



2008

# AN INTEGRATED FRAMEWORK FOR APPLYING LEAN MANUFACTURING AND OTHER STRATEGIES IN MASS CUSTOMIZATION ENVIRONMENTS

Gregory Brandon Stump  
*University of Kentucky*, [gbstum2@gmail.com](mailto:gbstum2@gmail.com)

**[Click here to let us know how access to this document benefits you.](#)**

---

## Recommended Citation

Stump, Gregory Brandon, "AN INTEGRATED FRAMEWORK FOR APPLYING LEAN MANUFACTURING AND OTHER STRATEGIES IN MASS CUSTOMIZATION ENVIRONMENTS" (2008). *University of Kentucky Master's Theses*. 563.  
[https://uknowledge.uky.edu/gradschool\\_theses/563](https://uknowledge.uky.edu/gradschool_theses/563)

This Thesis is brought to you for free and open access by the Graduate School at UKnowledge. It has been accepted for inclusion in University of Kentucky Master's Theses by an authorized administrator of UKnowledge. For more information, please contact [UKnowledge@sv.uky.edu](mailto:UKnowledge@sv.uky.edu).

## ABSTRACT OF THESIS

### AN INTEGRATED FRAMEWORK FOR APPLYING LEAN MANUFACTURING AND OTHER STRATEGIES IN MASS CUSTOMIZATION ENVIRONMENTS

Manufacturing organizations are facing fragmented markets and increased demand of variety from consumers. As a result, many of these firms have adopted mass customization manufacturing strategies in an effort to offer their customers the freedom of choice while maintaining operational efficiency. Lean manufacturing strategies have also seen heavy use in manufacturing environments. This study investigates the possibilities of integrating lean manufacturing principles and practices into mass customization environments in order to improve system performance. The feasibility of other manufacturing strategies such as agility, Quick Response Manufacturing and the Theory of Constraints assisting in the application of lean manufacturing for mass customization is also explored with the goal of developing a theoretical framework for the application of these manufacturing systems in different types of mass customization environments. The result of these investigations is tested and verified using a real world case study.

**KEYWORDS:** Mass Customization, Lean Manufacturing, Quick Response Manufacturing, Theory of Constraints, Agile

---

Gregory B. Stump

---

4 December, 2008

AN INTEGRATED FRAMEWORK FOR APPLYING LEAN MANUFACTURING  
AND OTHER STRATEGIES IN MASS CUSTOMIZATION ENVIRONMENTS

By

Gregory Brandon Stump

Dr. Fazleena Badurdeen

Director of Thesis

Dr. L. Scott Stephens

Director of Graduate Studies

4 December, 2008

Date

## RULES FOR THE USE OF THESES

Unpublished theses submitted for the Master's degree and deposited in the University of Kentucky are as a rule open for inspection, but are to be used only with due regard to the rights of the authors. Bibliographical references may be noted, but quotations or summaries of parts may be published only with the permission of the author, and with the usually scholarly acknowledgements.

Extensive copying or publication of the thesis in whole or in part also requires the consent of the Dean of the Graduate School of the University of Kentucky.

A library that borrows this thesis for use by its patrons is expected to secure the signature of each user.

Name

Date

---

---

---

---

---

---

---

---

THESIS

Gregory Brandon Stump

The Graduate School  
University of Kentucky  
2008

AN INTEGRATED FRAMEWORK FOR APPLYING LEAN MANUFACTURING  
AND OTHER STRATEGIES IN MASS CUSTOMIZATION ENVIRONMENTS

---

THESIS

---

A thesis submitted in partial fulfillment of the  
requirements for the degree of Master of Science in  
Mechanical Engineering in the  
College of Engineering at the  
University of Kentucky

By

Gregory Brandon Stump  
Lexington, Kentucky

Director: Dr. Fazleena Badurdeen, Professor of Manufacturing  
Lexington, Kentucky

2008

Copyright © Gregory Brandon Stump 2008

*This document is hereby dedicated to my family, who were a constant source of encouragement throughout my education, my teachers Dr. John Yingling, Dr. David Veech, and Parthi Damodaraswamy, who tirelessly sought to teach me the intricacies of manufacturing environments, and my advisor Dr. Fazleena Badurdeen, who provided invaluable counsel throughout the creation of this document.*

## Acknowledgements

The following thesis, while an individual work, benefited from the insights and direction of several people. First, my Thesis Chair, Dr. Fazleena Badurdeen, exemplifies the high quality scholarship to which I aspire. Next, I wish to thank the complete Thesis Committee: Dr. Arlie Hall, Dr. Larry Holloway, Dr. Kozo Saito, and Dr. Fazleena Badurdeen. Each individual provided insights that guided and challenged my thinking, substantially improving the finished product.

In addition to the technical and instrumental assistance above, I received equally important assistance from the engineering and management staff at the case study company, Skier's Choice, Inc. Lee Wadsworth, an engineer at said company, proved a valuable liaison between Skier's Choice and myself, aiding in obtaining information pertinent to the research contained in this document.



## Table of Contents

Acknowledgements.....	iii
Table of Contents .....	iv
List of Tables .....	v
List of Figures.....	vi
1. Introduction.....	1
2. Background.....	5
2.1. Lean Manufacturing Overview .....	5
2.2. Mass Customization Overview and Classification Systems .....	12
2.2.1. Single Dimensional Classification Schemes.....	13
2.2.2. Two Dimensional Classification Schemes.....	16
2.2.3. Comparison and Selection .....	18
2.3. Low Level and High Level Customization .....	20
3. Literature Review.....	23
3.1. Competency Models.....	23
3.2. Production Competencies.....	25
3.3. Other Competencies .....	30
3.4. Potential for Applying Lean Manufacturing For Mass Customization.....	32
3.5. Potential for Integrating Other Strategies.....	36
3.6. Discussion .....	42
4. Methodology.....	43
4.1. Critical Review.....	43
4.2. Framework .....	47
4.3. Objective .....	53
5. Case Study – Skier’s Choice.....	55
5.1. Brief Company Description .....	55
5.2. Mass Customization Product.....	56
5.3. Mass Customization Operations.....	59
5.3.1. Manufacturing Operations .....	63
5.3.2. SWOT Analysis .....	66
6. Experimental Model Development.....	67
6.1. The Current State .....	67
6.2. Discussion of Applicable Approaches .....	68
6.3. Restructuring the Operations.....	72
6.3.1. Lamination Shop.....	72
6.3.2. Small Parts Department .....	75
6.3.3. Upholstery Department.....	76
6.3.4. Rigging and Assembly Line.....	79
6.3.5. Inspection Line.....	81
6.4. Simulation Model Design.....	83
6.5. Experimental Design .....	93
6.6. Testing and Results .....	96
7. Discussion and Conclusions .....	106
List of References .....	112
VITA.....	117

## List of Tables

Table 1. Manufacturing System Comparison (Koren et. al., 1999).....	27
Table 2. Company Data .....	56
Table 3. Skier's Choice Model Offerings.....	57
Table 4. Example Cycle Time Data.....	84
Table 5. Variables and Levels of Experiment.....	95
Table 6. Experimental Results .....	97
Table 7. Average Lead Time Comparison.....	100
Table 8. Average WIP Comparison .....	101
Table 9. Effect of Lamination/Assembly Buffer Size .....	102
Table 10. Effect of Random Number Variation.....	103
Table 11. Summary of Case Selections .....	104

## List of Figures

Figure 2.1 The Toyota House (Liker, 2003) .....	6
Figure 2.2 Lean Standardization .....	7
Figure 2.3 Lean Pull.....	8
Figure 2.4 Different Types of Waste .....	11
Figure 2.5 Duray et. al. (2000) Model for Mass Customization Classification.....	18
Figure 2.6 Classification Model Decision Matrix.....	19
Figure 2.7 High Level Customization vs. Low Level Customization .....	21
Figure 2.8 Low Level Customization .....	22
Figure 2.9 High Level Customization.....	22
Figure 3.1 Mass Customization Competencies (Moser, 2007).....	24
Figure 3.2 Mass Customization Value Chain based on (Moser, 2007) .....	25
Figure 3.3 Mass Customization with Lean Principles and Practices .....	33
Figure 3.4 DBR Mechanism .....	39
Figure 3.5 POLCA Control (Suri, 1998) .....	41
Figure 4.1 Mass Customization Competencies by Strategy .....	47
Figure 4.2 Importance of MC Capabilities and Ease of Lean Implementation .....	49
Figure 4.3 Theoretical Framework .....	51
Figure 5.1 Supra Gravity 24SSV .....	58
Figure 5.2 Mobius XLV.....	58
Figure 5.3 Basic Process Map.....	63
Figure 5.4 SWOT Analysis.....	66
Figure 6.1 Skier's Choice Current State VSM .....	69
Figure 6.2 Lamination Shop .....	73
Figure 6.3 Lamination Shop CONWIP Cards .....	75
Figure 6.4 Small Parts Shop.....	77
Figure 6.5 Upholstery Shop .....	80
Figure 6.6 Rigging and Assembly Line .....	82
Figure 6.7 Inspection Line .....	83
Figure 6.8 Skier's Choice Simulation Model.....	85
Figure 6.9 Lamination Line Simulation Model .....	87
Figure 6.10 Small Parts Line Simulation Model .....	89
Figure 6.11 Upholstery Shop Simulation Model.....	90
Figure 6.12 Assembly/Rigging Line Simulation Model.....	92
Figure 6.13 Inspection Line Simulation Model .....	93
Figure 6.14 Low Demand ANOVA.....	98
Figure 6.15 High Demand ANOVA .....	99
Figure 7.1 Revised Theoretical Framework.....	106

## 1. Introduction

The processes of providing goods and services to meet customer need, and the strategies contained therein have been constantly changing and evolving over the past century, making great strides in efficiency, but more importantly increasing in complexity. This evolution of manufacturing paradigms can be easily modeled by the automobile industry.

In its infancy, the process of automobile manufacture was highly complex, expensive, and specialized, and was built to cater to the upper class citizen with excess money to spend. Automobile manufacture began using the craft model of production. Highly skilled craftsmen would design, fabricate, and build the vehicle from the ground up, which involved a great deal of individualization for the customer. Buyers were able to specify features such as size, color, engine power, upholstery, and much more (Ford, 1988).

While craft manufacturing provides a great deal of individualization for the customer and ownership for the craftsman, its downfall lies in its inefficiency and long lead times. Henry Ford changed all this with the implementation of standardization, the moving assembly line, and the atomization of work. This mass manufacturing strategy was highly effective and made Ford the premier auto manufacturer in the United States for many years (Womack et al., 1991; Ford, 1988).

While mass manufacturing can be a very efficient means of production, it is also well known for its drawbacks, including excessive inventory and waste. One of the most important shortcomings of mass manufacturing is the inability to produce a high variety of products on its production lines. The invention of lean manufacturing, or the continuous improvement strategy, by Toyota in post World War II Japan seeks to overcome mass production issues (Womack et al., 1991). Lean manufacturing makes use of the pull system, linking the shop floor to the customer, thereby greatly reducing inventory, throughput times, lead times, etc. Waste is also sought out and eliminated and employees given a great deal of ownership through a team structure. These improvements made it possible for the producer to add more variety to their products, but the strategy was still largely dependent on standardization (Womack et al., 1991).

### ***Problem Background***

The once stable and homogeneous markets have recently begun to fragment among different customer bases, each demanding their own customized goods and/or services (Pine, 1993). This has led to the emergence of mass customization, which can be defined in different ways. Broadly defined it is the ability to provide high variety and customization at the individual customer level through the use of flexible and highly responsive manufacturing systems (Pine, 1993). The “narrower” definition of mass customization is a “...system that uses information technology, flexible processes, and organization structures to deliver a wide range of products and services that meet specific needs of individual customers at a cost near that of mass produced items” (Da Silveira, 2001).

Also important to understanding the concept of mass customization is to recognize that there are different degrees of mass customization that are possible. There are several examples of literature that have developed classification schemes for mass customizers and each of these have their own strengths and weaknesses. However, most of them rely on the point of customer involvement in the value chain as a key classification criterion. The understanding of how the point of customer involvement affects the operation of the manufacturing system as a whole is tantamount to this research as it will directly affect the degree to which lean manufacturing and other strategies can be applied for mass customization.

This combination of mass production and customization may seem contradictory and unrealistic, but firms such as Dell, Motorola, Paris Miki, Bally Engineered Structures, and many others are pursuing the strategy successfully (Selladurai, 2004; Gilmore and Pine, 1997). Increased manufacturing capability due to flexible manufacturing and information system technologies, increased customization demand, and shorter product life cycles has steered the efforts of implementing mass customization (Da Silveira, 2001). Mass customization deals with niche markets (Berman, 2002), thus making it difficult to predict customer demand because the product is customizable. It requires the ability to dynamically adapt at all stages of the value chain to meet demand.

The need for efficient and flexible manufacturing systems to deliver mass customized products has been briefly discussed in the literature (Pine, 1993; Da Silveira, 2001). The

potential of lean manufacturing to meet these requirements has also been raised. While lean manufacturing has many capabilities that are essential for mass customization, the strategy can fail with higher degrees of customization. Therefore, it is important to conduct a critical investigation of how and what aspects of lean manufacturing are applicable for successful mass customization. This research is an attempt to critically review the use of lean manufacturing in the context of its application to mass customization manufacturing.

Many lean manufacturing principles, such as continuous improvement and waste reduction, have the potential to be readily applied in any mass customization environment. Other principles, however, are likely to fail in situations where the customer becomes involved very early in the value chain because of their reliance on stability and standardization as is the case with just-in-time and heijunka (load leveling). The high variability present in mass customization undoubtedly poses many challenges for lean manufacturing.

It is important to understand in which situations these various lean principles will fail, and what strategies can be used to fill in the gaps between lean and mass customization. For this reason, other common manufacturing system structures such as Quick Response Manufacturing, the Theory of Constraints, Agile, Leagile, and Job Shop Lean must be brought into the discussion as a possible means of supplementing and strengthening lean manufacturing in situations where its principles may fall short.

### ***Research Objective***

To date, there has been little research completed on lean manufacturing integration for mass customization, and there is a need for further investigations into the topic. Further, due to the varying degrees in which mass customization can take place, it is necessary to understand how the variance in the type of mass customization affects the ability of lean manufacturing and other strategies to improve the performance of the system. This research attempts to provide insight into the issue by qualitatively examining different manufacturing strategies to determine their strengths and weaknesses for application in mass customization environments, with the objective of developing a theoretical framework for the application of lean manufacturing and other strategies for

the different categories of mass customizers. A mass customizing manufacturer is employed as a case study to apply this framework and demonstrate the proper selection of manufacturing strategies for the restructuring of the operations.

The thesis document is organized as follows. In Chapter 2, an overview of the core principles of lean manufacturing is given along with a discussion and evaluation of different mass customization classification schemes that have been developed. Chapter 3 presents discussions on mass customization competencies, the application of lean manufacturing for mass customization, and the characteristics of other prominent manufacturing strategies based on the literature reviewed. In Chapter 4 the strengths and weaknesses of each of the aforementioned manufacturing strategies is critically reviewed and the theoretical framework is developed, while the characteristics of the case study company are given in Chapter 5. Finally, the restructuring procedure for the manufacturing operations of the case study company is detailed in Chapter 6 along with a simulation to validate the improvements made, while Chapter 7 concludes the work with a discussion of the findings.

## 2. Background

This chapter provides an overview of the mass customization and lean manufacturing strategies in order to investigate the opportunities for applying lean manufacturing concepts for mass customization. A brief discussion of lean manufacturing principles and practices that create this cohesive system is given, along with a discussion of mass customization and the classification strategies that have evolved over time to classify mass customizers. Lastly, these classification systems are critically reviewed, and one chosen for use throughout the research.

### 2.1. Lean Manufacturing Overview

Lean manufacturing is based on the Toyota Production System developed by Toyota after World War II by modifying Ford's mass production system to meet the specific needs of the Japanese market at that time. Toyota sought to reduce the inefficiencies of mass manufacturing by eliminating waste, reducing inventory, improving throughput, and encouraging employees to bring attention to problems and suggest improvements to fix them (Womack et al. 1991). Figure 2.1 illustrates "The Toyota House," a diagram showing the basic building blocks of lean systems operations (Liker, 2003). The following sections will briefly discuss each of these key areas and their place in a successful lean manufacturing system.

- ***Leveled Production (heijunka)***

One of the key principles of lean manufacturing is leveled production, or *heijunka*. Womack and Jones (1996) claim *heijunka* is a means "...to smooth out the perturbations in day-to-day order flow..." It refers to the method of mixed model assembly, in which products of different varieties are produced in a sequence, rather than in batches as with traditional manufacturing.

Also important for leveling is to produce only what is needed through accurate demand forecasting (Shingo, 1988). If a firm can understand the demand and sequence to meet the requirements, *heijunka* eliminates variability of throughput and lead time that batched production brings.



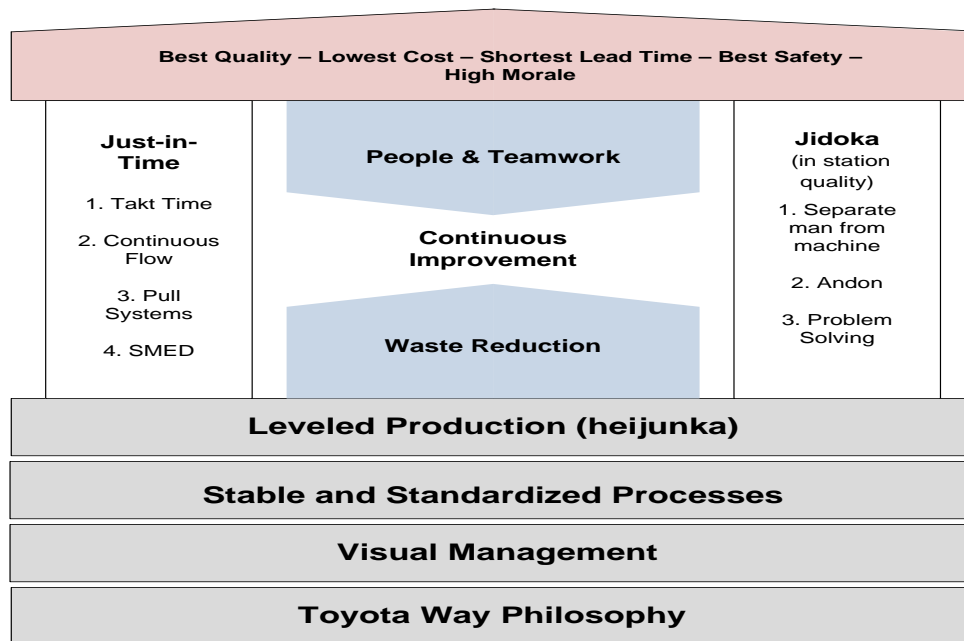


Figure 2.1 The Toyota House (Liker, 2003)

- ***Stable and Standardized Processes***

Lean manufacturing, while more capable of handling variety in production than mass manufacturing, is still built upon a platform of standardization, and thus constrained by it. Process standardization is achieved through the use of standardized work sheets, which outline the steps and the sequence in which those steps should be completed in order to fully process a component/product (Monden, 1998). Thus, lean manufacturing requires standardization and stability in the processes used to create a product rather than the product itself. In this sense the term standardization by no means implies a totally rigid and unvarying system, but rather is a means to aid continuous improvement (Bicheno, 2000) and refers to “the best way” at a given time, which can change as improvements are developed. Standardized work allows the comparison of results of suggested improvements to determine if the change was truly an advancement. See Figure 2.2 for an illustration of lean standardization.

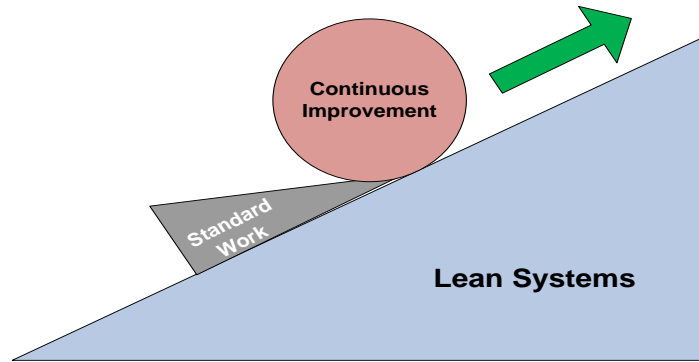


Figure 2.2 Lean Standardization

- ***Visual Management***

Management through the use of visuals to maintain the standard conditions of the workplace is paramount to success with lean manufacturing. Adding visibility to the production floor makes apparent the status of all operations allowing for efficient communication. The principles of visual management can be broken down into two basic categories: *5s* and *Visual Controls*.

*5s* principles for workplace organization, the “S’s” of which refer to five Japanese words later adapted by Shingo to stand for *sort*, *straighten*, *shine*, *systematize*, and *sustain* (Bicheno, 2000), offer shortened changeovers, reduced defects, lowered costs due to waste reduction, fewer delays, increased safety, fewer breakdowns, etc. (Hirano, 1995).

***Visual control*** refers to activities such as labeling, color coding, and visual information systems. Examples of these include maintaining WIP through first-in-first-out (FIFO) methods, control limit markings on machine gauges (Monden, 1998), or an information marquis displaying current plant conditions to employees, etc.

- ***Just-in-Time***

Just-in-Time (JIT) refers to the set of principles governing the flow of product through the manufacturing system. JIT manufacturing that operates through a pull system to maintain continuous flow of products/components at the rate required by customers constitutes one of the main pillars of lean manufacturing (see Figure 2.1).

- **Takt time** refers to the “pacing” of the production line, or the time allowable to produce each product in order to meet demand. Producing to a takt pace allows team members to be aware of their current status, enabling them to act accordingly (i.e. call for team leader aid if they are behind).
- **Continuous flow** of a steady stream of product at a takt pace through the production system helps maintain little WIP (ideally single-piece flow) with FIFO at all stages. This enables reducing lead time and increasing throughput, as products will not wait in large lines of WIP, but move quickly and directly to the next process in the order of arrival.
- **The Pull system** is at the heart of lean manufacturing philosophy. According to Wantuck (1989), the pull system serves as a linkage mechanism for the entire production enterprise, linking both internal and external elements. The pull system relies on the downstream customer to signal that production should commence, whether they be the end customer or the next process operator in line (Bicheno, 2000; Wantuck, 1989; Shingo, 1988). The traditional model of lean manufacturing is one that involves a single pull signal from the customer to the producer, the customer being the downstream process. Regardless of the resolution of the examination, with lean manufacturing, the system operates with a single (or a few) pull signal(s) as shown in Figure 2.3 (Liker, 2003. Ohno, 1988). A monument type process within a plant may feed multiple production lines, but conceptually the amount of signals it must fulfill is still finite and relatively small.

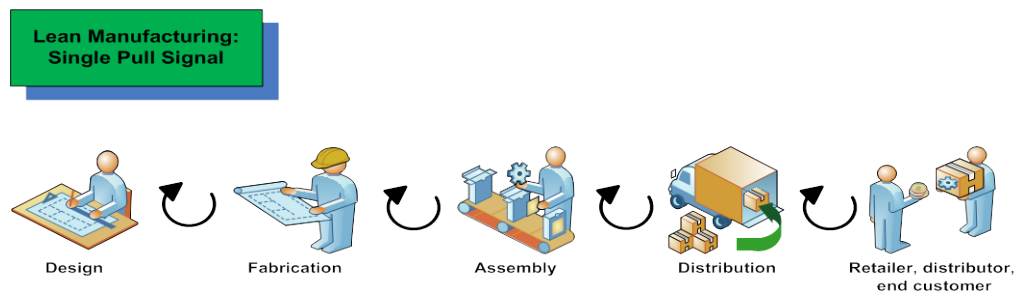


Figure 2.3 Lean Pull

### ❖ *Kanban and CONWIP*

Kanban and CONWIP are the two prominent control methods within lean manufacturing that enable the pull system to work. These systems seek to cap inventory and increase the ability for a set of manufacturing processes to flow (Co and Jacobson, 1994; Takahashi, et. al., 2005). Kanban pull systems operate by utilizing a kanban card or kanban square as a means of indicating a need to produce. For example, if a kanban card was attached to a bin of supplier parts, once that bin had been used the kanban card would be released indicating a new bin of parts would need to be ordered. The same can be said for a kanban placed between two processes, in which an empty kanban would indicate a need for the upstream process to produce (Kumar et. al., 2007).

While kanban operates completely on a pull system, CONWIP (constant work in process) seeks to combine elements of push and pull. This system works by employing a card system to cap the total inventory in a given set of processes. However while overall inventory is controlled via the total number of cards available, inventory between processes within the system are not and all product is pushed. Thus, for a product to enter the CONWIP loop a card must be available for it to be attached to, and the cards is not made available again until the product exits the CONWIP loop (Huang et. al., 2007; Framinan et. al., 2006). The combination of push and pull in a CONWIP system allows it to buffer work content variation between products and processes and better handle the issue of shifting bottlenecks due to variety (Takahashi, et. al., 2005).

- ***SMED*** (single minute exchange of dies) refers to the rapid changeover principle of lean manufacturing. If a firm is to have leveled, mixed model production, then lengthy changeovers must be eliminated. Wantuck, (1989), uses an example of Toyota changing over the die in an 800 ton press in less than ten minutes, a process that took one to two shifts at his own facility. Wantuck also claims that this was accomplished not with costly automation, but with rigidly applied systematic processes and some clever engineering.

Rapid changeovers are an enabler for continuous flowing, mixed model production with a pull system.

- ***Jidoka***

The Japanese term *jidoka* refers to in process quality, or quality at the source. One key area of source quality is *poke yoke*, or error proofing using simple mechanized error proofing devices. Conversely, many quality check elements can only be performed through sensory perception, which is the role of the man, not the machine.

***Andon*** is a highly visual and audible notification method in the form of a lighted, multi-colored board hung in a factory (Monden, 1998). Toyota, for example, places a cord and a light at each workstation. Team members can pull the cord to announce a problem, and stop the line if need be (Bicheno, 2000; Shingo, 1986).

***Problem solving*** is another important aspect to source quality. When a defect is created, multi-function work teams often work together to solve the problem and eliminate the threat of reoccurrence in the future. One example of such a team, given by Tsutsui (1998) is Toyota's quality circle, a cross disciplinary work team dedicated to solving problems that arise on the production floor.

- ***Waste Reduction***

Waste reduction is an important structural component of the Toyota house. The very term "lean" implies that wasteful excesses across the plant are sought out and eliminated. There are three types of waste, with the Japanese terms *muda*, *mura*, and *muri*.

- ❖ ***Muda*** refers to various wastes dealing with production and quality that occur on the shop floor. There are seven types (see Figure 2.4) (Womack, 1996; Bicheno, 2000; Ohno, 1988).

- ❖ ***Mura*** refers to the waste of overburden on workers. An employee whose work is too burdensome is more prone to defects and less empowered to aid in improvement (Ohno, 1988).

- ❖ ***Muri*** refers to the waste of unevenness. This relates to the benefits of heijunka as opposed to batch production as discussed earlier (Ohno, 1988).

