1	1	2	1	0	100
Small Lot Production	0	0	0	0	0	0
Supplier Development	2	2	2	2	2	200
Total Productive Maintenance	3	3	3	3	3	300

Rating	Impact	Rating	Impact
+5	Strong Positive Impact	-5	Strong Negative Impact
+3	Moderate Positive Impact	-3	Moderate Negative Impact
+1	Weak Positive Impact	-1	Weak Negative Impact
0	No Discernable Impact		
+4,+2,-4,-2	Intermediate value between the two adjacent judgements		

APPENDIX E: Automated EN-LEAN Model

The automated EN-LEAN model was developed using HTML and JavaScript codes. The model is best viewed in Microsoft Internet Explorer 6.0 or higher with the screen resolution set at 1024*768 and above.

The model can be run by the following two methods.

1. Double-click the attached file below to open the automated EN-LEAN model.
2. Right-click the attached file below and download the file to hard disk by selecting "Save Embedded File to Disk…". Then, open the downloaded file in Microsoft Internet Explorer.

VITA

Pamuk Teparakul was born in Chonburi, Thailand. He graduated from the Phelps School in Malvern, Pennsylvania. From there, he went on to study at The University of Tennessee, Knoxville and received a B.S. in Civil Engineering with a minor in Environmental Engineering.

Pamuk is completing his master of science with a concentration in Industrial Engineering at the University of Tennessee. During his graduate studies, he served in a group of research assistants under Dr.Rapinder Sawhney, where he helped to develop training materials in the area of Lean Enterprise Systems Design.