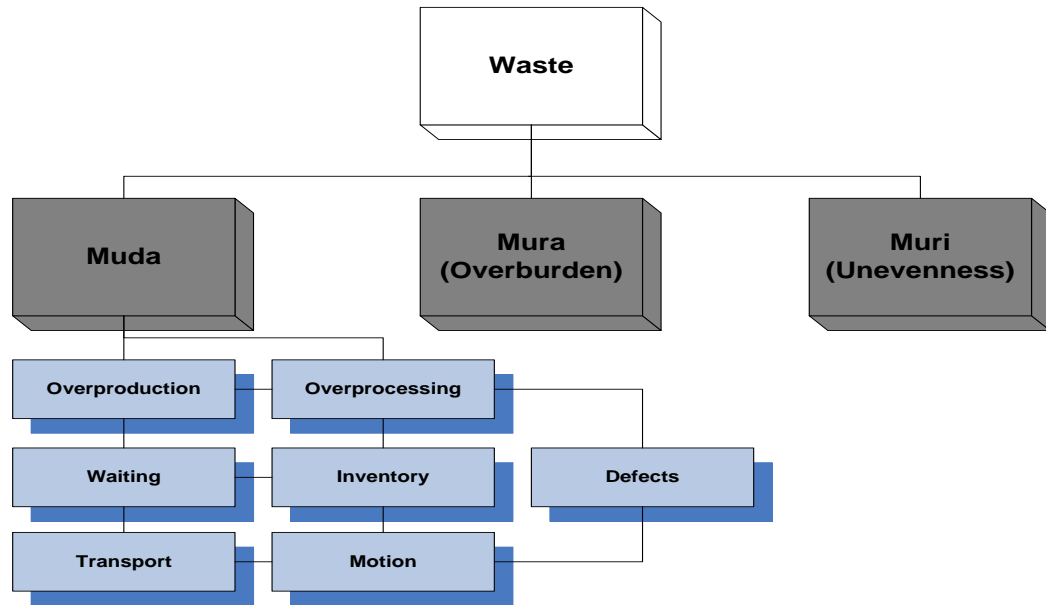


Figure 2.4 Different Types of Waste

- ***Continuous Improvement***

Lean systems are dynamic and change through continuous improvement, or kaizen. Improvements can be achieved through two types of kaizen; flow kaizen and process kaizen (Bicheno, 2000). Flow kaizen refers to improvement made throughout the value chain, while process kaizen refers to improvements that are isolated to specific processes. Everyone in a lean organization is responsible for improvements, from the team members to the plant manager. A lean organization understands that continuous improvement is the only way to improve upon the standard and stay competitive.

- ***People and Teamwork***

The people of a lean organization are what truly makes it work, and thus are supported by the components discussed above. While mass production sought to atomize work and eliminate employee thinking, lean manufacturing seeks to empower the worker, standardize the process, and encourage team members to improve their process. Lean manufacturing makes use of work teams, consisting of a small number of team members (5-10) who work under a team leader. Those team leaders are assigned a group leader, who may report to an assistant manager (Ohno, 1988). This system enables close relationships among employees, creating an environment conducive to safety and

improvement. Lean leaders also follow a model of servant leadership, meaning that the leaders function is to support and serve their team members.

### ***Summary***

The building blocks that make up a lean manufacturing system have been discussed briefly, and it becomes obvious that while many limit lean to simply a JIT or TQM practice, it in fact involves much more than that. Lean manufacturing implies a shift in the very culture of an organization; it is a philosophy or way of doing business that includes production methods, planning, and the way it treats people. Lean manufacturing is an all encompassing method for operating a manufacturing firm in an effective manner.

## **2.2. Mass Customization Overview and Classification Systems**

Mass customization began to emerge as a viable manufacturing strategy in the early 1990's and has since grown in popularity. Many businesses began to find that their markets were becoming more fragmented and customers were demanding more individualization, and sales were being lost to competitors able to deliver custom goods in a timely manner (Pine 1993). The main characteristic of mass customization is that absolutely no work is done in the manufacture of a product until the customer order is received. This differs from the pull system and "make-to-order" operations in that there is no forecasting and each order is unique. Essentially, a particular order does not exist in the system until the end customer submits it (Lampel and Mintzberg, 1996). Mass customizers often make use of some sort of product configuration tool such as a salesperson or software to assist the customer in choosing their options (Boynton et. al., 1995).

Systems operation for mass customization manufacturing can be very different from the single pull scenario of lean manufacturing as the manufacturer could potentially receive many signals from individual consumers rather than distributors or retailers. The effects of these multiple signals on operations depend upon the extent of mass customization; some strategies may have little or no impact, while others may alter it completely.

Prior to an in depth evaluation of the applicability of lean principles for mass customization, a system for the classification of different mass customizers is necessary.

This will allow firms to be classified based on business strategy, and identify capabilities needed for the particular type of mass customization. The following sections provide an overview of four well known mass customization classification systems, with an analysis to assess their suitability to serve as a framework to investigate the potential of using lean manufacturing principles and practices for mass customization.

### **2.2.1. Single Dimensional Classification Schemes**

#### **Pine (1993) Model**

Pine (1993) divided mass customizers into five different groups based on where customization takes place in the value chain: Development, production, marketing, or delivery. The first group is the *customizing of services around standardized products and services*. This is based on the ability of marketing and distribution to customize products by offering different services to customers, adding features to the product, packaging, etc.

For the second group, *create customizable products and service*, customization takes place in either the development or marketing stage of the value chain, while not affecting the production and delivery stages. With this system, a product is still mass produced, but because of the way it is designed, it will customize itself to the user.

*Provide point-of-delivery customization* involves catering to the customer's needs at the point of sale. Pine (1993) uses the age old practice of tailoring as an example. A customer chooses a standardized style of suit, after which the tailor measures and fits the suit to the customer's specific body dimensions, thus providing on the spot customization.

With *provide quick response throughout the value chain* customization begins at the delivery stage, and then filters back through the value chain all the way to development, causing the entire value chain to have to adapt rapidly to customer needs. The Hertz's #1 Club Gold is an example of this strategy, where the tasks of transporting customers, preparing vehicles, service contracts, etc. cannot be accomplished without a highly adaptive value chain (Pine, 1993).

The final mass customization strategy in Pine's (1993) classification is to *modularize components to customize end products and services*. Pine claims that this method of



using standard modular components as a basis for mass customized products is the most effective strategy.

In summary, this early classification model sought to break down the different mass customization strategies using point of customer involvement in the value chain. Pine's model displays a wide range of mass customization behaviors, however little attention is paid to mass customization in the design and production stages. This initial model is focused mainly on using as much standardization as possible while providing customization in the marketing and delivery stages. The concept of modularity is employed in one of the five strategies, but the concept's true place in mass customization practice seems to be underdeveloped.

### **Lampel and Mintzberg (1996) Model**

Lampel and Mintzberg (1996) divide manufacturers into five different groups: *Pure Standardization*, *Segmented Standardization*, *Customized Standardization*, *Tailored Customization*, and *Pure Customization*.

***Pure Standardization*** is "...based on a "dominant design" targeted to the broadest possible group of buyers, produced on as large a scale as possible, and then distributed commonly to all." With this strategy, the product is completely standardized with no distinctions made between customers, as with Henry Ford's Model T (Lampel and Mintzberg, 1996).

***Segmented Standardization*** involves building to the needs of "clusters" of buyers, with the product remaining standardized within those clusters. Here, customization is decided upon and produced based on predictions of customer needs rather than individual customer requests, as with designer lamps (where one can find huge variety without individualization) (Lampel and Mintzberg, 1996).

***Customized Standardization*** occurs when "...products are made to order from standardized components." Also known as assemble to order, this strategy simply allows the customer to decide what mass produced features, are or are not, present in their individual product. Allowing a customer to choose the options on their particular automobile, or choosing what ingredients are present in their hamburger at a fast food restaurant is an example (Lampel and Mintzberg, 1996).

***Tailored Customization*** occurs when “The company presents a product prototype to a potential buyer and then adapts or tailors it to the individual’s wishes or needs.” Here customization filters back to the fabrication stage, but not to the design stage, as there is still a standardized product prototype.

***Pure Customization*** is the highest degree of mass customization attainable, according to the Lampel and Mintzberg Model. Here, the customer’s needs are outlined and catered to beginning early in the design process, greatly affecting all steps of the value chain. Traditional artisans such as jewelers or residential architects, who design and build the product to the customer’s specifications, fall into this category (Lampel and Mintzberg, 1996).

This framework of classifying mass customizers is slightly more developed and a more concrete classification model than that of Pine, (1993). However, the first two classifications listed; pure standardization and segmented standardization, do not involve mass customization strategies at all. Further, this model, too classified strategies only by customer involvement in the value chain in the assembly, delivery, or design stage (for customized standardization, tailored customization, and pure customization, respectively).

### ***Gilmore and Pine (1997) Model***

Gilmore and Pine (1997), divided mass customizers into four groups: *Collaborative, Adaptive, Cosmetic, and Transparent customizers*. This model is an improvement over Pine’s previous model (1993) in that the criteria for each category have become more clearly defined and the model has shifted to include more customization in the design and fabrication stages.

***Transparent Customizers*** customize products based on predictions and observations of customer’s needs. In this case, customers do not know that the product has been customized for them. On the other hand, ***Cosmetic Customizers*** customize their products by making it appear different to different customers. Custom features can include packaging, specific feature advertisement, and personalization such as engraving.

With *Adaptive Customization* manufacturers produce a standard product which will then automatically adapt itself to a customer's needs. Here the desire is for the product to perform differently based on the specific need at a given time.

*Collaborative Customizers* work one on one with individual customers to understand and cater to their specific needs. This strategy most embodies the idea of mass customization as we usually think of it.

The Pine and Gilmore model is a much more generalized classification system compared to the two previous models. Here, the idea of a transparent customizer, one who customizes products without customer specifications, is a new and intriguing idea not considered in the earlier taxonomies. The customer essentially is only involved in the delivery stage, but their specific needs are taken into account from the design stage in that the mass customizer determines the needs of the customer themselves. We also find once again that three of the four strategies allow for customer involvement only in the assembly and/or delivery stages, and modularity is again unaccounted for.

### **2.2.2. Two Dimensional Classification Schemes**

The three classification schemes above include only point of customer involvement in their classification criteria. However, modularity is also an important aspect of mass customization.

When examining mass customization, one key concept that has played a large part in its success to this point is *modularity*. Swaminathan claims that modularity can be present in product, process, or both. A *modular product* can be manufactured by combining standardized modules into variable configurations. A *modular process* occurs when different products undergo the same set of processing steps (Swaminathan, 2001). Pine claimed that for true mass customization to take place efficiently, modularity must be used (Pine, 1993). Also, Duray states that modularity is a means to achieve some degree of economies of scale, as well as to "...provide variety and speed..." (Duray, 2000). Modularity allows firms to create base components, a kind of common denominator, among different product lines, thereby allowing for increased efficiencies for an individually customized product.

### *Duray et. al. (2000) Model*

The mass customization classification system developed by Duray et al. (2000) is one of the more recent and most advanced because it classifies mass customizers on two dimensions; point of customer involvement in the value chain, and type of modularity used by the producer. They divide mass customizers into the following four groups: *Assemblers, Modularizers, Involvers, and Fabricators.*

*Assemblers* involve the customer and use modularity in the assembly and delivery stages, enabling the customer to select different combinations of standard features to be interfaced with a base model of product.

*Modularizers* are characterized by involving the customer in the assembly and delivery stages, but using modularity in the design and fabrication stages. The producer uses standard modules to design and fabricate a base module, and specific customer needs are incorporated in assembly and delivery.

*Involvers* involve the customer in the design and fabrication stages while using modularity in the assembly and delivery stages. Customers are involved early in design, but this design must be created from a selection of standardized modules, as no new modules will be designed for them.

*Fabricators* involve the customer and make use of modularity during the design and fabrication process. Customers create their custom design, but modularity can be used to some degree to create similarities in components.

Major differences are present between the Duray et. al. model and others; this model not only classifies mass customizers based on point of customer involvement, but also use of modularity. Further, it is more detailed and able to identify mass customization in the early stages of the value chain. These are the major strengths of this latest model over the previous ones. Though modularity is mentioned in the Pine (1993) model, its usage and importance to mass customization is developed in greater detail in the Duray et. al. (2000) model. See Figure 2.5 below for a graphical representation of this model.

		Type of Modularity			
		Design	Fabrication	Assembly	Use
Point of Customer Involvement	Design	1 Fabricators		2 Involvers	
	Fabrication				
	Assembly	3 Modularizers		4 Assemblers	
	Use				

Figure 2.5 Duray et. al. (2000) Model for Mass Customization Classification

### 2.2.3. Comparison and Selection

In investigating the potential of applying lean manufacturing principles and practices for mass customization, a well defined taxonomy helps to classify, compare, and contrast different mass customizers. The time based progression and evolution of mass customization thinking is evident when examining the different models detailed above. As each model is developed, one can see the divisions between groups of mass customizers becoming clearer while the focus begins to shift towards customer involvement in the early stages of the value chain. Finally, in the latest model outlined here we have the aforementioned improvements becoming more developed, along with a new focus on a key concept in mass customization; modularity.

In the following section, a basic decision matrix is used to compare and contrast the strengths and weaknesses of each of the four models, the result of which will allow one of them to be chosen for further use in this article. The models are evaluated based on the following criteria as per the authors' opinions and observations.

**Customer Involvement:** Ability to classify customizers based on customer involvement in the key value chain areas of design, fabrication, assembly, and delivery.

**Modularity:** Ability to classify customizers based on modularity usage in the key value chain areas of design, fabrication, assembly, and delivery.

**Early customer involvement (CI) Focus:** Tendency for the model to focus on customization early in the value chain.

**Strength of Classification:** Ability of the model to crisply define and classify a mass customizer into one of its respective categories.

Each model is scored on a three point rating scale (corresponding to 0, 1, and 2 points) in order to identify their strengths and weaknesses. Figure 2.6 presents these results.

As can be observed from Figure 2.6, it is evident that when considering the concepts of customer involvement and modularity across the value chain spectrum, the Duray, et. al. (2000) model provides the most complete mass customization classification system. The model also provides detail on early customer involvement in the value chain, and therefore is the most appropriate for use in the following sections.

MASS CUSTOMIZATION CLASSIFICATION MODELS											
	Customer Involvement				Modularity				Early CI Focus	Classification Strength	Total
	Design	Fabrication	Assembly	Delivery	Design	Fabrication	Assembly	Delivery			
Pine (1993)	✘	▲	●	●	▲	▲	✘	✘	✘	▲	8
Lampel/Mintzberg (1996)	▲	▲	●	●	✘	✘	✘	✘	▲	●	9
Pine/Gilmore (1997)	▲	▲	●	●	✘	✘	✘	✘	▲	●	9
Duray et. al. (2000)	●	●	●	●	●	●	●	▲	▲	●	18

✘ = 0	▲ = 1	● = 2
Little or no evidence of criteria consideration	Moderate amount of criteria consideration and development	Criteria fully considered with well developed ideas and definitions

Figure 2.6 Classification Model Decision Matrix

### 2.3. Low Level and High Level Customization

Having chosen the Duray (2000) model for further mass customizer analysis, it is possible to create two more general categories based on the similarities between involvers/fabricators and modularizers/assemblers and the impact to the manufacturing operations. These categories will hereafter be referred to as *high level customization* and *low level customization*, based on the point of customer involvement in the value chain.

A high level customizer is a company where customized goods are offered through customer involvement at the fabrication stage or earlier. With low level customization, individualization is achieved by assembling (and/or packing and distributing) pre-fabricated, standard components in a custom manner.

A low level customizer will find it much easier to employ process modularity and will be able to more efficiently plan production so that WIP is reduced and flow is maximized. A high level customizer, on the other hand, will find the need for a highly flexible manufacturing system configuration much greater than the former, and will also be more reliant on organizational learning in order to improve. The two situations are illustrated in Figure 2.7.

Low level customization includes the assembler and modularizer strategies from the Duray model (Duray, 2000). In the case of assemblers, customized products are produced through assemble-to-order customization with customer involvement and modularity usage occurring at the assembly or delivery stage. Modularizers operate in a similar fashion, but they differ from assemblers in that modularity is employed in the design or fabrication stage (Duray, 2000). In either case, the design and fabrication stages of the value chain remain unaffected by customer involvement, warranting the combined discussion of these two strategies.

With these strategies, product modularity and postponement are used to reduce the variability and facilitate mass customization efficiently. Lean manufacturing principles and practices are very applicable in this context where standardized modules can be produced to forecasted demand (in the design and fabrication stages) for assembling-to-order as illustrated in Figure 2.8. As pull signals from consumers come in, those modules are assembled to the required configurations. However, upstream processes will only have a single pull signal from the upstream customer.

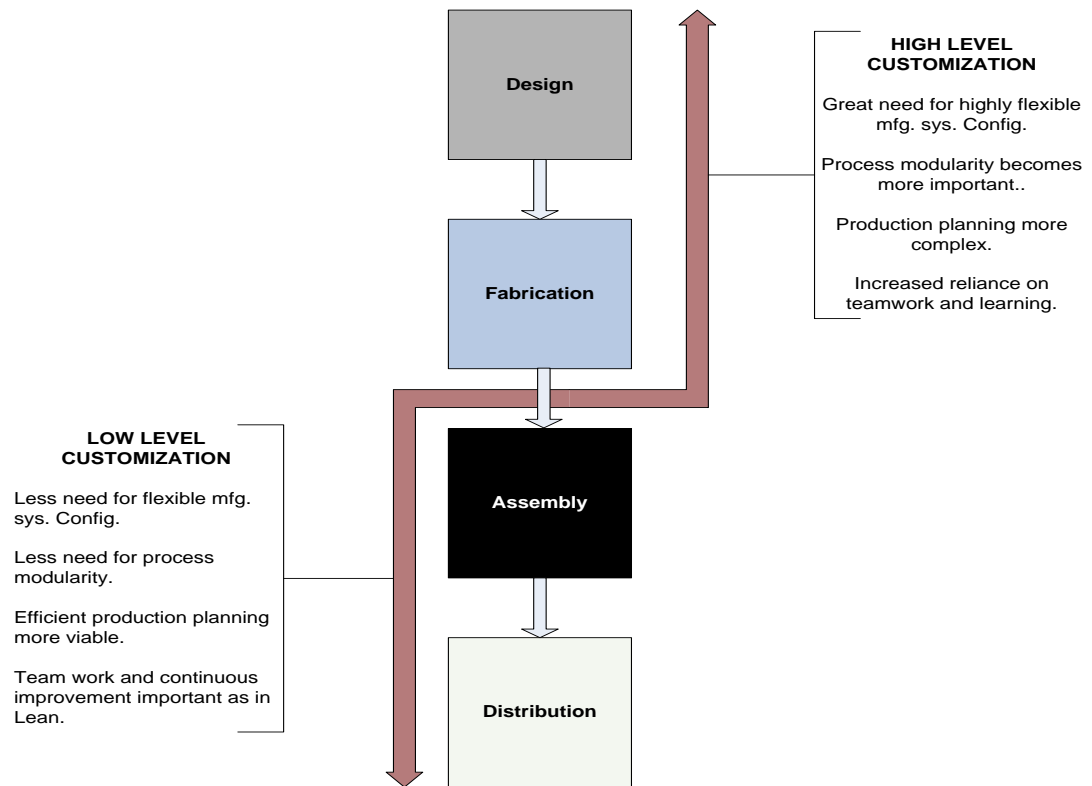


Figure 2.7 High Level Customization vs. Low Level Customization

High level customization, which includes the involver and fabricator strategies (according to the Duray model) involve the customer in either the design or fabrication stages of the value chain, allowing the customer to take part in the design of their product before its production has commenced. The difference between the two strategies lies in the point where modularity is employed in the production system. Involver make use of modularity in the assembly/delivery stage, while fabricators employ modularity in the design/fabrication stage. High level customization offers a high degree of customization by integrating the customer early in the value chain.

These strategies have a great effect on production because manufacturing must wait for the customer orders to begin fabrication, and then follow the customer's specifications in order to fabricate and assemble a customized product, with each successive product being different from the last. Thus lean manufacturing is not so easily adapted to high level mass customization, as it is essentially impossible to forecast



demand and plan for work content variability. See Figure 2.9 for a representation of the value chain for a high level customizer. These mass customization classifications are employed in the upcoming sections for discussions regarding integrating lean manufacturing and other strategies with mass customization.

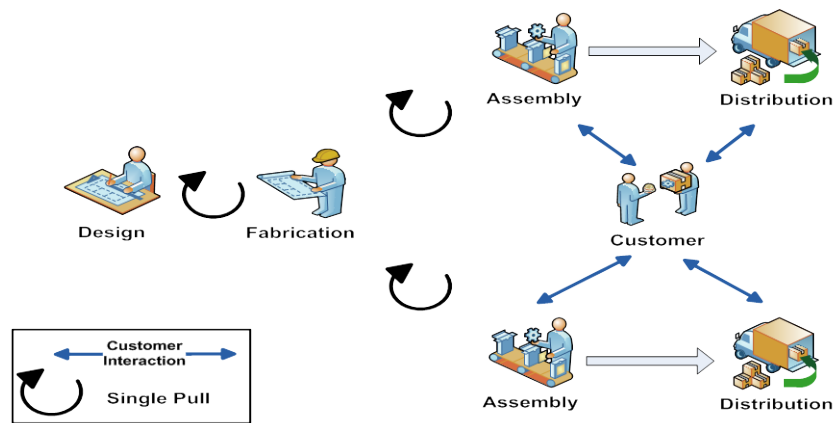


Figure 2.8 Low Level Customization

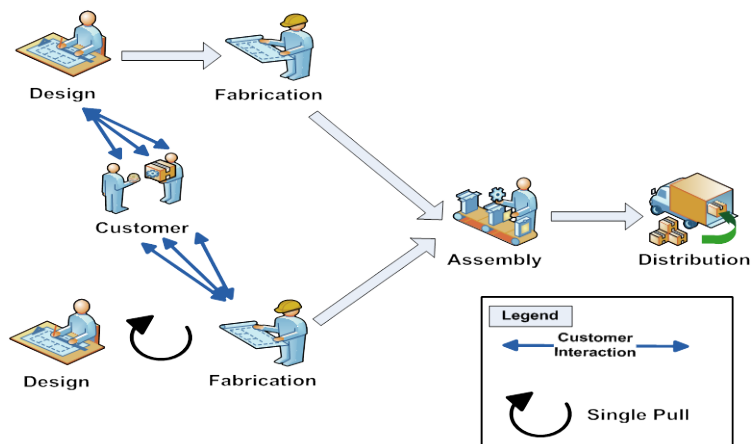


Figure 2.9 High Level Customization

### 3. Literature Review

In this chapter, an account of the literature found through the course of the research for this document is given, beginning with an overview of the competencies required of any organization that is to be successful in its quest to become a mass customizer. The competencies discussed therein pertain to both the production area of a manufacturing firm, as well as external areas such as logistics and information technology.

Next, an account of the available literature providing evidence of successful incorporation of lean manufacturing principles into a mass customization environment is given in order to lay the foundation for what has already been accomplished in this area. Lastly, an overview of some other strategies common in manufacturing is given along with a discussion of their application and benefits in order to investigate the feasibility of employing them in mass customization situations where lean manufacturing may fall short.

#### 3.1. Competency Models

Mass customization is a complete paradigm shift from traditional manufacturing, thus identifying appropriate manufacturing system configurations and evaluating the use of lean manufacturing principles and practices mandates a review of the capabilities necessary to successfully implement it. According to Moser (2007), there is currently no concrete, empirically founded set of core competencies that have been proven necessary to pave the road towards mass customization and increased performance and market share. However, there is ample literature that conceptually describes some of these necessary capabilities (Moser, 2007). In an effort to identify mass customization competencies, two models are evaluated.

Zipkin (2001) identified three major capabilities for successful mass customization as *elicitation, process flexibility, and logistics*. These terms are defined as follows:

**Elicitation** is the process of interacting with customers to determine their specific needs. This includes activities such as marketing, product configuration (via salesperson, Internet, etc.), and gathering the required information to customize the offering (Berman, 2002; Zipkin, 2001).

**Process Flexibility** refers to the various production methodologies and technologies that make the production of customized products possible. Flexible Manufacturing Systems (FMS), Reconfigurable Manufacturing Systems (RMS), effective production control and scheduling, and human factors such as team structures and cross training facilitate achieving process flexibility (Berman, 2002; Zipkin, 2001).

**Logistics** refers to processes involved in delivering raw materials to the production floor and delivering finished products to the customers. Here, mass customizers face a greater challenge than traditional manufacturers because the product must often be delivered to specific customers rather than distribution centers. Individual products must be tracked, customized, and delivered to the customer (Berman, 2002; Zipkin, 2001).

Moser (2007) presented another, more comprehensive model to classify capabilities for mass customization, defining eight distinct categories. He also exemplified the impact of these competencies using the mass customization value chain. Figure 3.1 provides the competency model put forth by Moser (2007), while Figure 3.2 illustrates the interaction of these capabilities in the value chain.

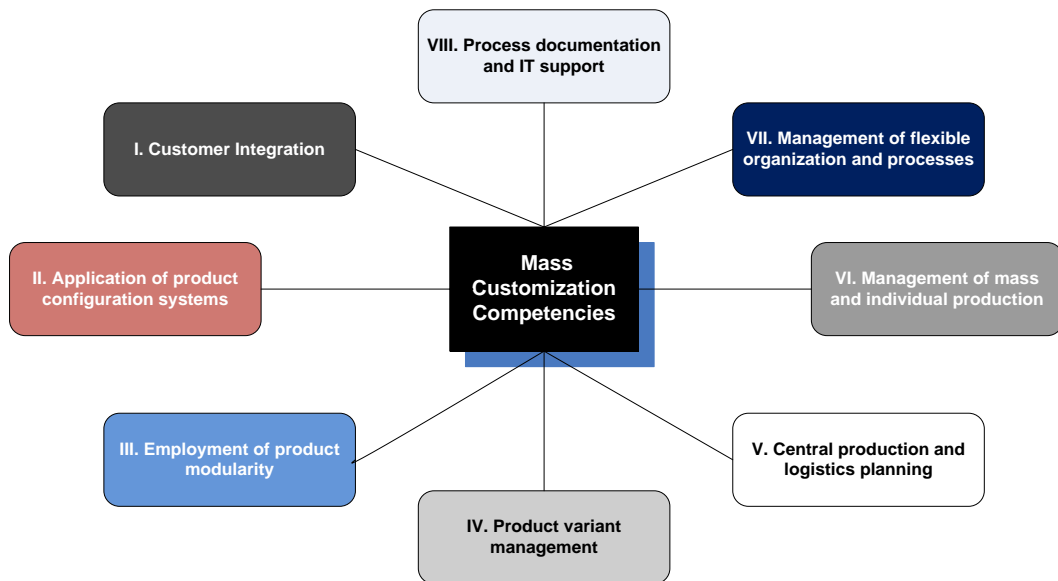


Figure 3.1 Mass Customization Competencies (Moser, 2007)

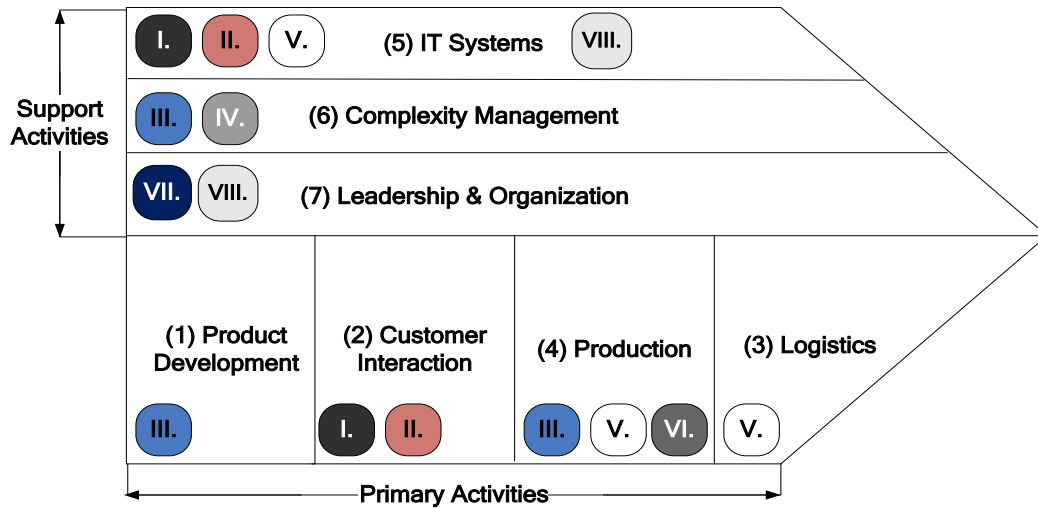


Figure 3.2 Mass Customization Value Chain based on (Moser, 2007)

Moser's model is more descriptive, identifying the capabilities needed in manufacturing and support activities as well, while the Zipkin model mainly focuses on primary activities of the value chain. However, both models cover the wide range of activities that must come together as one in order for a mass customized product to be marketed, configured, manufactured, and delivered. Restricting the discussion to the focus of this thesis, a detailed review of production competencies is provided in the following sections. A brief assessment of non-manufacturing (other) competencies is also provided.

### 3.2. Production Competencies

Production competencies are the various capabilities a firm must possess to efficiently receive orders from individual customers and manufacture them with short lead time and low cost; to operate under mass customization conditions. Based on the research reviewed and empirical evidence, these capabilities can be broadly classified into the following; *manufacturing system configuration* (Koren et al., 1999; Mehrabi et al., 2000; Berman, 2002; Zipkin, 2001), *process modularity* (Swaminathan, 2001; Selladurai, 2003), *production planning* (Da Silveira et al., 2001; Zipkin, 2001; Selladurai,

2003), and *organizational learning and continuous improvement* (Barnett et al., 2004; Pine, 1993). These manufacturing competencies are reviewed in further detail in the following sections.

### ***Flexible System Configuration***

Flexibility of the manufacturing system is a key success factor for a mass customizer. Zipkin (2001) dedicated one of his three areas of mass customization capabilities solely to process flexibility. Moser (2007) also places value on a flexible manufacturing system configuration with the capability labeled “Management of flexible organization and processes.” A company cannot hope to produce a mass customized product without a highly flexible and adaptive manufacturing system configuration.

There have been some improvements in strategy over the outdated dedicated manufacturing systems (DMS) (Koren et al., 1999; Mehrabi et al., 2000). Two such systems are flexible manufacturing systems (FMS), and reconfigurable manufacturing systems (RMS). An FMS is characterized by expensive computer controlled machines capable of producing a variety of products with variable volume mixes (Koren et al., 1999). FMS, however, has its drawbacks, which include lower throughput than DMS, high cost (due to producers building all possible functions into the machine regardless of its final set of tasks), inability to easily modify software, and the equipment being designed to operate at full capacity from purchase (Koren et al., 1999, Mehrabi et al., 2000).

According to Mehrabi et al. (2000), some of the key requirements for the future of manufacturing is rapid new product ramp up, “...rapid integration of new functions and process technologies into existing systems,” and high capacity flexibility, which they postulate can be provided through RMS.

An RMS consists of a highly flexible set of machines that are manufactured specifically for a certain product family, and are designed with a “middle of the road” capacity in mind, supplying capacity flexibility for changing market conditions. Thus, the RMS makes use of modularity both in machine and software to allow for quick capacity adjustment, low changeover/setup between products, rapid adaptability of

software, and quick ramp up to new product production. Table 1 provides a comparison between DMS, FMS, and RMS.

Table 1. Manufacturing System Comparison (Koren et. al., 1999)

	DMS	FMS	RMS
Machine Structure	Fixed	Adjustable	Fixed
System Focus	Part	Part Family	Machine
Scalability	No	Yes	Yes
Flexibility	No	Customized	General
Simult. Oper. Tool	Yes	Yes	No

Another manufacturing system configuration, proposed by Badurdeen and Masel (2007) is the modular minicell approach. They state that traditional cellular manufacturing usually consists of cells dedicated to a product family based on machine requirements. However, in a mass customization environment, there may be a limited number of products with a large amount of variations. If one were to build a cell that contained all the processes and machines needed to handle these variants, the cell would likely become large and unmanageable.

The proposed solution to this issue is to segregate products by the options that are or are not required for their manufacture. This will allow a network of minicells to be configured with the operators and machines necessary to produce a particular option. Thus, with this network of small cells in place, products and parts may be routed through the necessary minicells, while bypassing the unnecessary ones (Badurdeen and Masel, 2007; Badurdeen and Thuramalla, 2007).

Whatever the method, there is no doubt that for successful mass customization to occur, there must be a flexible and highly responsive manufacturing system configuration in place on the production floor. FMS, RMS, and minicells are just a few examples of the possible techniques for efficient mass customization.

### ***Process Modularity***

Modularity is a key concept for successful mass customization, enabling the creation of some commonality between products and allowing for higher efficiencies to be achieved while also permitting customization. Ulrich and Tung (1991) define modularity

as "...the use of *interchangeable* units to create product variants." As mentioned earlier, the two most general types of modularity are *product modularity* and *process modularity* (Swaminathan, 2001; Selladurai, 2003). The former is a design challenge while the latter is more significant from a systems perspective. Again referring to Zipkin (2001), process modularity falls under the process flexibility category. Moser (2007) accounts for process modularity by claiming that variant management, process documentation, and flexible processes are among the mass customization required capabilities.

A modular process is "...one where each product undergoes a discrete set of operations making it possible to store inventory in semi-finished form and where products differ from each other in terms of the subset of operations that are performed on them" (Swaminathan, 2001; Selladurai, 2003). A modular process allows a team member to be trained to do a set of operations (not necessarily based on a specific product), enabling the manufacture of many different products based on the general set of steps to be completed in the processing.

Postponement can be used along with modularity in both product and process to enable a higher degree of customization (Berman, 2002). By performing standard operations using standard modules and postponing customization until latter stages of processing, a firm can achieve higher efficiency, lower costs (purchasing modules in bulk, and mass production of modules), and reduce inventory on-hand (Berman 2002; Swaminathan, 2001). One example of such a strategy is that of Hewlett Packard (HP) Deskjet Printers. Historically HP produced its printers to completion at a single location but later began to use modularity and postponement. HP now assembles a base product using modular components and processes at a central locale, while the printers are later fully customized at various distribution centers. This change in strategy amounted to a reported 25% reduction in total cost of manufacture (Lee and Feitzinger, 1995).

### ***Dynamic Production Planning***

When purchasing customized products, customers are not willing to wait a large amount of time to receive them. Thus, the challenge with mass customization is achieving low throughput and lead times while enabling customizability. This necessitates reducing the amount of inventory on hand and the amount of WIP (work in

process) on the floor in order to maintain visibility of the system and reduce throughput through better flow. According to Swaminathan (2001), the keys to determining correct inventory levels are deciding "...which products to build-to-order, which to build-to-stock, and which products may be substituted for another if need be." Also important to maintaining inventory levels is the proper determination of capacity requirements. Accurately predicting over and under utilization of equipment and taking measures to control capacity can help to control inventory levels and maintain predictability (Swaminathan, 2001).

All of these key issues fall under the area of production planning. Zipkin (2001) accounts for production planning in the elicitation and logistics areas. Moser (2007) claims that central production and logistics planning, as well as management of individual and mass production are among the eight key mass customization capabilities. This leads to the notion that effective production planning is important for efficient mass customization.

### ***Organizational Learning and Continuous Improvement***

According to Selladurai (2003), the "...traditional mass production company is bureaucratic, hierarchical, and highly standardized. Workers operate under close supervision and perform highly routine, standardized, and repetitive tasks." Mass customizers will require a new breed of highly skilled workers, capable of working in cross functional teams and performing a multitude of tasks (Pine, 1993). Mehrabi, et al. (2000) state that the "...restructuring of organizations emphasizes moving from highly centralized to decentralized team-work (i.e., essentially creating modules and dividing the tasks among them to enhance flexibility, integration, and faster execution of new tasks)."

Mehrabi, et al. (2000) alludes to the concept of an intellectual worker, one which continually strives to gain further knowledge of product and process to better support their company and work team. The concept of the intellectual worker was first proposed by the lean manufacturing movement as a means to continuous improvement (Selladurai, 2002), and this trend must continue into mass customization. Given that "...mass customization environment typically entail shorter product life cycles..." thus intellectual workers capable of learning and continuous improvement are needed (Swaminathan, 2001).



Moser (2007) also accounted for learning and continuous improvement in his mass customization capability model. Moser's seventh capability is management of flexible organization and processes. Indeed, it is important that the mass customizing organization, from team member to manager, be flexible and strive to continuously learn. Only through learning can improvement take place. The knowledgeable and empowered employee will be vital to the swift introduction of new products. Thus, employees of a mass customization firm must be empowered to make decisions and actively pursue new knowledge in order to produce quality products with low lead times, and allow their firm to continually introduce new and improved products with rapid ramp up so as to maintain and increase market share.

### **3.3. Other Competencies**

Though not the focus of this paper, *external competencies* are noteworthy because they impact the production operations and system effectiveness for mass customization. The major non-manufacturing competencies significant for mass customization include: *IT and Customer Interfacing, Product Development, and Logistics*. These competencies are discussed briefly in the following sections.

A major development that has led to more prominent use of mass customization is the ever increasing popularity of internet business (Selladurai, 2002). The Internet has allowed producers to create web-based "product configurators," which allow customers to personalize products to individual preferences, within solution spaces defined by the producer.

In the past, customer interaction (*elicitation*) was costly and time consuming because it was performed by "skilled sales people," and thus was often reserved only for high volume consumers (Berman, 2002). Irrespective of the method, it is imperative that the consumers are able to decide on preferences, and then accurately convey their preferences to the producer in a timely manner. The ability to provide these capabilities to consumers can have a great effect on a company's market performance (Boynton and Pine, 1993). The IT aspect of mass customization directly influences the shop floor operations in that customer orders for specific products must be communicated accurately, scheduled appropriately, and materials made available to deliver custom products in a short lead time.

A mass customizing firm must be able to quickly and efficiently introduce new products into the markets in order to keep up with dynamic market conditions. Sanderson and Uzumeri claim that “the emergence of global markets has fundamentally altered competition as many firms have known it.” This has resulted in “forcing the compression of product development times and expansion of product variety” (Sanderson and Uzumeri, 1997). This does not mean, however, that standardization and commonality cannot be made use of. It has been found that the increasing focus on individual customers has led to “a failure to embrace commonality, compatibility, standardization, or modularization among different products or product lines” (Meyer and Lehnerd, 1997). This leads to the idea that product design is vital to the success of a mass customizer. Tseng et al. (1997) present the idea of *product family architecture (PFA)*, a set of products with some commonality and standardization that can be produced as a family, possibly among a work cell on the production floor.

Proper product development practices are directly related to the shop floor in that the developed product must be produced there. The more a developer makes use of standardization, modularity, and commonality, the easier and more efficient the task of production will be.

The third aspect of mass customization external competencies is that of logistics. Zipkin (2001) describes logistics as “...additional processing and transportation tasks.” One key issue with producing individualized products is that they must be tracked and produced by specific customer. One example of how a current mass customizer accomplishes this is Levi Strauss, who attaches a water proof barcode to the cloth with the customer’s information. This enables the products to be washed together, while maintaining the products individual identity (Zipkin, 2001).

Also vital to mass customization logistics is the supply chain, which must be coordinated and constantly in contact with the client. Berman (2002) claims that the key to a mass customized supply chain is “...close relationships with channel partners more capable than the firm in performing specific channel functions.” The important concept here is a close, partnership like relationship between supplier and client. This will allow for increased communication, trust, and integration between entities, enabling a mass customizer to obtain materials as needed.

The third aspect of logistics is distribution, which is difficult since products are now sent to individual customers, rather than “middle men” as with traditional manufacturing. Zipkin (2001) states that “...technologies underlying e-commerce logistics (including the internet, automated warehouses, and package delivery services) continue to develop, they will help bring mass-customization systems to fruition. Today’s problems are opportunities for such companies as Federal Express and United Parcel Service (UPS).”

Logistics is related to production in that it is vital for the shop floor to receive raw materials and components when they need them, so as to be neither starved nor overburdened with material. Finished goods must also be quickly transported from production floor to customer upon completion of processing.

### ***Discussion***

In the previous sections, mass customization competencies presented by different authors were reviewed, and based on these four broad categories of competencies required for successful mass customization manufacturing have been identified. It is evident, however, that as the degree of customization varies for different mass customization classification schemes as discussed in Chapter 2, so does the extent to which these competencies effect production. Having established these competencies, the objective is to assess to what degree lean manufacturing principles and practices can meet them.

### **3.4. Potential for Applying Lean Manufacturing For Mass Customization**

A brief history of manufacturing evolution has been given and basic definitions of lean manufacturing and mass customization established. Also, an examination of mass customization classification schemes was given along with a discussion on mass customization and lean manufacturing capabilities. Having fully defined and discussed these two manufacturing strategies, a conceptual investigation into the transferability of lean techniques for mass customization is pertinent at this point. An attempt was made to find literature pertaining to the application of lean manufacturing principles for mass customization, but there seems be little work in this area.

Boynton and Pine (1995) claimed that becoming lean was an important step for a company wishing to transition to mass customization, but gave no details on the actual

employment of lean while mass customization is taking place. The theme of viewing lean as a transitional step to achieving mass customization occurs with some regularity in the literature, but on the possibility of actual integration of lean principles into a mass customizing operation there is no supporting material to be found. Several works refer to lean manufacturing in a build-to-order or make-to-order environment, but these essentially mean building only to demand as in a pull system (Michel, 2002; Clarke, 2005). Make-to-order operations differ from mass customization in that no work is done until the customer configures their individual product and delivers their specifications to the manufacturer. This work will attempt to provide some insight into this previously unexplored topic. See Figure 3.3 for a visual representation of the overlap between lean manufacturing and mass customization that is to be explored.

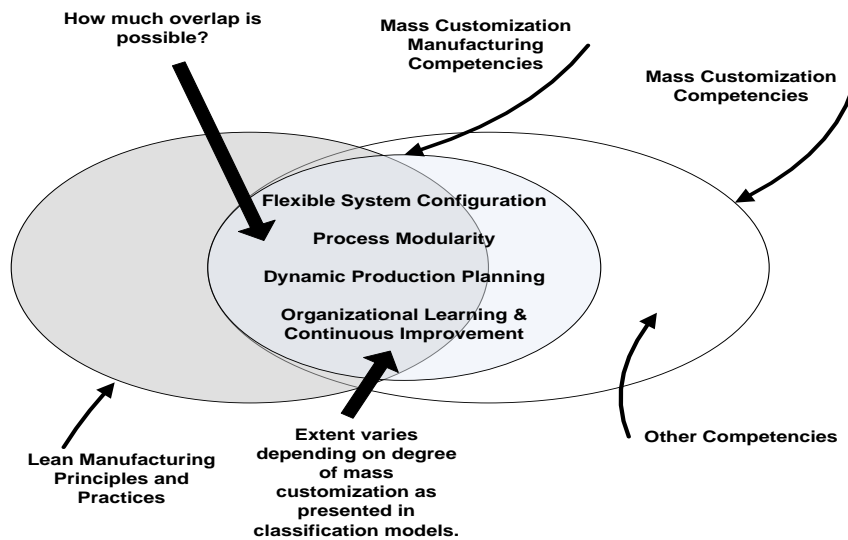


Figure 3.3 Mass Customization with Lean Principles and Practices

From the discussions above, it is evident that some aspects of lean manufacturing are directly transferrable to mass customization while others are not. Also, the lean capabilities and tools that are applicable will vary based on the type of mass customization in use. Lean manufacturing is readily adaptable to low level mass customization operations that delay customer involvement until later stages of the value chain such as assembly or delivery, but the uses of lean when the customer is involved in

the design or fabrication stage is much more abstract, and little research has been done on the subject.

It is obvious that some aspects of lean can easily be used, and are in fact likely required for efficient mass customization no matter what strategy is in place. One example of this is good team structures and continuous learning. An operation that hopes to use mass customization cannot do so without the intellectual worker. Employees must be highly trained and encouraged to continuously learn and share knowledge in order to improve their organization, just as employees of lean companies are required to do. This concept is even more important for mass customization however, as the difficulty and variability of the processing is significantly higher as variety increases.

Visual management is also a key lean practice that can be made use of in mass customization regardless of strategy. It is important to visually represent the status of the production floor at all times. This is especially so in mass customization as offering customized products while maintaining low lead times and throughput requires a high degree of organization. 5S can also be directly applied to mass customization, or to any environment, and will greatly aid in creating an organized shop floor.

Mass customizers must also seek to continuously improve their operations and eliminate waste wherever possible. While these lean capabilities may be more difficult in operation for some styles of mass customization, the principles still apply.

Lean concepts that are not so easily adapted to mass customization include stable and standardized processes, JIT, and Jidoka. The very definition of mass customization does not account for any degree of stability and standardization, and as variety increases and the customer becomes involved earlier in the value chain, these concepts become more difficult to apply. Nevertheless, some degree of standardization can be reached, however small, in any process. Tools such as process modularity can aid in creating some stability in the process when none is offered by the product.

Leveled production and JIT (which includes the concepts of takt time, pull, and continuous flow) are also very difficult to use in mass customization, at least for involvers and fabricators where customization occurs early in the value chain. When each product is completely individualized, accurately forecasting demand becomes increasingly difficult, and products are likely to have highly variable work content. This

makes leveling production and use of takt pacing a near impossibility in many mass customization environments. With little or no concept of takt and work leveling, it becomes difficult to continuously flow product through the plant. However, some degree of pull and flow can be implemented on the shop floor, especially with the aid of good visual management. This is much more possible for assemblers and modularizers.

Jidoka, or source quality, is also increasingly difficult to adapt to mass customization as the customer becomes involved early in the process. As products become increasingly more customized and variety rises, good quality control on the shop floor is more difficult. One can still implement self and successor checks, but with much lower degrees of standardization in the product and process, these checks become less efficient. When producing a product that was individually designed for a single customer, the concept of “good quality” becomes more obscure as there is essentially no quality example to compare the product to. The only quality standards available are those given in the design parameters. However, some degree of source quality can be used in any mass customization environment. For example, the characteristics of a quality weld are constant regardless of where and on what surface the weld is placed, and thus can be efficiently controlled with self and successor checks and other jidoka practices.

Above all, any firm, mass customizing or lean, should seek to continuously improve itself. Only through continuous learning, increased knowledge, and the active pursuit of solutions to problems and wastes can a producer hope to increase the efficiency of its operations and further itself in its market. While many common lean tools, such as takt pacing and leveled production, are seemingly inapplicable in some mass customization manufacturing environments, there are many lean aspects that can be transferred directly. Lean is often viewed as simply a set of tools and used interchangeably with terms like JIT and TQM, but lean is actually a *philosophy* that encompasses all aspects of production. Within this philosophy, there are certain “cultural” areas, such as team work, continuous improvement, visual management and 5s, problem solving, and waste elimination that can be directly applied to any mass customization environment.

### **3.5. Potential for Integrating Other Strategies**

Various other strategies have emerged in the literature to cope with changing market requirements. An investigation of these emerging strategies in the context of lean manufacturing and their applicability to mass customization is worthwhile at this point. These strategies include agile manufacturing, leagile manufacturing, job shop lean, Quick Response Manufacturing (QRM) and POLCA, and Theory of Constraints (TOC).

#### ***Agile/Leagile***

Agility is defined as "...using market knowledge and a virtual corporation to exploit profitable opportunities in a volatile market place," (Naylor et al., 1999). Indeed, unstable and volatile markets, characterized by short product life cycles and highly variable demand is one of the main drivers for becoming agile by developing market knowledge and methods to rapidly respond to volatility. Agile manufacturing is entirely different to the lean paradigm, and even mass customization (Stratton, 2003). The focus of agile manufacturing is fast response throughout the supply chain to mitigate the effects of variability, while mass customization is focused on delivering customized products to each individual customer. By nature, both paradigms are characterized by high variety and uncertain demand (Krishnamurthy et al., 2007).

Many studies have shown that neither lean nor agile supply is the answer to all production issues, but in fact a combination of both may often be the best solution. One such study consisting of a survey of some 600 companies in the United Kingdom concluded that it is more likely that lean and agile manufacturing should work together to be most effective (Yusuf and Adeleye, 2002, Agarwal et. al., 2006). This combination of lean and agile has been termed leagile and is defined as "...the combination of the lean and agile paradigms within a total supply chain strategy by positioning of the decoupling point..." (Mason-Jones et al., 2000). The decoupling point is the point at which the agile supply chain strategy and the lean supply chain are separated. Everything upstream of the decoupling point uses lean principles to enable leveled production from accurately forecasted demand, while all stages after the decoupling point use agile concepts to maintain customer responsiveness and buffer the volatility of the market. It is important to note that agile and lean sections must be used separately. This is accomplished either

through decoupling or time based variation in strategy usage, meaning the strategy in use could vary depending on the season, for example (Towill and Christopher, 2002).

With the decoupling point at the assembly stage, further improvements are feasible by incorporating leagile practices. This will enable upstream processes to operate very efficiently using lean, while assembly and other downstream processes can maintain customer responsiveness.

According to Goldsby et al. (2006), three methods to create lean and agile hybrids are available. The first uses the 80/20 rule, (i.e. 80% of the sales will come from 20% of the product varieties) to establish an efficient lean system for that 20% of high demand product, while agile and leagile concepts are used for the other 80% of the variations. While this concept may not be directly applicable to mass customization as the variety is potentially very high, it can in principle be used with accurate forecasting to reduce the variability in the system.

The second hybrid method involves investing in excess (production) capacity in order to handle varying demand and work content fluctuations, which is also a useful strategy considering the volatility of mass customization markets. Third is the principle of postponement (Goldsby et al., 2006).

One well known example assembler/modularizer that uses postponement is Scion, a division of Toyota. Customers are allowed to customize their cars online with a multitude of features. Base models are manufactured in Japan applying lean manufacturing, then customized later at distribution centers, or even at the dealerships that sell them (Goldsby, et al., 2006). Given that the customer involvement takes place late in the value chain for both low level customizers, these leagile strategies can possibly be implemented with a well placed decoupling point. The best strategy to use will depend upon the product and its market. While lean manufacturing is for the most part directly applicable to these mass customization scenarios, the use of a leagile hybrid system may increase customer responsiveness and further reduce the effect of variation on the supply chain.



### ***Job Shop Lean***

Job shop lean is a relatively new method in which certain lean manufacturing principles and practices are applied to job shop environments (Brink and Ballard, 2005). The main focus of job shop lean is to use value stream mapping to gain a system wide perspective. While it is difficult to quantify information such as processing times, lead times, etc. in a fully customizing production line, value stream mapping can still provide enough perspective over the system to enable the visualization many of the wastes (Brink and Ballard, 2005; Huang et. al., 2005; Alves et. al., 2005). Other lean principles such as 5s, visual management, WIP control through kanban, and total productive maintenance have found use in job shop environments (Brink and Ballard, 2005). There is very little literature available on the actual application of job shop lean and its methods. It is clear that this strategy is a variation of lean with many similarities, but accounts of successful implementation and the benefits of applying this strategy to custom manufacturing situations were unable to be found.

### ***Flexible Manufacturing Systems/Reconfigurable Manufacturing Systems***

Flexible/Reconfigurable manufacturing systems (FMS/RMS), as discussed earlier in the chapter, offer flexibility in the production systems for those manufacturing environments that heavily utilize equipment. FMS, while expensive, offer the ability to handle a large number of products with rapid changeovers and setups, while the less expensive and perhaps more practical RMS focuses on efficiently handling products across a given family (Koren et. al., 1999). The main advantage of RMS over FMS is the use of modularity in the equipment and software to quickly adjust capacity and allow for rapid new product ramp up (Mehrabi, et. al., 2000).

While FMS/RMS are certainly viable strategies, they are limited to application in equipment intensive environments where they can have a profound impact on throughput. Companies will likely see little benefit in adding these expensive systems to a single or a few processes on the shop floor, as it has been proven that maximizing the efficiency of a single process may not effect or in fact be detrimental to overall system performance (Goldratt, 2004).

### *Theory of Constraints (TOC)*

The Theory of Constraints (TOC) is another strategy that has found success in many manufacturing situations. Its focus is on the existence of a constraint or bottleneck which determines the throughput of the entire system and can be used as a pacemaker (Goldratt, 2004; Mabin and Balderstone, 2000). Control over the manufacturing system is established through the *drum-buffer-rope* (DBR) mechanism, where the constraint is the drum or pacemaker, a buffer is placed between the drum and the downstream processes to eliminate stoppage of the constraint, and the rope is employed to pull product to the bottleneck from the upstream processes (Klusewitz and Rerick, 1996; Goldratt, 2004; Mabin and Balderstone, 2000). Figure 3.4 shows the operation of the DBR mechanism.

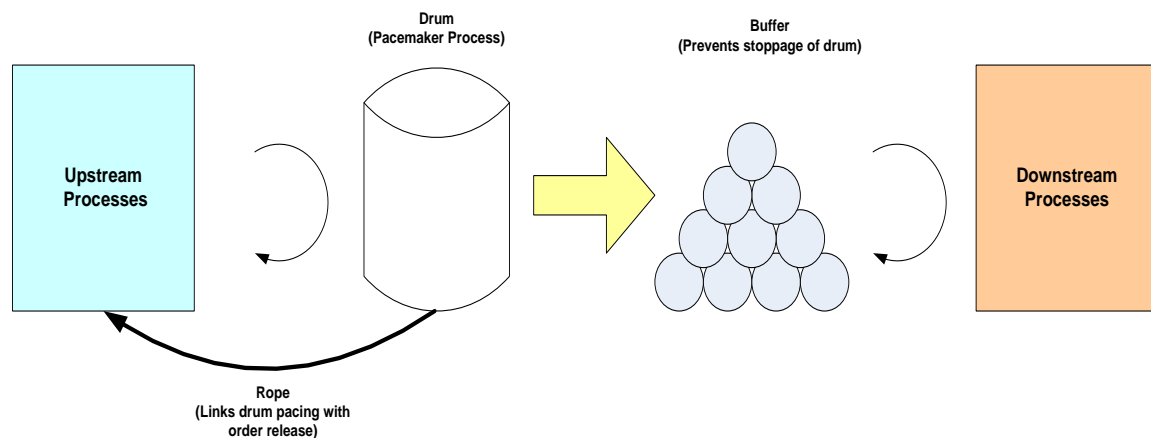


Figure 3.4 DBR Mechanism

TOC also seeks to create excess capacity for variability buffering in all non-constraint resources while only the constraint itself is run at nearly 100% utilization to maximize throughput on the shop floor (Goldratt, 2004; Steel et. al, 2005). This protective capacity has been proven to improve WIP and flow time, but with diminishing returns and benefits as variability increases (Kadipasaoglu et. al., 2000).

(TOC) and the DBR mechanism have been proven to be effective and have been accepted by many manufacturers over the years, but at this point there is still little literature qualitatively analyzing situations where TOC is made more or less effective as a control system. Mabin and Balderstone (2000) listed nearly 100 companies that had implemented TOC successfully, but little quantification of the results was given other

than accounts of reduced inventory and increased throughput. Thus it is difficult to understand from the literature just how effective TOC can be in different situations, especially that of mass customization. One key observation that can be made of the DBR mechanism is that it borrows from the lean principle of pull through the use of the rope for order release. However, literature discussing any integration of lean principles along with TOC was not found.

### ***Quick Response Manufacturing (QRM)***

Quick Response Manufacturing (QRM) is a manufacturing control strategy that has found use in many situations where variety can be high. QRM uses lead time reduction as its main performance measure and employs the *paired cell-overlapping-loops of-cards-with authorization* (POLCA) (Suri, 1998). QRM seeks to reduce lead times across all operations in order to gain responsiveness to the customer. POLCA is a control mechanism that is efficient for controlling flow and inventory in manufacturing environments that face a high number of complex product routings (Fernandes and Carmo-Silva, 2006). A POLCA system has cards for each possible product routing that are set to a number that can be determined through formulas based on indicators such as demand and lead time. The cards are set for a routing between two cells, and are attached to the product upon entering the first cell in the routing and detached upon leaving the second cell (Suri, 1998). In this way, POLCA controls inventory levels between each pair of cells and thus across all product routings. See Figure 3.5 for the operation of a POLCA system.

Figure 3.5 shows one possible routing for a product through this example system, and there would be a loop between each pair of cells for other product routings (i.e. P1F2, F1A3, A1S1, etc.). For an explanation of the usage of POLCA cards the P1F1 loop in Figure 3.5 can be examined. For a product to enter the P1 cell with a routing that had F1 as its next process, a P1F1 card would have to be available. The card would then be attached to the product and flow from P1 to F1 before being detached and returned to the P1 cell.

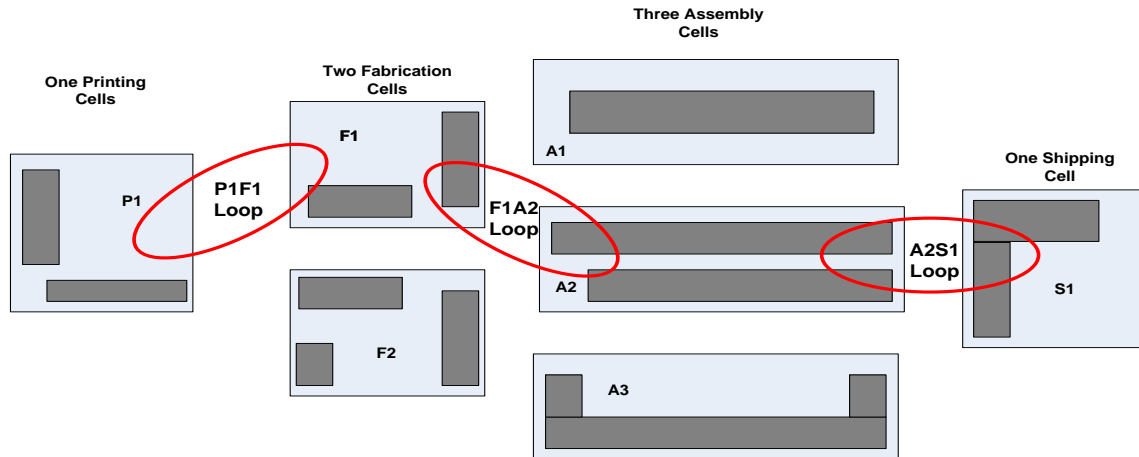


Figure 3.5 POLCA Control (Suri, 1998)

Similarly, and F1A2 POLCA card would have to be available before the product could enter the F1 process, and so on. In this way, POLCA controls inventory throughout a system with complex routing situations.

It is apparent from the literature that QRM and POLCA are robust systems that can aid in situations where variety is high. The focus on lead time reduction is an easy and effective performance measure to employ (Suri, 1998; Johnson and Harrison, 2004) where as lean manufacturing's focus on waste reduction is more difficult to quantify. However, the POLCA system does have its drawbacks. POLCA is intended to be used in the cellular manufacturing environment, and there is little literature to be found on the implementation of POLCA in non-cellular situations. It also can tend to become very complex due to the requirement of having a set of cards for every possible cell-pair routing, thus the physical operation of the system can be tedious in some situations.

The focus on lead time reduction and ability to handle high variety and product routings indicate that QRM could be a strong system for aiding in successful mass customization. The literature also indicates that it can be integrated with some aspects of lean, such as combining lead time reduction and waste reduction as performance indicators. POLCA and kanban can also be integrated by employing POLCA to control inventory between cells while kanban is used for control within each cell (Suri, 1994).

Short lead times in high variety situations is tantamount to successful mass customization by its very definition, and QRM can likely offer support for this.

### **3.6. Discussion**

While the competencies required for successful mass customization and the principles associated with lean manufacturing are well documented and defined, it is apparent from the literature reviewed that there is a need for further investigation into the topic of applying lean manufacturing principles and practices to mass customization. The literature on this subject is currently very sparse and no clear conclusions, empirical or otherwise, have been drawn on the applicability of lean or mass customization. Also important to the research is the investigation into the application of the other manufacturing strategies discussed in Section 3.5 to fill in the gaps where lean manufacturing falls short, if there are any. Overall there is little literature to support or discount neither the application of lean manufacturing in mass customization environments nor the successful integration of other common manufacturing strategies with lean. Thus, an attempt will be made to shed some light on this topic through further research. In the next chapter, the applicability for each manufacturing strategy discussed in Section 3.5 is discussed in terms of providing assistance for lean manufacturing, and a theoretical framework is developed showing the proposed interactions of the various systems based on the type of mass customization in place.

## 4. Methodology

Having provided a discussion of the characteristics of lean manufacturing principles and practices and mass customization, and the applicability of the former to the latter, it is now necessary to review some of the other strategies prominent in manufacturing today. In this section, strategies such as agile/leagile, job shop lean, quick response manufacturing, etc. are critically reviewed and arguments for or against their application toward filling in the gaps between lean manufacturing and mass customization are discussed. Next, a framework is provided showing the strengths and weaknesses of lean manufacturing when applying it to mass customization and where the other strategies that have been reviewed can supplement lean. Finally, the research objective and procedure is presented and the case study company introduced.

### 4.1. Critical Review

It is evident that lean manufacturing principles and practices are not wholly applicable in many mass customization environments, and that in many cases it will be necessary to utilize aspects of other manufacturing strategies. In chapter 3, these strategies and their characteristics were discussed. Here, their qualities are reviewed for robustness in their ability to fill in the gaps where lean manufacturing falls short.

#### *Agile/Leagile*

Agile and leagile are business strategies focused on the responsiveness of a manufacturing firm to the market conditions it must face. These strategies have received quite a bit of attention in recent time as a means of handling the increasing fragmentation of market conditions and shortening of product life cycles (Stratton, 2003; Krishnamurthy et. al., 2007). Again, Leagile differs from agile only in that it incorporates a decoupling point (Yusuf and Adeleye, 2002; Mason-Jones, 2000).

While there is no doubt that responsiveness to market conditions and the quick introduction of new products is important, one cannot help but wonder exactly how an organization might become agile. In all the literature reviewed, few accounts of an organization actually applying agility to their manufacturing system were found. This is

most likely due to the fact that agility has at its core no principles or structure that an organization could follow in an attempt to transition to an agile organization. The principles and practices of lean manufacturing, and to a lesser extent, mass customization, are well known and outlined, and the companies that have successfully employed them are numerous. However, this is not true of agile manufacturing.

The core objective of fast market response and new product introduction for agile/leagile manufacturing is certainly important for any business to have, however, the weakness of these strategies lies in the fact that it is limited to a business objective, an ideology to be applied across the enterprise, but lacking any tools for concrete application to the shop floor.

### ***Job Shop Lean***

It is difficult to see where this strategy differs from that of lean manufacturing other than the environment in which it is applied. Both approaches utilize value stream mapping heavily to visualize the system and employ a strong focus on waste elimination (Brink and Ballard, 2005). However, no tools or practices specifically unique to job shop lean were found in the literature, and case studies of organizations applying job shop lean were virtually non-existent. As with agile/leagile manufacturing, the question is raised of how an organization might actually apply job shop lean, as no core tools other than value stream mapping and a focus on waste reduction seem to be present.

While value stream mapping is a powerful tool and can be used in most any environment, it is difficult to see any solid benefits of applying job shop lean in mass customization organizations. It is likely that job shop lean will be further developed in the future, but for now it remains a slight variation of lean manufacturing made less effective by the environment in which it is applied.

### ***Flexible/Reconfigurable Manufacturing Systems***

Flexible/Reconfigurable manufacturing systems (FMS/RMS) provide a means to handle processing and changeover/setup in high variety equipment intensive operations (Korent et. al., 1999; Mehrabi et. al., 2000). The ability to handle a broad range of products in an efficient manner is a principle that is at the core of mass customization.

Lean manufacturing promotes fast setups and changeover strategies such as SMED, thus it is apparent that in applying lean manufacturing to mass customization the concepts of FMS/RMS hold some merit. However, their weakness lies in the fact that they are both equipment focused strategies, and are lacking as a means of system wide control and operation of the manufacturing system. Employing FMS/RMS will provide some benefit to many organizations, but focusing only on equipment must be avoided and close attention paid to the mass customization competencies such as dynamic production planning and process modularity.

For the efficient management of the shop floor in a mass customization environment a more robust strategy than FMS/RMS is needed. These approaches, however, depending on the products produced and their equipment requirements, can likely aid in filling in the gaps between lean manufacturing and mass customization.

### ***Theory of Constraints***

When considering the ability of TOC to aid in creating efficient mass customization, it is important to take into account the high variability that will be present. Each order that a mass customizer receives is different and individual to the customer, thus work content can differ greatly, especially for those companies who involve the customer early in the value chain as in high level customization. It has been found that once the DBR mechanism is implemented, the constraint can shift at times due to variation in the system (Goldratt, 2004), and these occasional shifts must be recognized and the system adjusted accordingly. With mass customization, many companies will deal with high work content variation from each work piece to the next, thus it is likely that the constraint will shift frequently, with a higher effect for low volume manufacturers with larger cycle time ranges.

For mass customizers of the low level variety, TOC and DBR could likely be a viable strategy for system control as these companies customize only in the assembly and delivery stages and efficient use of product modularity can help reduce the effect of order variability. High level customizers, on the other hand, face much more variation because of the customer being involved in the design and fabrication stages. For these companies,



it is likely that an attempt to implement TOC would result in implementing a strategy that requires a static constraint in a situation that is highly dynamic.

The theory of constraints is a more complete strategy than those discussed earlier. It provides a means of inventory control and system pacing on the shop floor. One of its strengths is its simplicity in managing the whole shop floor based on the constraint; however it does not have the strong set of tools that make up the core of lean manufacturing. The theory of constraints may be a very effective method of shop floor management for some manufacturers, but in many mass customization situations it will be difficult to implement due to its heavy reliance on a stable and consistent constraint in the system.

### ***Quick Response Manufacturing***

The focus on lead time reduction and the POLCA strategy of QRM make one of the more robust systems discussed thus far. In some ways it seems to nearly parallel lean manufacturing. For example, where the focus of lean is considered to be waste reduction, that of QRM is lead time reduction, and while lean utilizes the kanban/conwip card, QRM has the POLCA card. QRM, like lean is an enterprise wide philosophy for the employees to utilize and follow, however QRM is intended to fulfil the needs of those firms facing higher product variation and seeking to cater to more unstable and fragmented markets. POLCA itself is intended for use when many complex product routings are present, as a means of managing the inventory and flow from one cell to another (Suri, 1998; Suri, 1994; Fernandes and Carmo-Silva, 2006).

QRM as a whole is a strong strategy for any organization to follow. The simplicity of the measure of lead time reduction as the main performance indicator is a definite plus that can be applied across the enterprise. POLCA is a robust means of system control, but it is also much more complex in operation than more prominent methods such as kanban. It is meant to aid in managing a high variety of product routings and should not be used in situations where kanban will suffice. QRM has already seen much success with mass customizing firms and will likely continue to do so. It is apparent that QRM can provide some strength in the areas of weakness for lean manufacturing as customer involvement moves up the value chain.

## 4.2. Framework

The strengths and weaknesses of applying lean manufacturing to mass customization have been analyzed, and a critical review of other strategies that may aid in filling in the gaps has been provided. It is now necessary to provide a framework describing the findings thus far. The ultimate goal of this framework is to provide a road map for applying lean manufacturing to mass customization, including an account of which lean principles and practices are applicable and to what degree based on the particular type of mass customization in place, and how other strategies such as Quick Response Manufacturing and the Theory of Constraints can pick up the slack where lean falls short.

To begin, it is beneficial to once again examine the mass customization competencies put forth by Moser (2007), and show the varying degree to which each competency is important as customer involvement moves up the value chain (i.e. moving from assemblers to fabricators). Figure 4.1 graphically presents this analysis in a spider diagram of mass customization.

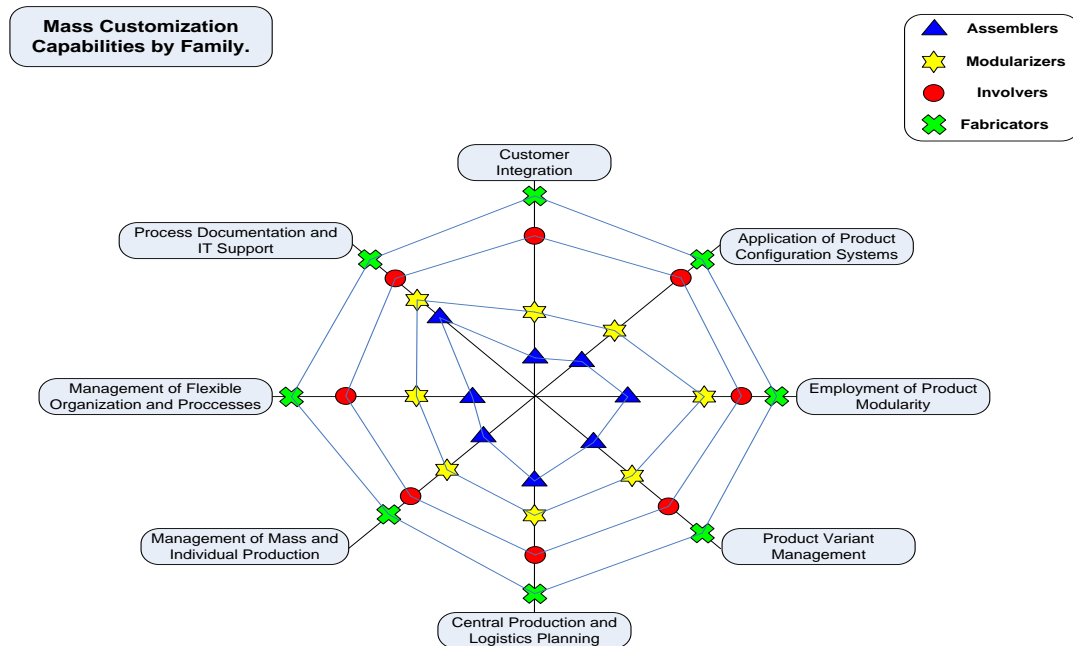


Figure 4.1 Mass Customization Competencies by Strategy

As can be seen from Figure 4.1, each mass customization competency can be considered to carry a varying degree of importance based on the point of customer involvement in the value chain. For the most part the importance of these competencies increases in a linear manner from assemblers with customer involvement taking place in the assembly or distribution phase, to fabricators who involve the customer in the design phase. However, some of the competencies vary in this regard; customer integration, application of product configurations systems, and management of mass and individual production.

Customer integration refers to the act of customers becoming involved in certain aspects of production, aspects that were likely once considered to be the sole responsibility of the manufacturer (Moser, 2007). In figure 4.1 it is apparent that there is a larger gap between assemblers/modularizers and involvers/fabricators than is present in most of the other competencies. The reasoning behind this is the fact that the need for customer input is much greater when customization takes place in the design and fabrication stages rather than the assembly and distribution phases. For assemblers and modularizers, the customer integration likely refers to some simple choices of options to be present or absent on the product, as with 121TIME, a Swedish watch manufacturer which allows customers to configure the appearance of their watch and order it online (Moser, 2007). This is a rather simple interaction that requires no efforts from the manufacturer itself to configure the product. However, with involvers and fabricators the interaction between customer and manufacturer are likely to be much more personal and lengthy. For example, Selve, a mass customizing shoe manufacturer, allows its customers to choose from a range of base models. From there a dedicated salesperson scans their foot, and the basic shoe is displayed before features such as material, color, soles, etc. are chosen. The salesperson works with the customer through this entire process as the customer becomes fully integrated into the production process from the fabrication stage (Moser, 2007).

The reasoning behind the placement of the mass customization styles in the area of application of product configuration systems is much the same as those provided in the customer integration discussion. Product configuration systems are important because they allow the customer to see the choices available to them and essentially build their

product in a virtual environment. These product configurators can range from software programs to dedicated salesmen, and as the degree of customer integration increases, so does the necessary robustness of the product configuration system.

Having shown the varying degree of importance of mass customization competencies for different types of mass customizers, it is now important to show that the same variation is true for lean manufacturing principles and practices. Figure 4.2 takes the ideas on the importance of mass customization competencies expressed in Figure 4.1, and adds in the lean application aspect in terms mass customization style ranging from assemblers to fabricators. Figure 4.2 attempts to give a sequence of mass customization competency importance and lean manufacturing principle and practice application. Starting from the top on the mass customization side, the Figure shows that customer integration is important for all mass customizers, but increases in importance as customer involvement moves up the value chain.

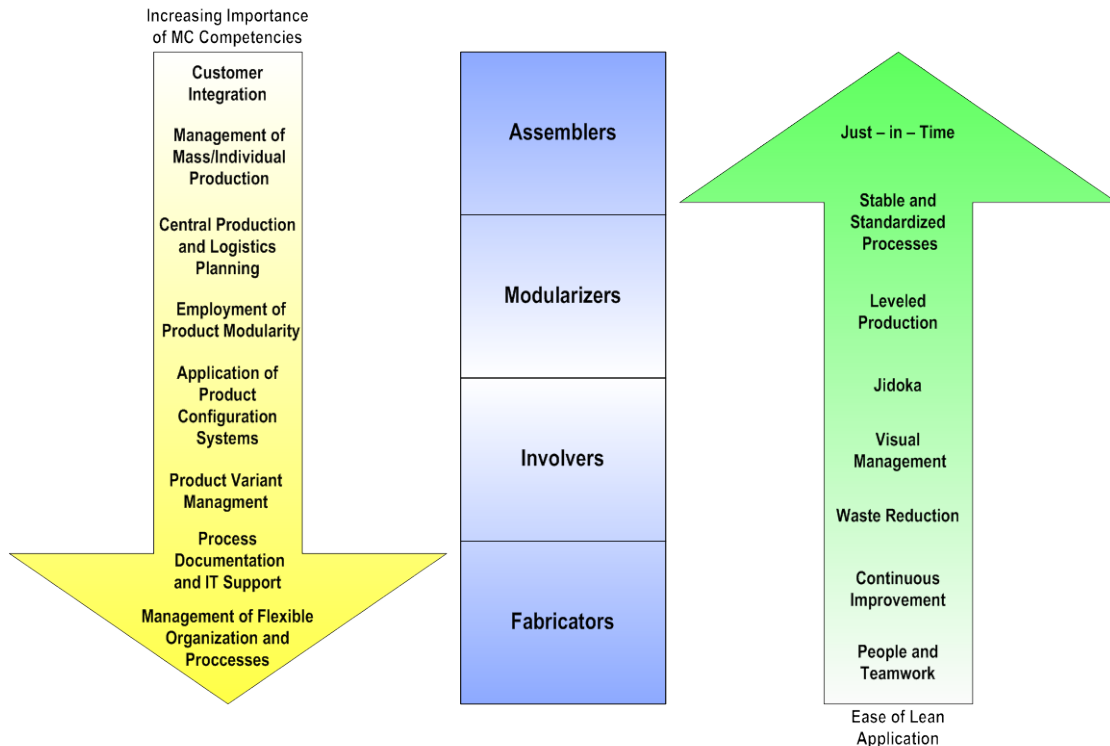


Figure 4.2 Importance of MC Capabilities and Ease of Lean Implementation

When moving from assemblers to fabricators, these mass customization competencies become more pronounced and important to the efficient operation of the organization. For example, extensive product variant management techniques may not be prominent in an assembler type mass customizer, but will certainly be so for a fabricator and to an even greater extent for a fabricator. The underlying idea is that different mass customizer families will strongly employ different core competencies with increasing applicability and importance of these competencies as customer involvement moves up the value chain.

On the lean side of the figure, the increasing applicability of lean manufacturing principles and practices as customer involvement moves down the value chain is shown. For a fabricator, for example, only certain lean aspects will be readily applicable to the organization. Principles such as people and teamwork, continuous improvement, and waste reduction are easily applied and important to any organization. Visual management and jidoka are also likely to be applicable for all mass customization families, but become increasingly difficult to apply as the inherent variation of the products increase. Finally, the principles of leveled production, stable and standardized processes, and just-in-time will almost certainly be applicable for mass customizers of the assembler/modularizer type, if at all. This is due to the heavy reliance of these principles on the existence of consistent demand and work content, as well as a relatively low number of product variants.

Having provided a theoretical representation of mass customization competencies and lean principle and practice application, it is now necessary to tie these two strategies together with those discussed in the critical review section into a comprehensive framework for this research. See Figure 4.3.

Figure 4.3 attempts to combine lean manufacturing, mass customization, and the other strategies that have been discussed into a comprehensive framework. Across the top the core lean principles and practices are listed, and once again the trend of increasing ease of lean applicability as customer involvement moves down the value chain is demonstrated. Above the lean principles the inventory control tools of CONWIP and Route Specific Kanban are listed in order to show that these are some key strategies that

aid in the implementation of the principles of Just-in-Time, stable and standardized processes, and leveled production.

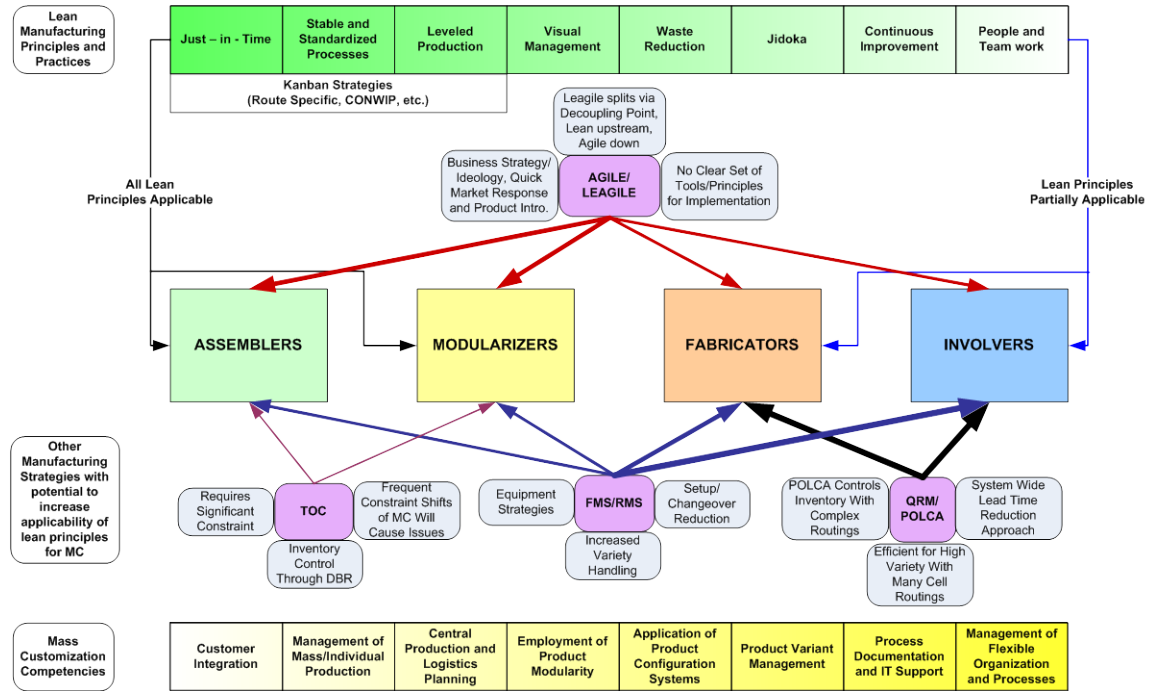


Figure 4.3 Theoretical Framework

Also shown are the mass customization competencies as outlined by Moser (2007) across the bottom. Here the increasing importance of these core competencies as customer involvement moves up the value chain is demonstrated.

The most important aspect of this framework, however, is the information given on the possible application of other strategies (*QRM*, *TOC*, *Agile/Leagile*, *FMS/RMS*, *Job Shop Lean*) in combination with lean manufacturing to aid in effective mass customization. Arrows of varying thickness are used to show for which mass customizer families a particular strategy is most likely to be useful, and to what degree it could be useful in relation to other types of mass customizers.

The Theory of Constraints (*TOC*) strategy is shown in the figure as being most likely applicable in the cases of assembler and modularizer mass customization. Since the customization takes place at earliest in the assembly stage for these mass customizers, variety and work content variation will be much lower than in the cases of fabricators and involvers. For fabricators and involvers, the work content variation is likely to be such

that any constraint in the system will experience frequent shifts, thus hindering the ability of TOC to control the system flow. For these reasons TOC is likely to find some beneficial application for those low level mass customizers.

In the framework figure, FMS/RMS are shown as being beneficial to all types of mass customization, with increasing benefits as customer integration moves up the value chain. It is apparent that high level customizers face more manufacturing challenges due to variety than low level customizers, and for this reason would benefit more from the implementation of an effective FMS/RMS. Lean manufacturing also advocates setup reduction, so the combination of lean manufacturing principles on the shop floor with FMS/RMS capable equipment will be beneficial to any mass customizer whose products require significant machine time.

Quick Response Manufacturing (QRM) is represented as being beneficial in filling in the gaps between lean and mass customization for the high level mass customizers. Lean methods of Just-in-Time, stable and standardized processes, and leveled production fail at this point and inventory control through kanban is likely to be impossible. Other lean principles such as visual management, jidoka, continuous improvement, etc. remain applicable but increase in difficulty of implementation. One of the key aspects of combining lean and QRM is the integration of the lean principle of waste reduction with a heavier focus on the QRM main performance measure of lead time reduction to help in the evaluation of the system's status.

Often in these situations the issue of complex routings and inventory control between cells must be overcome, and POLCA, as discussed in Chapter 3 can do this. Manufacturers can also use POLCA in tandem with kanban, employing POLCA to manage routings and inventory between many cells, while kanban controls material flow within the cells themselves. This combination of lean and QRM card-based control system would undoubtedly be of benefit to many mass customizers.

Agile/Leagile manufacturing, as mentioned earlier in this chapter, does not have a concrete set of implementation tools and benefits of its own but is limited to a business perspective on market responsiveness and new product introduction. The concept of the decoupling point in leagile manufacturing however, can likely be beneficial to those able to implement it. This is more likely to occur for low level customizers than high level

ones, as the customization for high level customizers takes place so early in the value chain.

Job shop lean is not in place on the figure but is discussed here as a strategy of note. It is difficult to view this strategies as robust and substantial as at this point there seems to be no significant tools or methods for implementation and control, and therefore any benefit they would provide to the shop floor of a mass customizing organization is unclear.

It should be noted that while this framework attempts to give a clear picture of how lean and other manufacturing strategies can be combined for mass customization, it is by no means a complete representation of all cases. For instance, the indication that QRM is beneficial for high level mass customizers is meant to show that these are the areas where QRM will most likely be needed. Obviously, the specific applications of these strategies will differ on a case by case basis, and there are no doubt instances of low level customization that would benefit from QRM implementation, and the same is true of the other strategies present. Overall the figure is an attempt to combine the findings thus far into a comprehensive framework to aid in the further research and experimentation of this work.

### **4.3. Objective**

Having developed a theoretical framework for incorporating lean manufacturing with mass customization, it is now necessary to provide some validation of these theories. The objective is to prove that the application of lean manufacturing principles is beneficial in the mass customization environment, but also that some mass customizers, mainly high level customizers, will often require the use of other manufacturing strategies such as QRM to supplement lean manufacturing. However, to investigate all combinations of these strategies for all the styles of mass customization is too large of a task to be completed in this work. For this reason, a single investigation into a mass customizer of the assembler family will be presented.

The case study company in question is Skier's Choice, a manufacturer of competition quality wakeboarding boats based in Maryville, Tennessee. The competition wakeboarding boat market is the epitome of the types of markets many mass customizers



face; a fragmented niche market with high end products marketed towards adults with extra money to spend and who demand a plethora of customizable options.

Throughout the remainder of this work, the operations of Skier's Choice will be thoroughly investigated. In Chapter 5, a detailed look into the features of the company, its product and option offerings, its mass customization competencies, and its overall manufacturing process is given. In Chapter 6, the validity of applying the other strategies discussed in Chapters 3 and 4 (*TOC, QRM, Agile/Leagile, FMS/RMS, Job Shop Lean*) in the context of the case study company will be analyzed. From this discussion, a strategy for restructuring the manufacturing operations will be chosen, followed by a step-by-step look and the restructuring process by department. Finally, a simulation will be conducted comparing the current and future states in order to validate the benefits of restructuring the plant in the proposed manner

## **5. Case Study – Skier’s Choice**

Skier’s choice, a company based in Maryville, Tennessee, is involved in the manufacture of boats built for water sports such as wakeboarding. This is a market that is highly specialized and targeted at a rather small group of consumers. Also, as this is considered a luxury product, market conditions are highly turbulent. Changes in the status of the economy can have a large effect on consumer demand as opposed to a product that would be considered more of a necessity. Also, it is imperative that the producer constantly seek to update their product with improved functions, more options, and new aesthetic qualities, at least on an annual basis, in order to remain competitive in such a niche market.

The market for these sport boats has been in existence for over 30 years, but as time has gone on the design of the boats has adapted to become more specialized specifically for wake boarding/water skiing. Overall, demand has increased over the last decade, so the market can be considered to be new and growing.

All manufacturers in this market offer a varying degree of mass customization to their consumers in the options that can be chosen for the boat. Generally, a manufacturer will build a certain percentage of boats to be sold at a dealership, with options chosen by the dealer. These boats usually represent a “middle of the road” model as far as options and expense are concern. The remaining production will be mass customized items that were custom configured and individualized by the consumer working with a sales representative, usually a dealer.

### **5.1. Brief Company Description**

Production at Skier’s Choice began over 26 years ago with their Supra model boat, one of two base models still built today. Eleven years ago, they added a more basic, less expensive model called the Moomba. Skier’s Choice has been under its current ownership for the last 11 years, and during that time has sought to increase market share by offering high quality products that cater to a wide range of budgets with many customizable options. This motivation has led the company to become the fastest growing manufacturer in the market over the last eight years and propelled them to third

place in overall market share. These trends of growth and improvement are projected to continue in the near future.

When walking through the Skier’s Choice facility, one is reminded of the most traditional and basic manufacturing system, craftsmanship. There is an almost total lack of automation, with operations being performed by highly skilled and trained team members. Skier’s Choice has only one facility that manufactures this product, and thus the employees take great pride in knowing that when they see a Supra or Moomba on the water, they played a direct role in its manufacture.

Indeed, it is this pride and drive for quality, along with allowing the customer to choose from many options to fit their needs and budget that has allowed Skier’s Choice to solidify and strengthen its position in a turbulent market. See Table 1 for an overview of the company data and contact information.

Table 2. Company Data

	Company data
Name	Skier’s Choice
Address	1717 Henry G. Lane St. Maryville, TN 37081
WWW	www.skierschoice.com
Year of foundation	1980
Number of employees	375
Industry	Boat manufacture
Products	Supra and Moomba boats
Markets	Wakeboarding/Water skiing tow boats, 1,840 unit sales for 2007.

## 5.2. Mass Customization Product

As stated before, Skier’s Choice offers two base model lines of boats; the Moomba and the higher end Supra. Within these lines, there are several different models from which the customer can choose. See Table 2 for a listing of the offerings.

Table 3. Skier's Choice Model Offerings

Skier's Choice Model Offerings by Product Line (2007)										
	Sunsport Series			Launch Series						
Supra	20 V	22V	24V	20	20 SSV	21 V	22 SSV	24 SSV	Gravity 24 SSV	Worlds Package
		Mobius			Outback					
Moomba	LS	LSV	XLV	XLV Gravity Games			Outback	Outback V		

From Table 2 we see that there are 10 distinct models within the Supra line and 6 models within the Moomba line. The main differences between these models are in the area of horsepower, fuel tank capacity, ballast, length, width, draft, and occupant capacity. For example, a Moomba Outback, a lower end model, features a length, width, and draft of 22'8", 94", and 24", respectively, as well as a 40 gallon fuel tank, seating capacity of 10 people, and ballast options of 400 and 1200 pounds. The higher end Moomba Mobius Gravity XLV, on the other hand, has a length, width, and draft of 25', 98", and 26", respectively. This boat also features a 40 gallon fuel tank, seating capacity of 16 people, and ballast options of 650 and 1950 pounds.

The more luxurious Supras vary in the same manner, but offer generally larger boats with lengths varying from 22'10" to 26', fuel tank capacities from 34 to 52 gallons and higher ballast and seating capacity on average. All models of Supra and Moomba offer a 5.7L V-8 engine with 325hp except for the Supra Gravity 24 SSV which offers a 340hp V-8 power plant. See Figures 5.1 and 5.2 for examples of the product lines.

Within the 16 base models of Supra and Moomba boats, there are many different options that the consumer is able to customize. One of the most highly customizable areas of the boat is the gel coat pattern, or paint scheme. Within the Supra line there are 37 possible gel coat spray patterns with individual models accounting for 1 to 8 of the variants (i.e. Gravity 24 SSV has only 1 pattern, 21V has eight possibilities). The Moomba line has a total of 20 spray pattern varieties with individual models accounting for 1 to 7 of the variants. Note that these variations take into account only the pattern of the gel coat spray scheme, not color information.

**GRAVITY24SSV** ✕



Length w/o Platform	24'
Length w/ Platform	26'
Length w/ Trailer	27' 4"
Beam	102"
Weight of Gravity III Ballast	1,950 lbs
Draft	26"
Weight (Boat Only)	3,950 lbs
Weight (Boat & Trailer)	5,050 lbs
Capacity- Passengers	16 ppl
Capacity- Weight	2,300 lbs
Capacity- Fuel	52 gal
Engine	ETX/CAT, 340 HP, V-8

**G24SSV**

**LEARN MORE**  
ABOUT THIS BOAT




**WATCH VIDEO**



Figure 5.1 Supra Gravity 24SSV

**MOBIUS XLV**



Length:	23'
Length w/ Platform:	25'
Length w/ Trailer:	26'8"
Width (beam):	98"
Draft:	26"
Weight - Boat:	3,600 lbs
Weight - w/ Trailer:	4,700 lbs
Capacity:	16 ppl
Fuel:	40 gals
Base Engine:	5.7L, V8
Horsepower:	325 hp
Ballast Options:	Gravity I - 650 lbs Gravity II - 1,950 lbs




Figure 5.2 Mobius XLV

For color options, there are three areas that can be customized, the base gel coat, main gel coat, and small accent gel coat. The base gel coat offers four color variants, while the main and small accent gel coats each offer 15 distinct choices.

Besides gel coat schemes, there are many other customizable options for each boat, including engine option (engine size, salt water cooling system, etc.), appearance options (teak platform, docking lights, etc.), canvas options (tonneau cover, cockpit cover, etc.), audio/video options, performance options (tower w/ mirror bracket, Gravity III-d ballast system, etc.), trailer options (galvanized frame, 18" chrome wheels, etc.), and other miscellaneous options such as an automatic fire suppression system.

### **5.3. Mass Customization Operations**

According to the classification method developed by Duray et. al. (2000), Skier's Choice can be classified as an assembler in that the customer is allowed to configure their product by choosing from a selection of options. Standard modules (the product models) are used as a baseline and specific customer needs are taken into account in the assembly and use stages. The company incorporates a combination of make-to-stock and make to order production, the former being sent to dealerships based on forecasted demand while the latter is configured through customer-dealer interaction and made-to-order.

While Skier's Choice delivers a state of the art product to its consumers, their manufacturing capabilities are anything but. They are very proficient in the area of product development as is evident from their frequent model changes and upgrades; however, in the area of manufacture their greatest asset is worker skill. The production line uses the traditional push system, and a manifest moves along with the boat to indicate its model and options. Orders are released to the floor on a daily basis based on a monthly production schedule. Load leveling and hiejunka are not taken into account when making the schedule.

In order to fully understand the complete operation of Skier's Choice, its activities can be broken down and analyzed based on the mass customization competencies outlined in Chapter 3.

## **Production Competencies**

### ***Manufacturing System Configuration***

The manufacturing system at Skier's Choice is set up as a traditional moving assembly line with various feeder lines. All feeder lines are functionally arranged by department. The main components of each boat; the deck and hull, move in a linear manner through lamination, rigging, final assembly and inspection, while components such as upholstery and small parts sync up with the product along the way.

The ability to handle high variety at Skier's Choice comes from the flexibility of its work force instead of the utilization of advanced and costly tooling. There is, however, an opportunity to improve the flexibility and responsiveness of the feeder lines by restructuring and combining departments to create a cellular manufacturing process. While modular minicells are likely unnecessary for this particular application, the system would surely benefit from the use of some traditional lean cells. This is discussed in further detail in Chapter 6.

### ***Process Modularity***

Process modularity is in use in nearly every process at Skier's Choice. While each successive product is significantly different than the last, the subset of steps for completion of a particular process is similar, if not the same, for each product. For example, in lamination, each boat must have its mold prepared then be gel coated. The gel coat process involves spraying several different layers of a gel paint substance into the mold, with each layer being of different color, thickness, and shape. This is the point of variety explosion in the manufacturing process. To re-quote Swaminathan (2001) and Selladurai (2003), a modular process is "...one where each product undergoes a discrete set of operations making it possible to store inventory in semi-finished form and where products differ from each other in terms of the subset of operations that are performed on them." The gel coat process follows this definition in that the basic set of operations performed on each boat is standard, while the details of each operation differs. Essentially all of the processes at Skier's Choice follow this trend.

### ***Dynamic Production Planning***

Dynamic production planning refers to the ability of a firm to maintain low lead times while enabling customizability. Skier's Choice is a combination make-to-stock/make-to-order operation, and managing both of these components while also controlling work in process (WIP) on the floor and limiting over/under utilization of people and equipment is important to the operation. That being said, Skier's Choice has no means of WIP control save floor space in the plant, nor does it have any clear picture of cycle times in any of its processes that could be used to predict capacity requirements. This makes dynamic and efficient production planning virtually impossible. By gathering some basic data on cycle times, and cycle time variation, as well as implementing some WIP control measures, Skier's Choice could greatly improve their production planning capabilities.

### ***Organizational Learning and Continuous Improvement***

Organizational learning and continuous improvement is an area where Skier's Choice is actively seeking to improve. They have given classes to every team member in the plant on the basics of lean manufacturing principles and practices, and assigned lean projects (such as 5S) to teams made up of members from all levels of production, from team members to managers. They have also created clearly defined teams with team leaders and group leaders on the shop floor, and are continuing to give more advanced classes in lean manufacturing, as well as assigning more involved improvement projects to the employees. It is evident that Skier's choice is committed to change and has begun by seeking to educate their entire workforce of the value of learning and improvement.

### **Other Competencies**

#### ***Information Technology and Customer Interfacing***

Information technologies are also lacking at Skier's Choice. Materials requisition is not accomplished by a computerized system, but rather by a team of employees that are charged with constantly updating parts inventory information and ordering what will be needed for the next month's schedule. Typical lead time for supplier parts is four weeks. There is no method for visually representing the status of the production line to combat



problems, and individual departments within production cannot efficiently communicate what is needed. These factors all combine to create a rather lengthy lead time of four to six weeks. As a mass customizer, Skier's Choice must seek to offer much faster lead times to their consumers.

### ***Product Development***

Skier's Choice undergoes a model change process every year during the summer and fall seasons in preparation for the upcoming boating season. These model changes often involve significant alterations to boat size and shape, paint schemes, and option offerings. Due to the frequency at which model change occurs, the product development cycle at Skier's choice, from design to production, is well defined and provides for smooth transitions from one model to the next. Model change has the largest effect on the rigging and assembly lines where the majority of the major components and option work are added, and the employees here are well trained and readied to transition to the new product and produce it efficiently and correctly.

### ***Logistics***

Logistics is an area where Skier's Choice has both strengths and weaknesses. The plant is located in somewhat of a boat manufacturing center, and thus many component part suppliers are located within a small radius of it. The tower manufacturer, for example, is located within a half mile of the factory, while the trailer manufacturer is next door. This enables Skier's Choice to maintain close supplier relationship and low inventories for many of its component parts.

The materials requisition and ordering system at Skier's Choice are very outdated, however. There is no computerized system such as MRP in place. For parts requisition, there are various managers assigned to different aspects of the manufacturing operation. These managers use a paper booking system to know what parts are present in the warehouse, what is being used and will be used on the shop floor, what will be needed for manufacture in the next period. By this system, parts are ordered on average every 2-6 weeks.

The nature of this system makes it anything but dynamic, and does not allow Skier's Choice to take full advantage of the close proximity of many of its suppliers.

### 5.3.1. Manufacturing Operations

In order to fully understand the nature of the manufacturing process at Skier's Choice, a basic process map is given in Figure 5.3, followed by a detailed description of the operations.

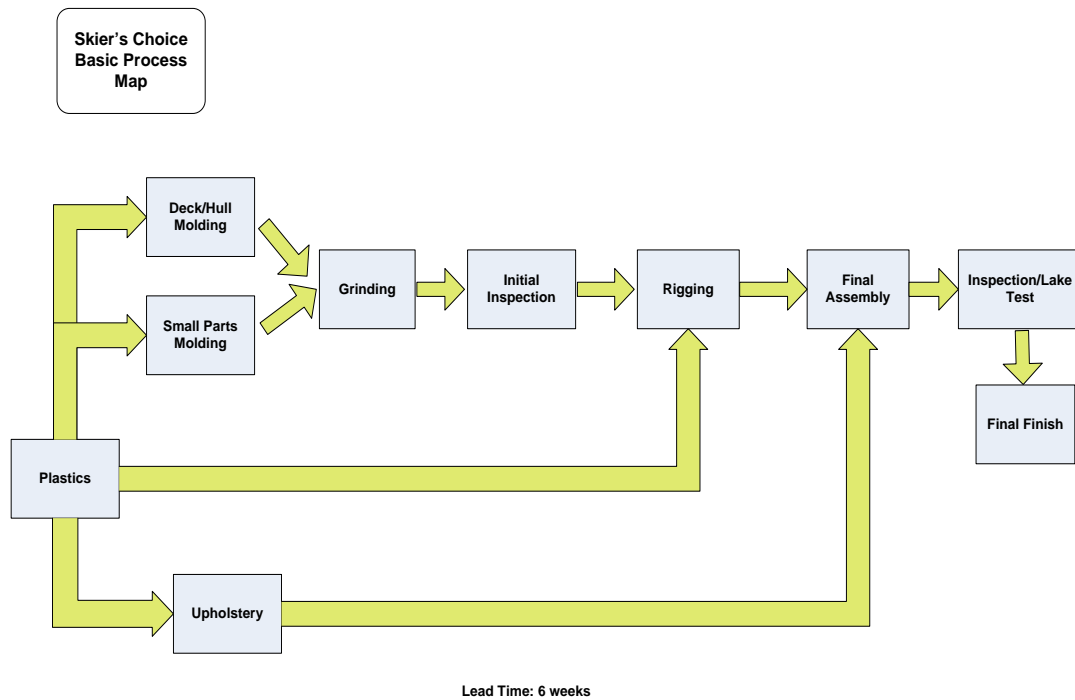


Figure 5.3 Basic Process Map

#### *Lamination*

The process begins in the lamination department where the deck and hull components are molded. Mold prep is the first operation, where matching deck and hull molds are selected and taped off according to the customizable paint scheme ordered by the customer. From there, gel coat is sprayed onto the mold in multiple colors and thicknesses according to the scheme laid out by mold prep. After drying, another coat of “barrier coat” is added for strength and allowed to dry. Next fibreglass resin is sprayed

onto the molds along with fibreglass sheeting called bulk, and a coat of core spray is added. Once this last coat has dried, the empty cavities of the mold are filled with foam which hardens for strength, and then the molds are pulled and sent to a grinding booth where excess material is removed and holes cut for future component parts to be added.

### ***Small Parts***

The small parts department operates in a similar manner to that of lamination, but creates simpler, smaller parts to be installed in various stages of production. It supplies parts that are installed in the lamination line, such as the floor component, as well as some that are installed later in final assembly, as with the motor cover. The process again begins with mold prep, and is followed by a single gel coat. The major difference is that after gel coat the fibreglass resin is added and once dry the mold is pulled and sent to grinding, completing the process. The barrier coat, core spray, bulk, and foam are not necessary in the construction of these parts.

### ***Plastics***

The plastics department is functionally arranged and consist of several machines that would be commonly found in a wood shop, such as table saws, routers, and mitre saws. The purpose of this area is to create a large variety of simply shaped plastic pieces which are cut from 4'x8' sheets of raw material. The finished parts are supplied to various areas of the plant, but their main function is to provide structural support for components added in assembly, and frames for components made in the upholstery department such as seats.

It is a make-to-stock operation with a large storefront of finished parts. Each type of part is stored in a rack with a minimum level denoted. Team members in the area make parts to restock each part type when it nears its minimum level using the machines and a large variety of available jigs. Because of the large variety of parts made here, and the nature of a make-to-stock operation, inventory contained here is enormous.

### ***Upholstery***

In the upholstery department, parts are acquired from the plastics store front and assembled into frames based on the specifications of the boat. Foam, which comes

roughly pre-cut from the supplier, is then glued to the frames and excess foam is removed. Meanwhile, a CNC cutting machine, the only computerized equipment in the plant, cuts out pieces of vinyl based on the size, shape, and color required by the boat specifications. Once these pieces are cut, they are sorted and sent to a sewing department where team members sew the various pieces together to create a skin. Lastly, the skins and frames are matched, and the skins are pulled over the frames and stapled before being sent to various stages of final assembly.

### ***Rigging and Assembly***

After leaving lamination, the deck and hull components are briefly inspected and any blemishes from the molding process are repaired. The deck and hull are also mated to ensure proper fit. From there, boats are split by model (Supra or Moomba) and sent to separate lines where decks and hulls run parallel to each other. In the next few processes, interior components such as bilge pumps, the engine, and wiring are added, as well as underwater gear such as propellers.

Next, the deck and hull are mated permanently together and the boat undergoes a series of final finish processes, where components such as seats, the windshield, instrument panel, the tower, lighting, and the speaker system are installed based on the options specified by the consumer.

### ***Inspection***

The last stage of the manufacturing process is inspection. Here, boats are removed from the plant and placed in a small pool where it is checked for leaks and the engine is hot tested. Other aspects are also tested such as the sound system, steering, and instrumentation. Each boat is then placed on its trailer and hauled 20 minutes each direction to a nearby lake where employees run each boat through a series of tests designed to put it through a wide range of operations and fully inspect its functionality and performance. After testing is complete and the boat approved, it is hauled back to the factory where it is cleaned, and final components are added such as decals and compartment covers.

### 5.3.2. SWOT Analysis

To conclude this chapter, a SWOT (strengths, weaknesses, opportunities, threats analysis) is provided as a capstone to the discussion of the operations and capabilities of the case study company; Skier’s Choice. Overall, Skier’s Choice is a strong company with a strong mass customization product. They have a solid hold in the marketplace and have experienced consistent growth. However, there is much room for improvement in their manufacturing process which could enable them to obtain higher visibility and understanding of their system, and allow for shorter lead times, reduced inventory and workforce, creating a more dynamic and responsive system as a whole. See Figure 5.4 for the SWOT analysis.

<p><b>Strengths</b></p> <ul style="list-style-type: none"> <li>• Strong market niche is present</li> <li>• Solid foothold in market</li> <li>• Knowledgeable workforce</li> <li>• Open to improvement</li> <li>• Non-union</li> <li>• Strong product development cycle</li> </ul>	<p><b>Weaknesses</b></p> <ul style="list-style-type: none"> <li>• No knowledge of cycle times or capacity</li> <li>• Production planning not dynamic</li> <li>• No inventory control, low system visibility</li> <li>• Push system throughout plant</li> </ul>
<p><b>Opportunities</b></p> <ul style="list-style-type: none"> <li>• Improved supplier relations, some parts delivered JIT</li> <li>• Advancement of materials requisition system.</li> <li>• IT interfacing with the consumer, possible use of product configurators</li> <li>• Continuing education of workforce could lead to great improvement</li> </ul>	<p><b>Threats</b></p> <ul style="list-style-type: none"> <li>• “Pleasure craft” market, fluctuates highly with state of economy.</li> <li>• Technological advancement of competitors’ manufacturing systems could cause SC to fall behind</li> </ul>

Figure 5.4 SWOT Analysis

## **6. Experimental Model Development**

The theoretical framework for this research has been laid based on the literature reviewed and the goals of the work, and a detailed overview of the case study company has been provided. The next step is to systematically restructure the given case factory based on the framework provided in Chapter 4. In this chapter, an account of the current state at Skier's Choice is provided, followed by a discussion of the validity of applying the strategies (excluding lean) that have been discussed in an attempt to identify any area where the need for a supplemental method may be needed due to a failure of lean principles to provide adequate control for the system. From this discussion, the overall strategy for restructuring the plant is chosen and each department is reconfigured. Finally, both the current state and future state are input into simulation software and performance measures are obtained for the comparison of the systems and measurement of improvement.

### **6.1. The Current State**

The current state at Skier's Choice is typical of the mass production environments. At first this does not seem to be the case when observing the manufacturing line as this is a relatively low volume producer, however closer inspection reveals that most of the same faults of mass manufacturing are present. One of the first things one will notice is the lack of any kind of pacing of the assembly lines, which is evident even with the long processing times. There is no inventory control in the system leading to WIP piling up in front of some processes, and others being starved.

Overall, there is little control over the system as a whole, and even less visibility. There is a lack of any kind of visual management and processes often seem to run together. Employees also have little knowledge of line pacing, making them unable to know whether they are ahead, behind, etc. The amount of WIP on the shop floor is large in comparison to the daily volume the plant produces, and this WIP amounts to a significant cost given the relatively high cost of products in this market.

Also of note is the fact that for the vast majority of the production process the main body of the boat is in two pieces which must be matched late in the assembly stage.

Upholstery parts are also custom made for each particular boat. Obviously if these components are not ready the assembly is halted, yet there is no clear method of sequencing each section and correctly matching the components to the correct boat.

During the course of the initial investigation it was quickly discovered that there was no quantitative knowledge of processing times in the factory. In order to obtain this information, a tagging process was employed to gain information on the processing times for several different boat models. While the products of Skier's Choice can be configured in thousands of ways and processing times vary, the data obtained from this sampling activity provides a reasonable representation of the actual cycle times. See Figure 6.1 for a current state value stream map generated from the process mapping and data collection activities conducted at Skier's Choice.

## **6.2. Discussion of Applicable Approaches**

Prior to a detailed discussion on the restructuring of the operations, it is necessary to examine all the manufacturing strategies discussed thus far and choose those that will serve best for improving the performance of the system. In this section a discussion on the applicability of each of these other strategies is given in the context of their ability to be integrated with lean principles in improving the overall flow and lead time in the system.

### ***Agile/Leagile***

At Skier's Choice, the use of postponement is not an option as the variety explosion occurs early in manufacturing at the gel coat process. When customers choose their base model of boat and the gel coat scheme and color options, they are affecting the first two operations in the manufacturing process, thus creating high variety at the beginning of manufacturing. There is no possibility of restructuring the order of operations to postpone variety in this case, as the decks and hulls which must be molded and painted are the very foundation of the overall product and all downstream operations depend on them. For this reason it is apparent that the use of a decoupling point, at least in the

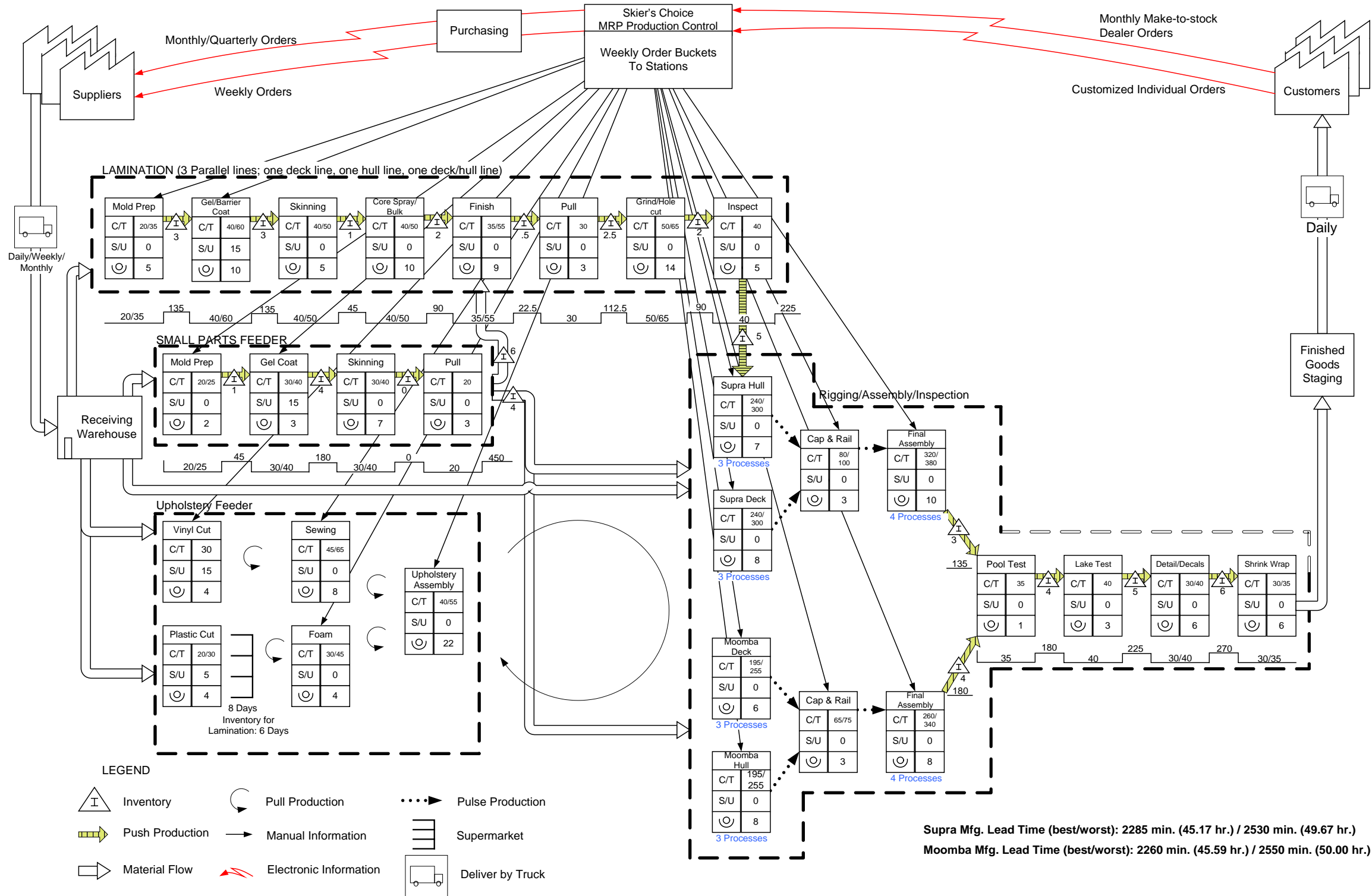


Figure 6.1 Skier's Choice Current State VSM



context of the manufacturing operations which are the focus of this research, is impossible.

While being agile is certainly a desirable feature for mass customizers in terms of responding to markets, the inability to employ a decoupling point and the lack of tools and methods for making a manufacturing system agile makes these two strategies unviable for application at Skier's Choice.

### ***Job Shop Lean***

Value stream mapping has already been shown to be useful for gaining a system perspective at Skier's Choice in Figure 6.1, and Job Shop Lean advocates the use of this tool. However, at this point, this strategy seems rather undeveloped from the literature reviewed and its full merits are yet to be known. However it is known that Skier's Choice is a mass customizing manufacturer, not a job shop. Skier's choice does have a set of base models from which all their products are created, and thus a strategy intended for job shops is not highly applicable.

### ***Flexible/Reconfigurable Manufacturing Systems***

These equipment design strategies will be useful in many cases for reducing setups and changeovers; however, they are of little value in the context of Skier's Choice. The process of manufacturing a boat in this company is almost wholly manual in nature, the only automated process being a CNC cutting machine for cutting out vinyl in the upholstery department. The only changeover for this equipment is changing out the vinyl colors and the only setup required is programming the cutting parameters for the next boat, thus there is no need to employ an FMS/RMS here. The rest of the manufacturing processes require little more than basic hand tools to complete, thus installing expensive FMS/RMS systems is totally unnecessary and unviable for Skier's Choice at this point.

### ***Theory of Constraints (TOC)***

While TOC is a stronger and more complete strategy than those mentioned thus far in the context of system control for the manufacturing system, its weakness lies in its

reliance on the existence of a stand-alone and at least somewhat consistent constraint in the system. As a mass customizer with high variability in work content, Skier's Choice faces the problem of inconsistent cycle times in many of its processes. Indeed, through investigations of the cycle times in the tagging process it was found that a single significant and consistent constraint to throughput could not be determined. This means that the constraint is likely to shift on a boat by boat basis.

The ability of TOC to control flow and WIP in the system will be greatly diminished in this situation of a frequently shifting constraint, as it will be very difficult to control the system based on a single process when this constraint to throughput is constantly moving. This is a problem that will be faced by many mass customizers like Skier's Choice. While TOC as a whole is a solid method for systems control in manufacturing, the high variability faced by Skier's Choice will make it difficult to apply the strategy.

### ***Quick Response Manufacturing (QRM)***

QRM can be a viable strategy for mass customizers to employ, and the POLCA (*paired cell-overlapping-loops of-cards-with authorization*) system can aid in manufacturing that involves many complex routings. Its focus on lead time reduction can be compared to lean's focus on waste reduction, while the POLCA system is comparable to the kanban system of lean. Thus it is important to decide which of these strategies is most viable at Skier's Choice.

The kanban and CONWIP systems are meant to handle for the most part linear product routings from one process or cell to another, while POLCA provides for many different possible routings from one product to the next. When examining the operations at Skier's Choice, it is apparent that all boats undergo the same product routing from beginning to end, while each process along that routing differs from one boat to the next. Because POLCA is a robust system for high routing variation, it can be a somewhat complex system to operate and should not be unnecessarily implemented. The degree of linearity and small number of departments/cells at Skier's Choice imply that POLCA is not needed and that kanban will suffice.

The lead time reduction aspect of QRM, however, is a focus that can and likely should be implemented as a performance measure. Skier's Choice can combine lean

manufacturing and QRM by encouraging departments to reduce both lead times and waste in order to seek continuous improvement.

Having discussed the applicability of each of these other strategies to the operations of Skier's Choice, it is apparent that in this particular situation lean manufacturing is the best choice for seeking improvement to system performance. Each of these other strategies has their own strengths and weaknesses and can support lean manufacturing in improving mass customization operations in their own right. In the following sections, combinations of lean principles such as kanban and CONWIP will be employed in order to restructure the manufacturing system at Skier's Choice on a department by department basis.

### **6.3. Restructuring the Operations**

The main concern at Skier's Choice is the improvement of product flow and reduction of lead time across the system. Various lean principles such as kanban, CONWIP, just-in-time, and others are used to facilitate the transition to a lean system.

#### **6.3.1. Lamination Shop**

The lamination shop (see Figure 6.2) is where the boat manufacturing process begins. Most of the major issues with this line relate to flow, inventory control, and visibility. Currently Skier's Choice runs three parallel lines, one for hulls, another for decks, and another which essentially works on any deck or hull that is available. It is entirely a push system building to a schedule of boats to be started on a particular day, and there is little visibility of the current status. There is no means to visually deduce which deck matches which hull and what their current status is in terms of processing. First-in-first-out (FIFO) is often not maintained which results in products getting off schedule. Also, the physical layout of the line itself makes it difficult to see the actual flow of work and what processes are behind or ahead. Because of these problems in the system are not made obvious and cannot be recognized early and counter-measured as would be done when

Lamination Shop

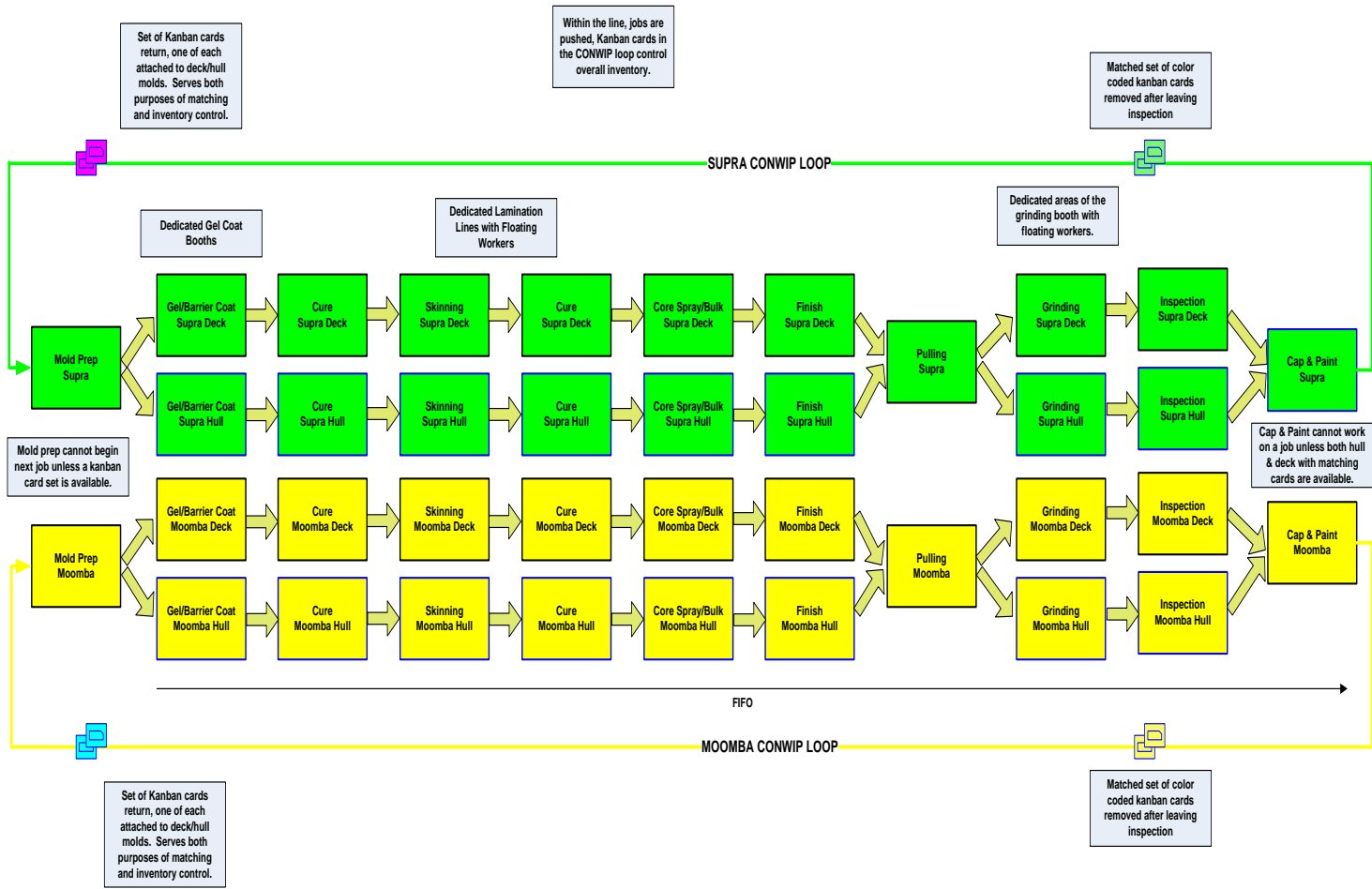


Figure 6.2 Lamination Shop

the principle of jidoka is employed. The ability to immediately and visually understand the status of the shop floor is important to any system, lean or otherwise, but the current structure in the lamination shop does not allow for this, nor does it have any means of flow and inventory control.

For the restructuring of the lamination shop the proposed system involves the lean principle of dedication for the Supra and Moomba product lines and the use of a CONWIP method to control WIP. First, the physical layout would be changed to allow for four parallel lines instead of the current three. One line each will be dedicated to Supra decks, Supra hulls, Moomba Decks, or Moomba hulls. The reasoning behind this change to four lines is to allow the deck and hull for each boat to run parallel to one another, which will allow employees to quickly know where one component is in processing in relation to the other. Also with these dedicated lines product variation will be less because each line works only on a deck or a hull for a particular product line, thus the processes become more stable and standardized. Utilizing jidoka becomes more viable because delays can quickly be recognized and counter-measured.

To control inventory in the lamination shop, CONWIP loops for the Supra and Moomba lines can be employed. CONWIP excels over kanban in manufacturing systems that are linear and face variable cycle times, as is the case here. The CONWIP system can also help with the key issue of matching decks to hulls in each pair of product lines. At the end of the lamination line the deck and the hull for each boat undergo a process of pre-fitting to make sure the molds come together as they should, meaning this process requires both components to be present. To enable the quick matching of decks and hulls, a set of two CONWIP cards can be employed as opposed to a single one, and the principle of visual management can be used to color code each set of cards. Thus, in order for the first process, mold prep, to start on a boat, a set of color coded cards must be available, and are attached to the deck and the hull. Information contained on the card should include boat model and number for further verification purposes. Once a set of cards has been attached to a deck and hull, it travels along with the components through the lamination line to the final inspection process. Here team members can quickly match the deck and hull based on the color coded CONWIP cards and perform their operations. Finally, after the process is complete the boat exits the lamination line, and

the cards are detached and physically returned to the mold prep station. See Figure 6.3 for an example of these CONWIP cards.

By dedicating lines to product type and decks/hulls, the processes will be more standardized and the visibility in the system increased enabling problems to be recognized and resolved sooner.

The employment of the CONWIP system allows overall WIP to be capped while still using push within the system to help reduce the effect of variable work content. It also helps with matching each deck to its respective hull. The optimal number of these sets of CONWIP cards for this shop is not yet known, but is investigated further using a simulation of the restructured system later in the chapter.

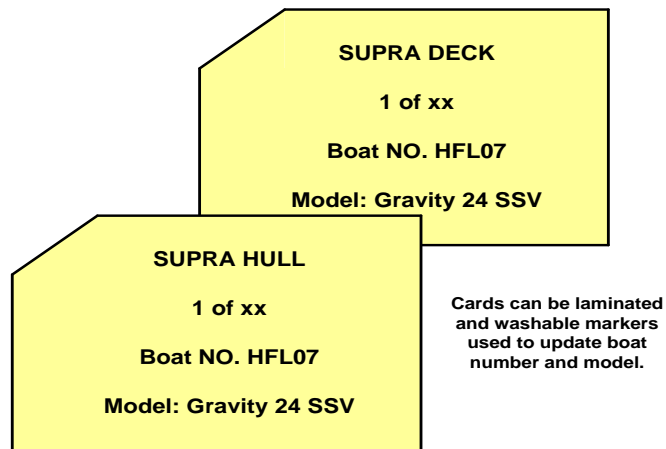


Figure 6.3 Lamination Shop CONWIP Cards

### 6.3.2. Small Parts Department

The problems of lack of visibility and poor inventory control present in the lamination line also appear in the small parts shop. However, with the small parts line, the cycle time variation is much less significant, as the processing for the parts from one boat to the next usually differ only in size and color. This lower amount of variability is

made evident from the tagging process conducted in the plant, which also shows that cycle times are shorter in general than lamination and the line as a whole appears to have some excess capacity.

It is important to place some sort of control over this line, and the choice again is between kanban and CONWIP. Due to the lower variation in cycle times and the fact that this feeder line has excess capacity, the best choice for control of the system is kanban. Part specific kanban is not an option due to the high number of models manufactured, so route specific kanban is the obvious choice. Route specific kanban squares placed on the factory floor can serve as a visual management aid to cap WIP in the system, meaning a process does not have authorization to produce unless there is an empty kanban square. Since each boat requires multiple parts from the small parts line it is also desirable to employ kitting at the end of the line. Kits can be created as a very visual means of showing what parts are yet needed to produce a finished boat of a particular type, with a full kit indicating completed processing of a boat for the small parts line. A simple tag can be attached to each kit to give the boat number that it belongs to. Lastly, the small parts department should be realigned to contain two parallel manufacturing lines, with one manufacturing small parts for Supra and the other for Moomba. This again allows for more stability and standardization in the processing.

The restructured small parts line is intended to operate very similar to the restructured lamination line. As in lamination, manufacturing lines specific to product type run parallel to one another. By using route specific kanban the WIP in the small parts line is capped and it can operate on a pull system with lamination pulling finished kits of parts. With this system, interaction between small parts and lamination will be smoother, overall visibility of the current status is improved, and the level of standardization from one product to the next is increased. See Figure 6.4 for a representation of the restructured small parts line.

### **6.3.3. Upholstery Department**

For restructuring this department, the employment of dedicated work cells is the best route for Skier's Choice to take. They have already taken the initial steps to do this in that they have defined the number of cells and the parts that will be manufactured in each

of them. They call these cells stage 1, 2, and 3, based on the point at which the components that are made in the cell are actually installed during the final assembly process. While this is an important initial step for the department, it can certainly be taken further.

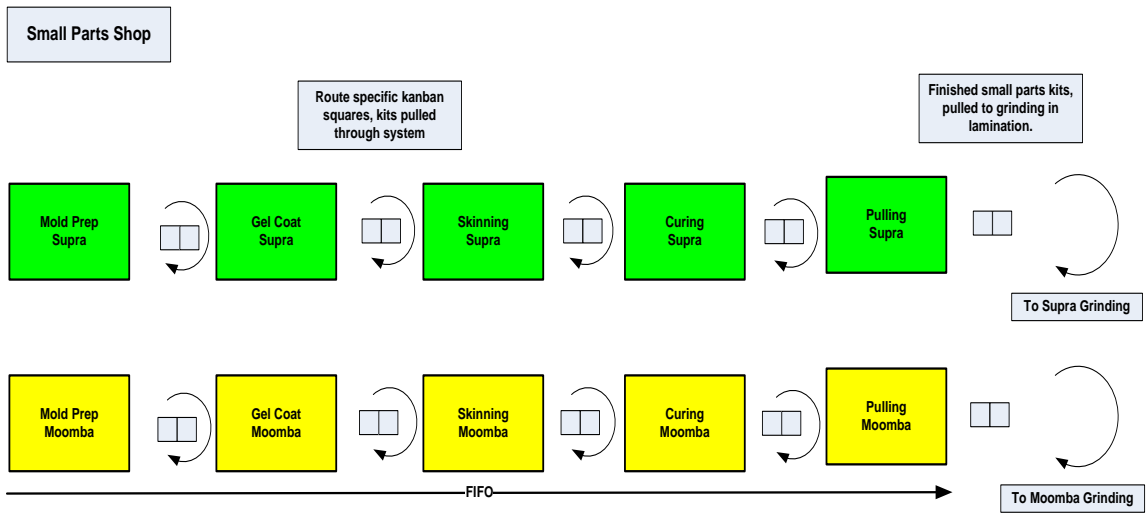


Figure 6.4 Small Parts Shop

Currently, the work cells include only the processes of sewing, foam, and assembly, while the plastics shop is a standalone department that works to fill a very large storefront of finished goods. This shop supplies parts across the plant, but most of its work is done for the upholstery department. Because of the large variety of plastic parts needed, there are two solid walls around the plastics shop consisting of sections dedicated to each possible type of plastic part that is used in a boat. Since the rest of the operations at Skier's Choice operate on a make to order basis, there is no reason why the plastics shop cannot do so as well. In order to accomplish this, it is proposed that Skier's Choice buy replicates of their plastic cutting equipment and dedicate them to the stage 1, 2, and 3 sewing cells. While equipment replication is often a considerable obstacle to dedication and work cells, in this case the equipment required is rather common and inexpensive, and the gains would far outweigh the costs of equipment. If the equipment is replicated, the large storefront of finished goods can be eliminated and communication in the cells increased by completing all processes except vinyl cutting within a cell. A fourth cell



with the necessary equipment could also be created to handle demand external to the upholstery department based on a pull system with kitted parts.

The vinyl cutting process differs from plastic cutting in that the CNC equipment is expensive and not economical to replicate. This is not a significant obstacle to increased efficiency in the upholstery department; however, as the basic operation of the vinyl cutting machine will remain the same. Once the vinyl components needed for each boat are cut they are sorted and kitted based on their destination of either the stage 1, 2, or 3 cells.

Having established the design of the cells, it is now necessary to impose some form of inventory and flow control on the system overall and within the cells. When making the choice between CONWIP and kanban, there are several factors to consider. First, the upholstery department operates in a fan structure rather than a linear line due to the shared resource of the vinyl cutting machine and the three work cells and if CONWIP were employed there would have to be three separate loops of cards. Second, the upholstery present on each boat is for the most part consistent, differing in color and size only, thus cycle times are more consistent than in other areas of the plant. Thirdly, like small parts the upholstery department is a feeder line whose goal is to have a set of parts ready for use when they are needed by assembly, and thus should be placed on a pull system linked with assembly in order to have high responsiveness between the two departments. For these reasons, employing route specific kanban in a similar manner as was used in the restructuring of the small parts line is the most viable solution.

When employing route specific kanban, it is important to again consider the matching factor that was present in the lamination line. Here the vinyl skins manufactured through the vinyl cut process and sewing must be matched with the frames created through the plastic cutting and foaming processes. Color coded sets of cards can again be used to accomplish this matching and synchronization. Whenever an order is launched into the vinyl cut process, a colored card will be attached with the vinyl for that boat. At the same time, the second card in the set would be placed in a FIFO queue in front of the plastic cutting process. By operating in this manner, orders are launched for both the frames and the vinyl at the same time and the cards which are attached to kits of parts can be easily

matched in order to mate the two components of each upholstery part in the final assembly stage.

By operating in work cells, Skier's Choice can again gain some degree of standardization in the upholstery processes based on product family, and employing visual management techniques through the use of kanban squares and color coded cards will increase the visibility of the system. Responsiveness between upholstery and assembly will also be greatly improved through the pull system and cell structure. Lastly, the inventory in the system will be reduced due to WIP capping with the pull system and the elimination of the make-to-stock operations in the plastic shop. Figure 6.5 shows the proposed restructuring of the upholstery department.

#### **6.3.4. Rigging and Assembly Line**

The rigging and assembly line is the only department in the factory that already has some sort of inventory control method in place. Skier's Choice uses what they have termed a "pulse line," where no boats move until all processing is complete in the line. For example, once every process is complete in the Moomba line from rigging 1 to assembly 4 (see Figure 6.6), every boat will shift downstream by one process. While this method does effectively control inventory, it can result in an excessive amount of waiting for those processes that finish earlier than others, and those workers who are cross trained must move and help with other processes once they have finished their own. For these reasons it is apparent that a different control mechanism may prove more beneficial to performance.

Like the lamination line, the rigging and assembly line is linear and faces high work content variation, thus a CONWIP loop can once again be implemented. Also as in lamination, the deck and hulls travel separately until the cap and rail process, so there is again a need for a matching mechanism. This is not currently an issue with the pulse system because all boats move at the same time, but with CONWIP there will be a push system in the line and inventory will tend to gather in different areas based on the work contents of the boats currently in the system. The color coded sets of CONWIP cards can once again be employed to solve this problem. With these changes in place, the rigging and assembly line will pull boats from the inspection process in the lamination

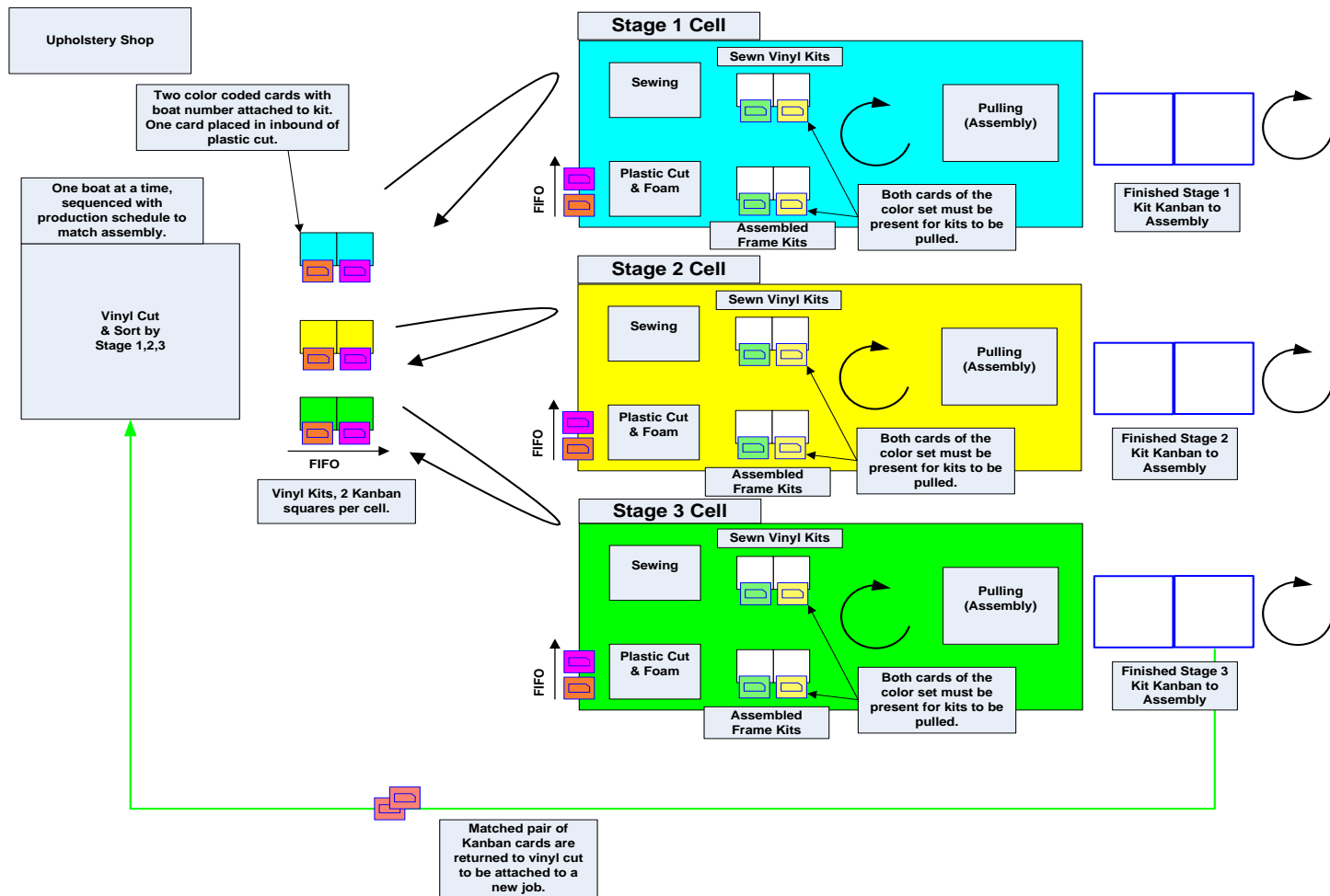


Figure 6.5 Upholstery Shop

department. There will be a set number of CONWIP cards for the system (which will be determined in the experimentation section) and in order for a deck and hull to enter the process one set of cards must be available. Both the deck and hull will receive a card and travel through their respective lines before the cap and rail process utilizes the matching cards to mate the deck with the hull. Once the boat has traveled through the assembly processes and exits the line the cards are detached and sent to the beginning of the line.

This CONWIP system will help to buffer out the issues caused by work content variation and shifting bottlenecks, while also enabling easy matching of components. Visibility of the lines' status will also be increased and problems with work flow made apparent early. Like the current pulse system CONWIP will also cap inventory but with the added benefit of being able to handle variability from one boat and one process to the next. See Figure 6.6 for a representation of the restructured rigging and assembly line.

### **6.3.5. Inspection Line**

The last stage of the manufacturing process at Skier's Choice is the inspection process (see Figure 6.7). As with most of the other departments in the plant, the inspection process has no method of inventory control. The line is fully linear with only a single routing and all boats undergo the same processing regardless of product line, thus the processes are shared between Supras and Moombas. The processing in this line is very simple in relation to others in the plant, and the only real issue with the current system is a lack of inventory control. While the cycle times for pool and lake testing are only slightly variable, the tagging data makes it evident that the time required for detailing/cleaning the boat can vary greatly. For this reason and due to the fact that the processing is the same across all models, a simple CONWIP loop can serve to cap the inventory and help to control flow in the system. Since the boats are fully assembled at this point, there is no need to employ the color coded card matching system used for restructuring other departments. Figure 6.7 shows the restructured inspection line.

Rigging and Assembly Line

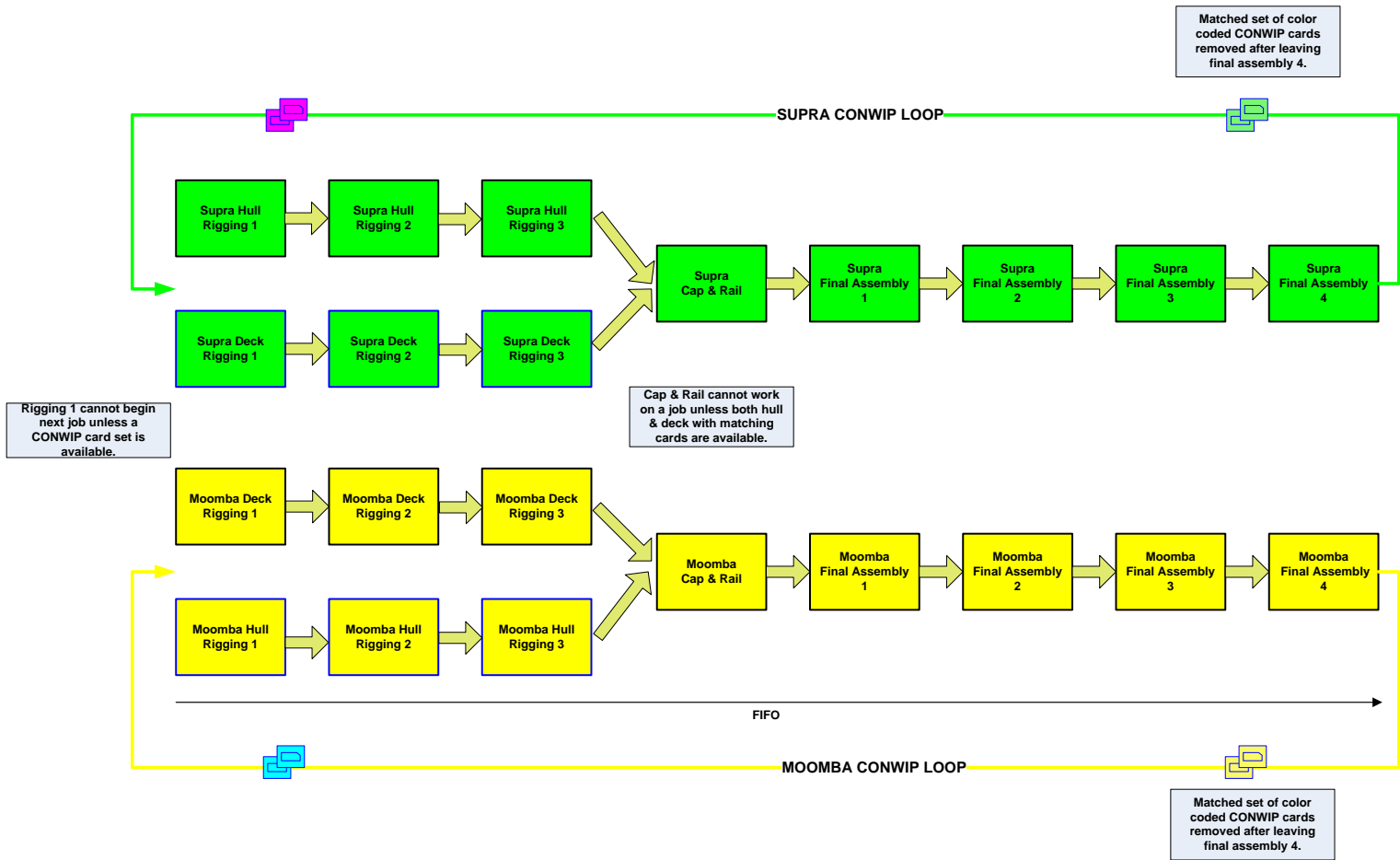


Figure 6.6 Rigging and Assembly Line

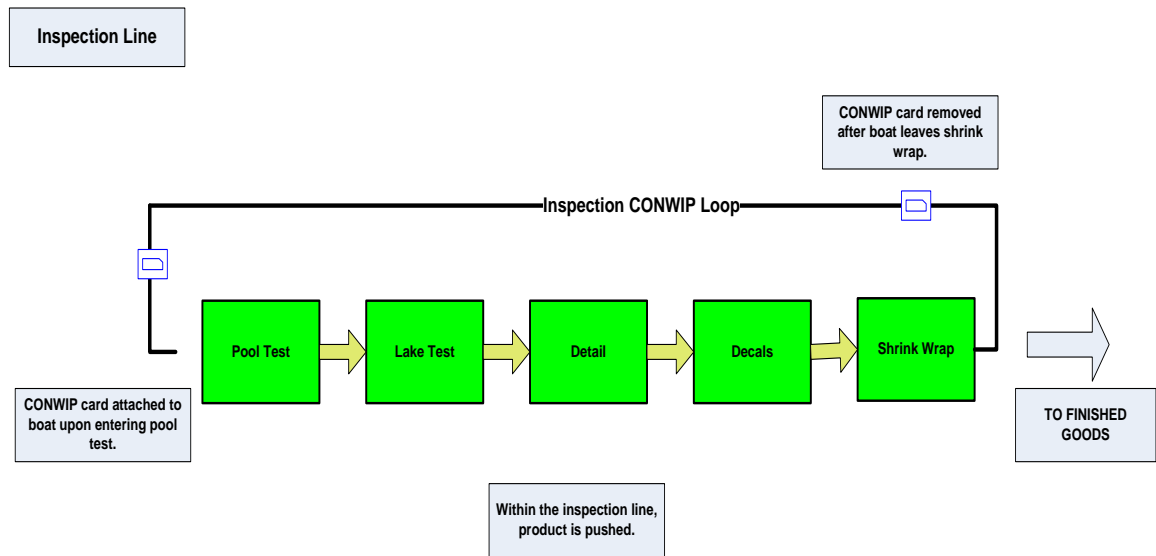


Figure 6.7 Inspection Line

Over the course of the last few sections lean principles such as CONWIP, route specific kanban, visual management, dedication, work cell design, and others have been employed in order to restructure the manufacturing operations at the case study company Skier's choice. The goal of these activities has been to improve the performance of the system by decreasing lead time and inventory and improving the flow of the entire operation. The remainder of this chapter is dedicated to experimentation procedures through simulation in order to examine the performance of this new system and analyze the effect of varying demand and number of CONWIP cards.

#### 6.4. Simulation Model Design

Before any testing of the current or future state model can be carried out it is necessary to obtain cycle time data for each of the processes at Skier's Choice. Any knowledge of how long a particular process took to complete was wholly tacit obtained from experience by the employees on the shop floor. To resolve this issue a simple tagging exercise was developed in conjunction with the production engineering department at Skier's Choice. Data sheets were distributed across the plant in one of three different categories; main line, upholstery, and small parts.

The main line data sheets included processes for the lamination line, the assembly line, and the inspection line. Here, the tagging sheet moves with the boat and receives a timestamp upon the beginning and ending of work for each process. The upholstery shop data sheets were broken down by cell (stage 1, 2, or 3) and the processes contained within the cell, and each work item was time-stamped upon the beginning and ending of the upholstery items for a complete boat. The same was true for the small parts shop, with one key difference. The amount and type of small parts required varies greatly from boat to boat, but the two constant items are stringers and floors which are structural components. Thus, these data sheets were able to give a representation for the variation of work time by showing the variation in the number and type of parts required based on boat type, and how long each of these parts took to manufacture.

With this structure in place, data was collected for approximately one week and the results were compiled in a spreadsheet in order to find the mean, standard deviation, maximum, and minimum values for each process based on boat model. Table 4 shows an example of a few data points for Supra boats in the assembly line.

Having obtained all the necessary cycle time information the next step is to construct a simulation model for testing the new system. The future state model was built using the program Simul8<sup>®</sup>. The overall layout of the model is shown in Figure 6.8. The figure is too large to study in detail, thus a further discussion of the simulation models for each individual department follows.

Table 4. Example Cycle Time Data

SUPRA MAIN LINE CYCLE TIMES (minutes) (n=14)										
Model	Gravity 24 SSY	Launch 21Y	Sunspot 22Y	Launch 22SSY	Launch 22SSY	Launch 24SSY	Launch 21Y			
Boat Number	HFL07	HB034	SW007	HV037	HV036	HFL06	HB032	Mean	Standard Deviation	
Hull 1	105		95	63	63	89	45	69	18	
Deck 1	75		120	85	74	120	95	91	18	
Hull 2	73	90	100	100	125	130	110	104	18	
Deck 2	110		110			100	145	105	20	
Hull 3	90		90	70	80	80	70	80	18	
Deck 3		90		90	115	100	85	105	20	
Cap & Rail	120	115		115	100	135	150	131	20	
Final Assy 2	65	120	62	95	100	115	90	96	20	
Final Assy 3	90	100	75	85	105	105	140	101	18	
Final Assy 4	80	170	105		135	140	120	122	23	
Final Assy 5	50	85	50	75	82	85	55	74	22	

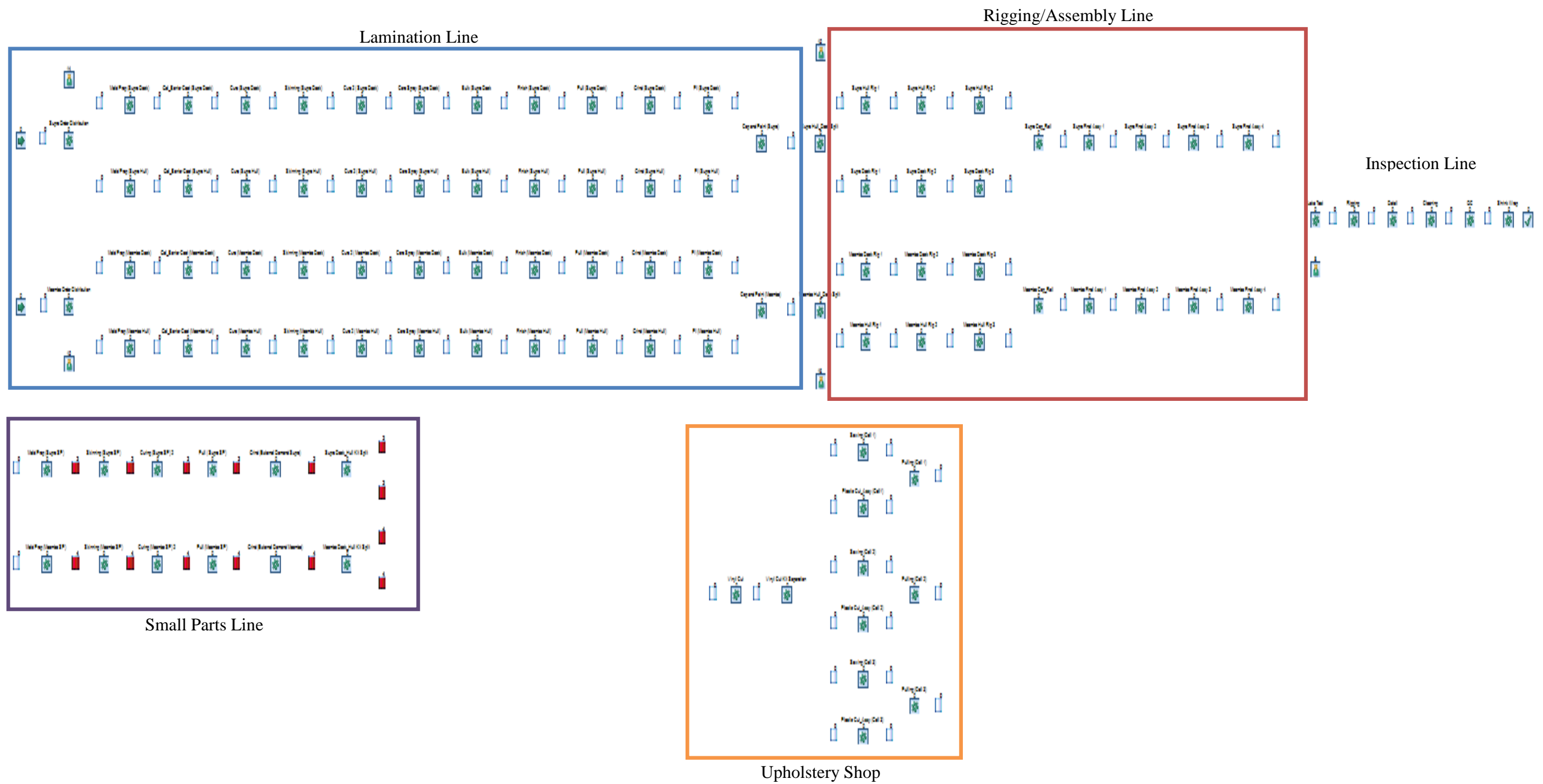


Figure 6.8 Skier's Choice Simulation Model



### ***Lamination Line Model***

Work begins in the simulation from two work entry points, one for Supra and one for Moomba. The inter-arrival time is set to an average value based on the demand level that is to be tested. Once the work is released, it enters a pre-system queue of orders that are ready to be manufactured on a first-in-first-out (FIFO) basis. The next process is an order distribution mechanism with a fixed cycle time of zero. The function of this process is to take an order from the queue and communicate to the feeder lines (small parts and upholstery) that a particular work item has entered the system and will require component parts. These processes for Moomba and Supra essentially control the entire system, as they require a lamination CONWIP card for their specific product type to begin work. If a CONWIP card is available, they will pull a work item from the queue and split it into four orders which are sent to the mold prep stations for decks and hulls, the small parts shop, and the upholstery department for its respective product type. From the mold prep stations the deck and hull travel through the various processes until they reach the cap and paint station where they are joined. Following the cap and paint process there is a buffer with a fixed maximum level (discussed in testing and results section) which separates the lamination and assembly loops. If this buffer has available capacity the work item will leave the cap and paint process and the CONWIP card attached to it will be made available for more work to enter the system. A detailed view of the lamination simulation model is shown in Figure 6.9.

### ***Small Parts Line Model***

The small parts feeder line receives orders from the order distribution processes. Each order goes to its respective dedicated feeder line based on Supra and Moomba product types. Again, no products can be launched into the small parts line until the lamination loop indicates the system is ready based on the presence of a free CONWIP card. Between each process is a buffer which indicates kanban squares and thus have a fixed maximum level. This maximum level was determined by observing the minimum level which prevents starvation of the lamination line in the simulation, which was found

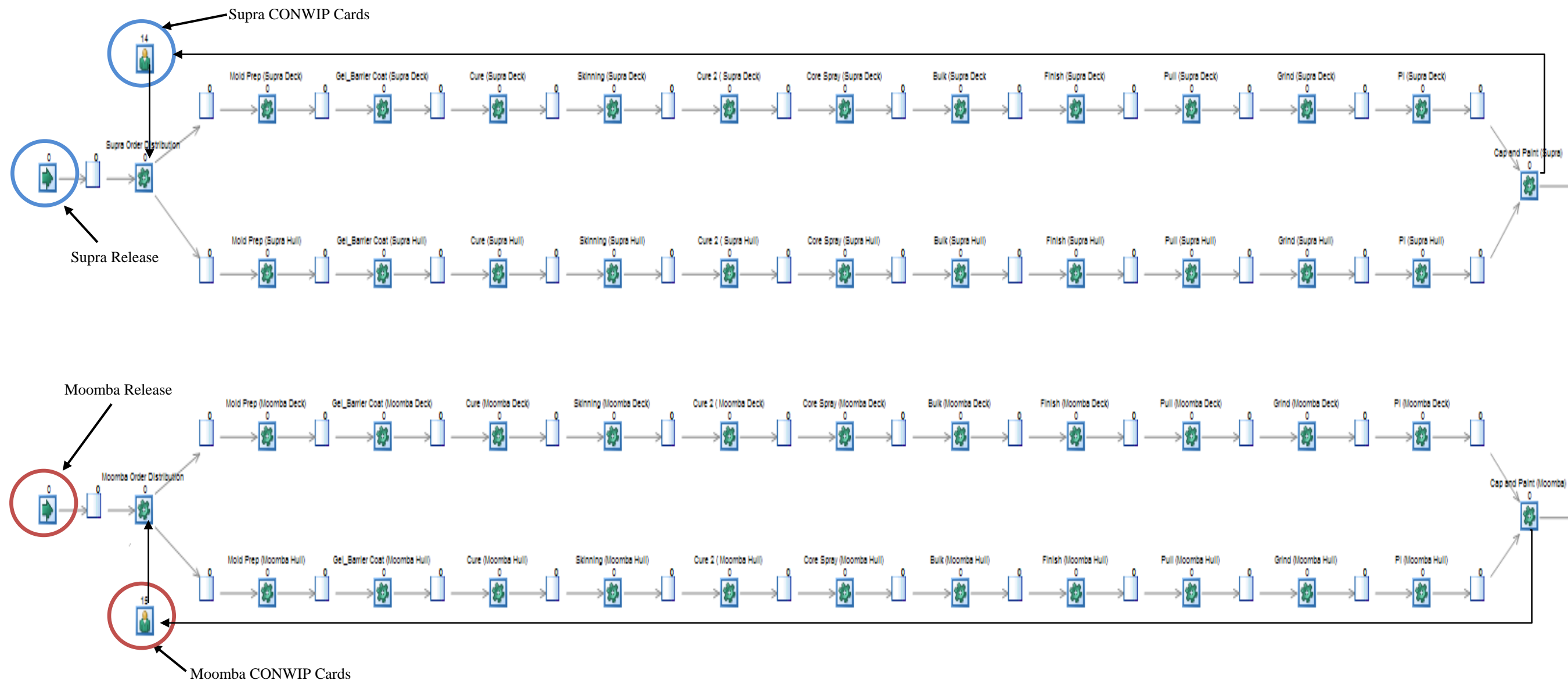


Figure 6.9 Lamination Line Simulation Model

to be 2 for Supra and 4 for Moomba. It was also found by observation that if the small parts line is started empty as the other departments are, lamination will be starved at the beginning and the data will be skewed. For this reason, the small parts line is started with full buffers. The entire line operates on a strict pull system in which no products are manufactured until the lamination line has pulled components from the end buffer. At the end of the line, there is a “kit-splitting” process with a fixed zero cycle time. The purpose of this process is to divide work items created by the small parts line into two components, one of which goes to the deck line and the other the hull line in lamination. Figure 6.10 shows the model of the small parts line.

### *Upholstery Shop Model*

Like the small parts line, the upholstery shop receives orders from Supra and Moomba Order release, the main difference being that this line does not employ dedicated product lines. Instead, the cell structure presented in the upholstery restructuring discussion is employed. When an order is received, it is sent into the vinyl cutting process where all of the vinyl needed for a particular boat is cut out. From there, the work item is sent into a kit separation which represents the vinyl being split into stage 1, 2 and 3 components. This process takes the single work item from vinyl cut and creates six work items, 3 of which represent kits of vinyl parts and the other three representing corresponding orders for frames for the upholstery parts. Thus, orders are not launched for frames until the vinyl is ready, which aids at balancing the cells and matching the components together for assembly. For inventory control buffers are again used as kanbans and set to a maximum level. Since the main concern of this experimental investigation is the main line including lamination, assembly, and inspection, these buffers were set to the minimum level to prevent starvation of the assembly line, which was found by observation to be 3. Figure 6.11 shows a detailed view of the upholstery shop simulation model.

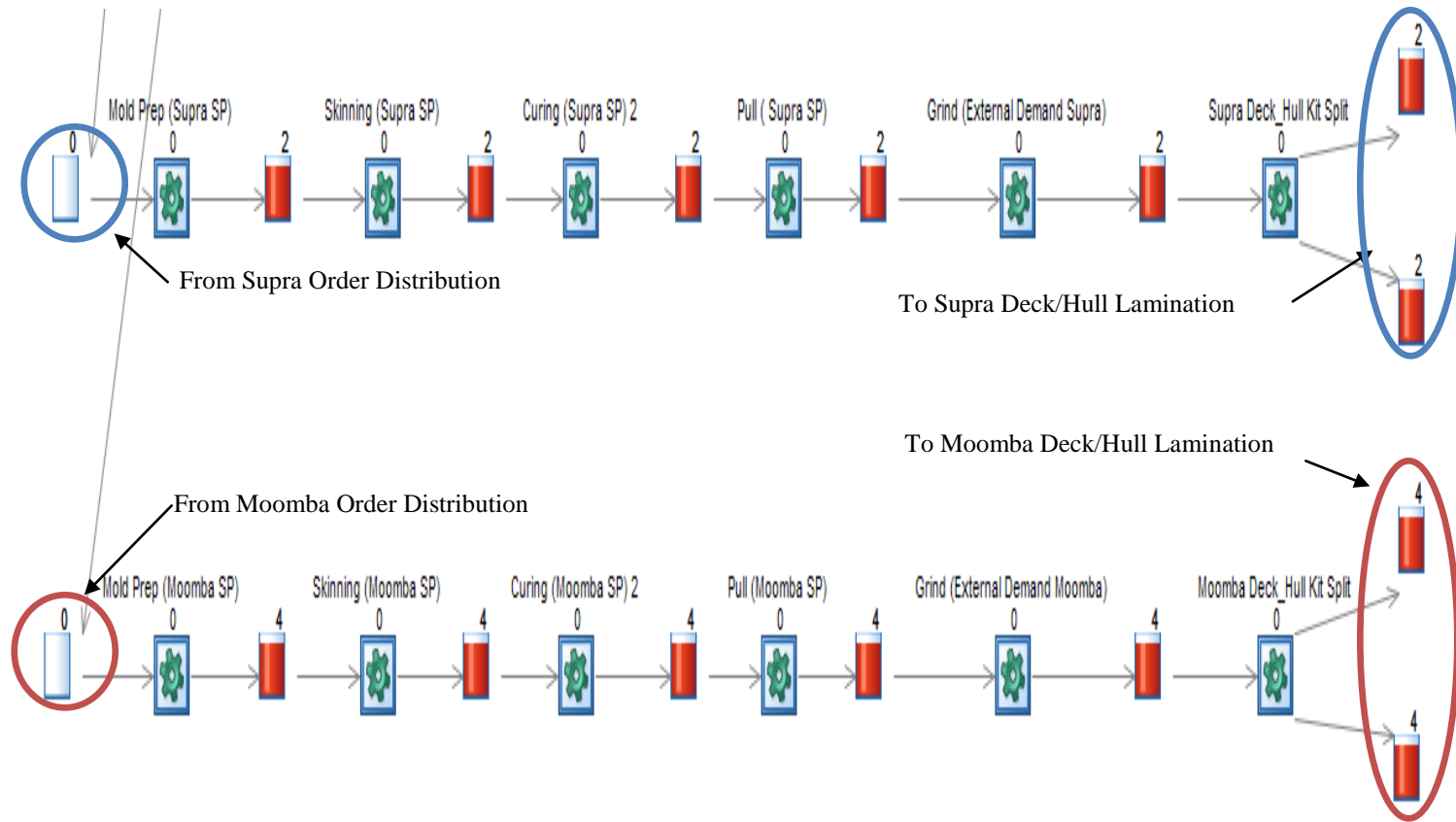


Figure 6.10 Small Parts Line Simulation Model

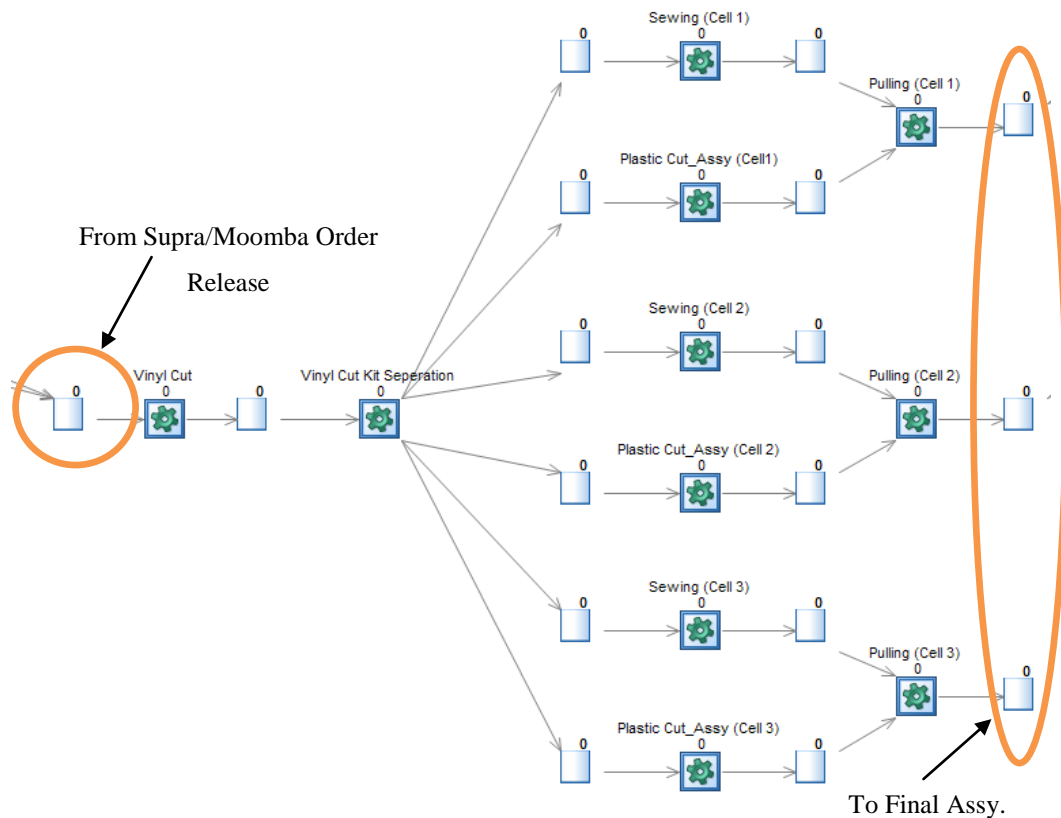


Figure 6.11 Upholstery Shop Simulation Model

### *Assembly/Rigging Line Model*

The assembly and rigging line receives work items from the buffer after the cap and paint process in lamination. At the beginning, a splitting process (with a fixed cycle time of zero) splits decks and hulls which were combined in the cap and paint process back into individual components. This process cannot bring any work items into the line unless there is a CONWIP card available for its respective product type.

Once this condition is met and the decks and hulls have been separated they travel down their respective rigging line before being joined for good in the cap and paint process. The boat then travels through the four final assembly stages along with its CONWIP card. During final assembly 2, 3, and 4, upholstery kits are pulled from upholstery cells 1, 2, and 3, respectively.

Since upholstery does not have dedicated Supra and Moomba product lines, it is important to constrain the simulation model such that Moomba upholstery parts are not placed in Supra boats. To accomplish this, the assembly in these processes is conducted on a matching basis. Upholstery parts and boats are mated based on a unique identification label. This “Label Unique ID” is set from the order release processes, and the processing on the work item cannot be completed unless the upholstery part with the required identification is available.

Once all of the processing in the final assembly stage is complete, the boat exits into a buffer between the assembly and rigging line and the inspection line. Through observation it was found that these buffers never grow in size but are usually starved for work due to the inspection line being faster than the assembly line. For this reason, no capacity restriction was placed on the buffers. Figure 6.12 shows the detailed view of the assembly/rigging line model.

### ***Inspection Line Model***

The inspection line gathers work items ready for final processing from two queues, one being Supra final assembly and the other Moomba final assembly. The WIP in the inspection line is wholly controlled by its CONWIP cards. A work item cannot enter the line from one of the aforementioned buffers unless a CONWIP card is available, and the CONWIP card is freed for more work to enter the line only upon the completion of work. The first process in the line, lake test, chooses which queue to pull from based on time in the system. Essentially, the work item that has been in the system the longest from either queue is pulled, which maintains FIFO. The detailed view of the inspection line simulation model is shown in Figure 6.13.

With the addition of the inspection line, the entire manufacturing system at Skier’s Choice has been successfully modeled based on the restructured departmental setups presented in Section 6.3. This model can now be used to test the performance of the system with respect to the current state, as well as test the effect of and optimize the number of CONWIP cards in the system. Simul8 gives many performance measures which can be used to understand the system as a whole and choose the best combination of different types of variables in order achieve the desired performance improvements.

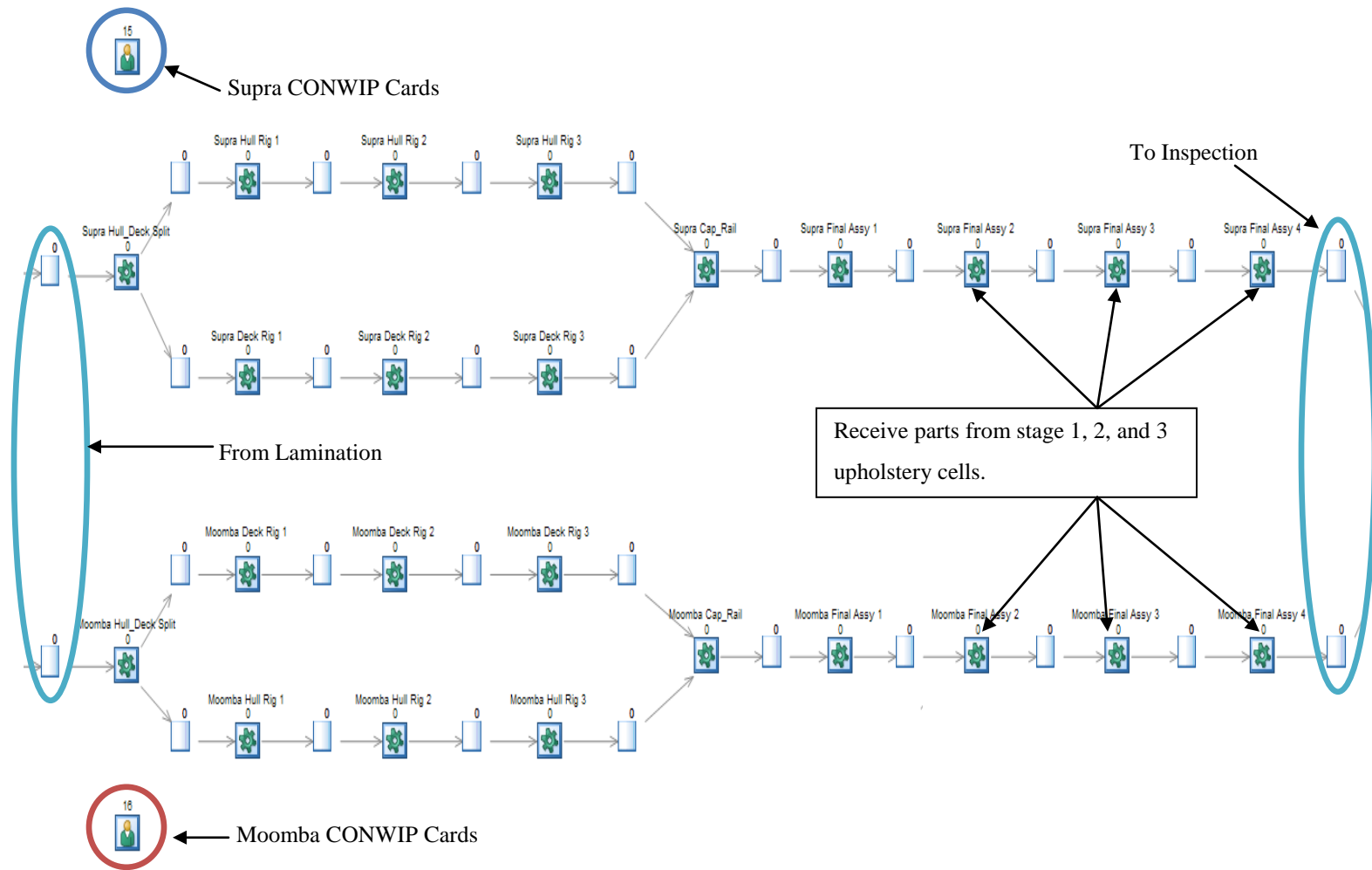


Figure 6.12 Assembly/Rigging Line Simulation Model

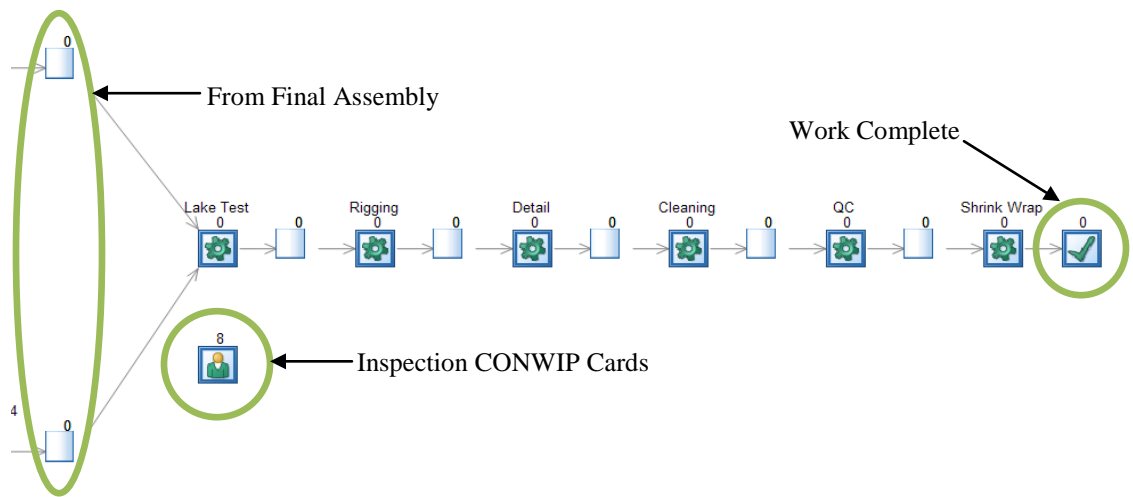


Figure 6.13 Inspection Line Simulation Model

## 6.5. Experimental Design

A set of experiments was designed to test the simulation model and determine optimal values for various parameters including the number of CONWIP cards in each loop. Responses variables that are of key interest to this experimentation are lead time and work in process. In order to fully test the performance of the system based on these responses under different demand scenarios and CONWIP card amounts, an approach similar to that used in a mixed-level factorial design of experiments was employed.

The first step in designing the experiment is to determine the variables that will be changed over the course of the experiment. The main areas of interest in the system are the lamination line, assembly/rigging line, and the inspection line, as these departments make up the main line and determine the overall throughput of the system. Through observation appropriate buffers between the small parts and upholstery departments and the main lines which they feed were placed in order to prevent starvation. Since lead time through the system is a key performance indicator, it is logical to elect the CONWIP card levels of each of the main-line departments as three factors that must be varied in the system, while ignoring the feeder lines as a limiter to throughput.



The fourth variable that is changed in the experiment is the demand level. Skier's Choice feeds a seasonal market as demand will tend to be higher in the warmer parts of the year, thus they face a cyclical demand scenario as is the case with many mass customizers. Because of the relatively low volume of the operations, a small increase in demand can cause a significant effect on the performance of the system, and it is important to test the ability of the new system to handle this variability.

With the experimental variables chosen as demand level and amounts of CONWIP cards in each of the three loops, the next step is to determine the levels of each of the factors that will be tested in the experiment. When setting the number of levels for each factor, it is important to keep the number of experiments to a reasonable level while still showing accurate results. Of the three CONWIP loops, lamination and assembly/rigging have the greatest affect on the system, as observation of the simulation shows that the inspection loop is often waiting on work from the assembly line. Thus the inspection line CONWIP card factor is given two levels, while the lamination and assembly/rigging loops are given three levels in order to analyze their effect on system in more detail. The demand factor is given two levels in order to represent the cyclical periods of higher demand in the spring and summer months and lower demand in the fall and winter.

The demand was varied between two levels one of which represents the fall and winter months and corresponds to a 96 minute inter-arrival time for Supras and an 80 minute inter-arrival time for Moombas. To represent higher demand in the spring and summer months, the daily demand on the system is raised by two boats; one Supra and one Moomba (18% increase in daily demand). With the higher demand of six Supras and seven Moombas daily, the inter-arrival times at the work release points are set to 80 and 68 minutes, respectively.

When setting the number of CONWIP cards in the lamination loop, the number of processes must be taken into account. For a CONWIP loop the minimum number of cards is generally considered to be the number of processes in the loop. Both the Supra and Moomba lamination lines have 10 processes (excluding curing processes), which is a reasonable initial level of cards to set. To take into account the slightly higher demand of Moomba products over Supra, the card count for the Moomba lamination line is raised by one card to 11. For the medium and high levels of the factor, both Moomba and Supra

card values are raised in increments of two, to 12 and 13 for the medium level and to 14 and 15 for the high level, respectively.

For determining the levels of the CONWIP cards in the assembly/rigging lines, a key observation from running the simulation that must be taken into account is the fact that these lines run slower than the lamination and inspection lines and usually end up blocking/starving them. While the assembly/rigging lines have only 8 processes as opposed to the 10 of lamination, it is advisable to set the lowest level of cards to a higher value than the number of processes to take into account the bottleneck effect. Thus, the amount of CONWIP cards for Supra is set to 11 while the Moomba value is set to 12, with Moomba again having one more card due to higher demand. For the medium and high levels, the values are once again raised in increments of 2 for a total of 13 Supra and 14 Moomba and 15 Supra and 16 Moomba respectively.

There are six processes in the inspection loop, thus the number of CONWIP cards was varied from 6 to 8. Table 5 summarizes the variables and levels set for the experimentation. The notation that is used here and for further discussions is (0) for the low level, (1) for the medium, and (2) for the high.

Table 5. Variables and Levels of Experiment

Summary of Variables and Levels		Levels					
		Low (0)		Medium (1)		High (2)	
		Supra	Moomba	Supra	Moomba	Supra	Moomba
Variables	Inter-arrival Times (Minutes)	96	80	N/A	N/A	80	68
	Lamination CONWIP Cards	10	11	12	13	14	15
	Assembly CONWIP Cards	11	12	13	14	15	16
	Inspection CONWIP Cards	6		N/A		8	

The warm up period for the simulation is the time set to allow the system to fill with work and reach steady state operation. Simul8 has a function that will inform the

operator if warm up and results collection periods are too short to truly show system performance. Through the use of this tool and observations and testing, an appropriate warm up period was found to be 5,000 minutes or roughly two work weeks. The results collection period was set to 10,000 minutes or approximately four work weeks.

## **6.6. Testing and Results**

Based on the variables and levels described above, the statistical analysis program NCSS is used to create a test matrix. From the test matrix, the CONWIP cards and inter-arrival times are set up based on the levels of each treatment and the simulation run for results collection. The performance measures of interest that results are collected for include average lead time, total WIP in the system, average WIP in each CONWIP loop, average amount of orders waiting to be manufactured in the pre-system queue, and average amount of boats completed. All of the results are collected based on averages from a five trial replication with a base random number set of one. Table 6 summarizes the test matrix and resulting performance measures. When examining the results of the experiment it is worthwhile to consider the two levels of demand separately, as demand level will have a great effect on system performance.

Examining the table from left to right, it is evident that the WIP levels in the lamination, assembly/rigging, and inspection loops are simply a validation of the number of CONWIP cards in the loop. The value for WIP is consistently equal to the total number of cards for Supra and Moomba in each respective loop, which shows that the CONWIP cards are accomplishing their objective of limiting the total inventory in the loop. The total system WIP is simply the sum of the three CONWIP loop inventories, and as expected increases as the number of CONWIP cards increase.

The pre-system WIP column corresponds to the total amount of boats (Supra and Moomba) waiting to be launched into the system. Again, this response measure behaves as expected, as it decreases with increasing CONWIP cards indicating more WIP in the system and less waiting to be launched. An important observation is that this queue is large compared to the boats completed over the time period of the simulation, especially for the high demand case.

Table 6. Experimental Results

	Case No.	Variables			RESPONSES (Random Number Set = 1)						
		Lamination CONWIP Cards	Assembly CONWIP Cards	Inspection CONWIP Cards	Pre-System WIP	Lamination Loop WIP	Assembly Loop WIP	Inspection WIP	Total System WIP	Boats Completed	Lead Time
Low Inter-arrival Times	1	0	0	0	37.36	21	23	5.33	49.3	126	4437
	2	0	0	1	37.36	21	23	5.33	49.3	126	4421
	3	0	1	0	33.69	20.97	27	5.3	53.3	125	4485
	4	0	1	1	33.69	20.97	27	5.31	53.3	125	4469
	5	0	2	0	29.97	20.94	31	5.28	57.2	124	4474
	6	0	2	1	29.97	20.94	31	5.3	57.2	125	4460
	7	1	0	0	33.4	24.97	23	5.33	53.3	126	4429
	8	1	0	1	33.4	24.97	23	5.33	53.3	126	4400
	9	1	1	0	29.79	24.89	27	5.29	57.2	125	4455
	10	1	1	1	29.79	24.89	27	5.3	57.2	125	4437
	11	1	2	0	26.27	24.79	31	5.27	61.1	124	4473
	12	1	2	1	26.27	24.79	31	5.26	61.1	124	4452
	13	2	0	0	29.83	28.88	23	5.28	57.2	125	4451
	14	2	0	1	29.83	28.88	23	5.28	57.2	125	4434
	15	2	1	0	26.03	28.69	27	5.28	61	124	4464
	16	2	1	1	26.03	28.69	27	5.28	61	125	4443
	17	2	2	0	22.37	28.49	31	5.28	64.8	124	4458
	18	2	2	1	22.37	28.49	31	5.29	64.8	125	4436
High Inter-arrival Times	19	0	0	0	80.39	21	23	5.6	49.6	123	5416
	20	0	0	1	80.39	21	23	5.25	49.3	124	4356
	21	0	1	0	76.35	21	27	5.18	53.2	122	5409
	22	0	1	1	76.35	21	27	5.19	53.2	122	5394
	23	0	2	0	72.17	21	31	5.17	57.2	122	5429
	24	0	2	1	72.17	21	31	5.17	57.2	122	5415
	25	1	0	0	75.68	25	23	5.28	53.3	124	5377
	26	1	0	1	75.68	25	23	5.28	53.3	124	5355
	27	1	1	0	71.71	25	27	5.26	57.3	124	5384
	28	1	1	1	71.71	25	27	5.27	57.3	124	5363
	29	1	2	0	67.98	25	31	5.22	61.2	123	5389
	30	1	2	1	67.98	25	31	5.24	61.2	123	5374

	31	2	0	0	71.23	29	23	5.3	57.3	125	5341
	32	2	0	1	71.23	29	23	5.31	57.3	125	5298
	33	2	1	0	67.27	29	27	5.29	61.3	124	5345
	34	2	1	1	67.27	29	27	5.3	61.3	125	5328
	35	2	2	0	63.89	29	31	5.25	65.3	123	5368
	36	2	2	1	63.89	29	31	5.26	65.3	124	5358

This indicates that the manufacturing system at Skier's Choice, based on the cycle time data obtained from the tagging activity, is lacking adequate capacity to handle the current demand level and any increase in demand will make this inadequacy more prominent. Skier's Choice should investigate the possibilities of reducing cycle times and increasing their capacity. One possible solution is to conduct kaizen events with the shop floor employees to identify and eliminate sources of process waste.

In order to further validate the results, an analysis of variance (ANOVA) is performed, again using NCSS, to show which factors and/or interactions are most significant to the performance of the system. The ANOVA was performed using two replications of the simulation with two different random number sets. Based on the setup of the CONWIP loops, it is obvious that the factors corresponding to the amount of cards in each loop will be highly significant to determining the total WIP in the system, and therefore an ANOVA with total WIP as the response is arbitrary. However when considering average lead time it is not clear which of the factors have the most significant effect, and thus an ANOVA is necessary. Figures 6.14 and 6.15 show the summary of the ANOVA results for the high and low demand scenarios, respectively.

Analysis of Variance Table							
Source	DF	Sum of Squares	Mean Square	F-Ratio	Prob Level	Power (Alpha=0.05)	
A: Lamination_CONWIP_Cards	2	1862	931	0.11	0.893388		0.064783
B: Assembly_CONWIP_Cards	2	5068.5	2534.25	0.31	0.738141		0.091647
AB	4	2397	599.25	0.07	0.989464	0.061584	
C: Inspection_CONWIP_Cards	1	2272.111	2272.111	0.28	0.605191		0.078939
AC	2	6.888889	3.444444	0.00	0.999580	0.050053	
BC	2	1.055556	0.5277778	0.00	0.999936	0.050008	
ABC	4	40.44444	10.11111	0.00	0.999997	0.050190	
S	18	147722	8206.777				
Total (Adjusted)	35	159370					
Total	36						

\* Term significant at alpha = 0.05

Figure 6.14 Low Demand ANOVA

Analysis of Variance Table						
Source	DF	Sum of Squares	Mean Square	F-Ratio	Prob Level	Power (Alpha=0.05)
A: Lamination_CONWIP_Cards	2	2115.722	1057.861	0.24	0.787364	0.082313
B: Assembly_CONWIP_Cards	2	3803.389	1901.694	0.44	0.653567	0.109894
AB	4	376.9445	94.23611	0.02	0.999001	0.053350
C: Inspection_CONWIP_Cards	1	1201.778	1201.778	0.28	0.606248	0.078766
AC	2	12.05556	6.027778	0.00	0.998621	0.050176
BC	2	42.38889	21.19444	0.00	0.995159	0.050619
ABC	4	30.27778	7.569445	0.00	0.999993	0.050267
S	18	78597	4366.5			
Total (Adjusted)	35	86179.55				
Total	36					

\* Term significant at alpha = 0.05

Figure 6.15 High Demand ANOVA

Figures 6.14 and 6.15 show that none of the factors or interactions are statistically significant with an alpha value of .05. However some important information can be gathered from these ANOVA tables. First, it is confirmed in both scenarios based on the probability level that each of the three factors are much more significant than any interactions between them. Also based on the probability level both figures show that the amount of cards in the lamination loop is the most significant factor to the response of average lead time, followed by inspection CONWIP cards and finally assembly/rigging CONWIP cards. This is likely due to the fact that assembly as a whole is a bottleneck loop and is never starved or blocked by the upstream and downstream loops.

Based on the key performance indicators of lead time and WIP, best case scenarios can be chosen from Table 6 for further analysis. Examining the results, it is evident that for the low demand level case numbers 2 and 8 provide the best results. Case 8 has the lowest average lead time with a total system WIP of 53.3 boats, while case 2 offers a slightly higher lead time but with a decrease in WIP of 4 boats for a total of 49.3. Similarly for the high demand level, case number 32 offers the lowest average lead time of 5,298 minutes, while case 20 has a higher lead time of 5,356 minutes but with a WIP reduction of 8 boats in the system. These four cases, based on their better performance as compared to the others, are further analyzed and compared to the current state situation based on total WIP and lead time.

### ***Lead Time Comparison***

While average lead time data for the experimental treatments in question are readily available from Table 6, a measure of current state lead time is necessary for a quantification of the improvements gained. The current state value stream map shown in

Figure 6.1 might suggest that the current state lead time can be taken from there, but this is inadvisable for a comparison with the simulation results. The lead times present in the value stream map represent only manufacturing lead time and do not include the time that each order is waiting to enter the manufacturing system. The simulation model, on the other hand, does include this queue time. To resolve this issue, a second simulation was created that is very similar to the first, but without the constraint of CONWIP cards and capped buffers. With this simulation the inter-arrival times can be set to the levels used in the future state evaluation and a measure of average lead time obtained for comparison with the restructured system's performance. For validation of the current state lead times given by the simulation, they can be compared to the current lead time that Skier's Choice quotes from time of order placement to the completion of the product, which is 4-6 weeks. The values for lead time given by the current state simulation (and shown in the current state cases in Table 7) for the low and high demand levels are 8,045 minutes and 9,147 minutes, respectively. This corresponds to an approximate total lead time of 3.35 weeks for the low demand level and 3.8 weeks for the high demand, which is in line with and in fact lower than the times quoted by Skier's Choice. Table 7 summarizes the results.

Table 7. Average Lead Time Comparison

Case No.	Demand	Inter-Arrival Time (Minutes)		Average Lead Time (Minutes)		% Reduction
		Supra	Moomba	Future State	Current State	
2	Low	96	80	4421	8045	45
8	Low	96	80	4400	8045	45
20	High	80	68	5356	9147	41
32	High	80	68	5298	9147	42

Table 7 shows a highly significant reduction in lead time from the current state to the future state manufacturing system of 45% for the low demand scenario and 41-42% for the high demand scenario. It is apparent from these results that the CONWIP loops are accomplishing their task of limiting WIP and helping the system to flow smoothly. Due

to this smoother flow boats do not wait in the pre-system queue as long as they do in the current state.

***WIP Comparison***

Just as the current state lead time cannot be accurately compared with the future state using the value stream map, the WIP values cannot be fully compared using only the simulation. When simulating the current state there is no constraint for work in process and thus inventory tends to pile up in several areas across the plant where cycle times are higher. In reality, these WIP levels are simply controlled by the amount of storage space available. Thus comparing future state WIP with that of the current state simulation is unrealistic and an alternative method is needed. The current state value stream map can be employed as this alternative, since during the generation of the map a snapshot of the WIP conditions was created which can be considered the general state of the system. Using the total WIP values for the treatments in question and comparing them to the current state total WIP, Table 8 is generated for the comparison.

Table 8. Average WIP Comparison

		Inter-Arrival Time (Minutes)		Average Total WIP (Boats)		
Case No.	Demand	Supra	Moomba	Future State	Current State	% Reduction
2	Low	96	80	49.3	64	23
8	Low	96	80	53.3	64	17
20	High	80	68	49.3	64	23
32	High	80	68	57.3	64	10

Table 8 shows that a 17-23% reduction in WIP for the low demand case and a 10-23% reduction for the high demand case can be achieved by implementing the restructured manufacturing system. When considering the high cost of these products it is apparent that these reductions equate to a significant reduction in investments that are tied up in the system at a given time.



### ***Further Analysis***

Two other analyses that must be performed in order to complete the experimentation are investigations into the effect of the buffer size between lamination and assembly and the effect of random number variation on system performance. From observation the simulation shows that the assembly/rigging line blocks the lamination line and the buffer between the two is usually at full capacity. During the preliminary experimentation this buffer was set to a capacity of five boats of each product type for a total of 10 boats. The reasoning behind this value is that 10 boats, which corresponds to a little less than a day of inventory, is likely representative of a maximum inventory that Skier's Choice would wish to keep between the two CONWIP loops.

Having chosen the best cases for further analysis, experimentation can now be performed to determine the effect of this buffer size on system performance. While it is obvious that increasing the buffer size will increase the WIP in the system, the effect on average lead time is unknown. Thus, the buffer was set to various levels ranging from 4 to 12 boats and lead time data collected. Table 9 summarizes the results.

Table 9. Effect of Lamination/Assembly Buffer Size

	Case No.	Lamination/Assembly Buffer Size				
		4	6	8	10	12
Lead Times (Minutes)	2	4415	4408	4414	4421	4430
	8	4386	4404	4400	4400	4418
	20	5296	5297	5315	5356	5395
	32	5270	5295	5297	5298	5302

Table 9 shows that for all cases an increase in buffer size will result in an increase in lead time, while a decrease in buffer size reduces the lead time. While the size of the buffer does affect lead time, the increases/decreases are small and not very significant. The size of this buffer could be reduced in the simulation to a value of 4 or 6 boats which would result in lower WIP and a slightly decreased lead time, however it is important to keep in mind one of the key purposes that a buffer serves which is handling variability. Factors such as process downtime and employee absence can greatly affect the ability of

a system to keep a buffer consistently filled, and these concepts must be taken into account when setting the buffer level so as to prevent starvation of the bottleneck assembly/rigging lines.

Simulation analyses are to some extent limited by the random demand and cycle time patterns generated for the multiple replications tested. Since Simul8, too, initiates the same random number patterns of the inter-arrival and processing times for products for any trial run with five replications, the scope of the results is limited to the corresponding data set. All of the trials thus far have been conducted using a base random number set of 1, and the effect of changing this parameter must be tested. Cases 2, 8, 20, and 32 were run using different random number sets, the variation of which was kept consistent from one case to the next. Average lead times were taken from each run so that standard deviations could be found on a case by case basis. Table 10 shows that simulating each of the treatments in question for 10 different random number sets will result in an approximate standard deviation of 90-100 minutes of the average lead time. When compared with average lead times of 4,440 to 5,653 minutes for the treatments in question, a standard deviation of this size is not largely significant to system performance. Overall this test shows that variability will affect system performance, but not to an excessive degree.

Table 10. Effect of Random Number Variation

	Case No.	Random Number Set										Mean	Std. Dev.
		1	2	3	4	5	6	7	8	9	10		
<b>Lead Times</b>	2	4421	4299	4389	4447	4438	4569	4519	4371	4250	4418	4412	94
	8	4400	4293	4373	4426	4424	4560	4504	4353	4259	4371	4396	90
	20	5356	5434	5490	5631	5600	5653	5597	5525	5396	5540	5522	102
	32	5298	5423	5533	5565	5613	5640	5613	5509	5442	5512	5515	105

### ***Discussion and Selection***

The experimental procedures are complete and the system performance has been fully analyzed. These procedures have proven that if this restructured system were

implemented Skier’s Choice would achieve significant improvement in average lead time and WIP on the shop floor. These tests also prove that the size of the buffer between lamination and assembly does not have a large affect on lead time and needs only to be kept at a minimum appropriate level to buffer any variation and prevent starvation of the assembly/rigging line. Lastly, the tests show that the system performs much the same regardless of the base random number set used to conduct the simulation.

Upon the completion of these analyses, the levels of CONWIP cards that should be used for each demand level can be chosen. For the low demand scenario, cases 2 and 8 were presented as the best options for optimal system performance. Case 2 corresponds to an average lead time of 4,421 minutes with a total system WIP of 53.3 boats, while case 2 has a lead time of 4,400 minutes with a WIP of 53.3 boats. Based on these values, Skier’s Choice should elect to employ case 8 when setting the CONWIP card values as they can obtain a four boat reduction in WIP with only a 21 minute increase in lead time.

For the high demand level cases 20 and 32 were shown as the best options from the preliminary experimentation. Case 20 has a 5,356 minute lead time with a system WIP of 49.3 boats while case 32 has a lead time of 4,298 minutes with a WIP of 57.3 boats in the system. Again, Skier’s Choice should choose the lower WIP case 20, as they can decrease the overall WIP in the system by 8 boats with a lead time increase of 58 minutes. Table 11 summarizes these choices and shows the resulting CONWIP card values that should be set.

Table 11. Summary of Case Selections

Case No.	Demand	Inter-Arrival Time (Minutes)		Lamination CONWIP		Assembly CONWIP Cards		Inspection CONWIP Cards
		Supra	Moomba	Supra	Moomba	Supra	Moomba	
2	Low	96	80	10	11	11	12	8
20	High	80	68	14	15	11	12	8

The investigation of the Skier’s Choice case study began with a need to evaluate the application of lean manufacturing principles and/or other strategies in order to achieve

performance improvements for the manufacturing system. Based on the framework presented in Chapter 4 each of the manufacturing systems were evaluated in the context of application at Skier's Choice and it was discovered that lean manufacturing principles alone were the best fit for the given situation, and from this each of the departments in the system were restructured according to lean principles. Through system modeling and experimentation it has been proven that should the restructured system be implemented, significant gains in average lead time and system WIP would be gained while maintaining the ability to handle the high variation inherent in the products of this mass customizer.

## 7. Discussion and Conclusions

Over the course of this research the validity of incorporating lean manufacturing principles and practices in mass customization environments has been thoroughly examined. A classification scheme for mass customizers was selected, and the principles inherent in lean manufacturing and the competencies required of a successful mass customizer have been clearly defined and discussed. The possibilities for integrating other manufacturing strategies in areas where lean may fall short as a tool for efficient mass customization have also been investigated and from these discussions and atheoretical framework for combining lean and mass customization was developed. Based on this framework, each of these manufacturing strategies were evaluated in their ability to offer performance improvements for Skier's Choice. The framework can now be reevaluated based on the findings from the investigation into the Skier's Choice case study. See Figure 7.1 for the revised theoretical framework.

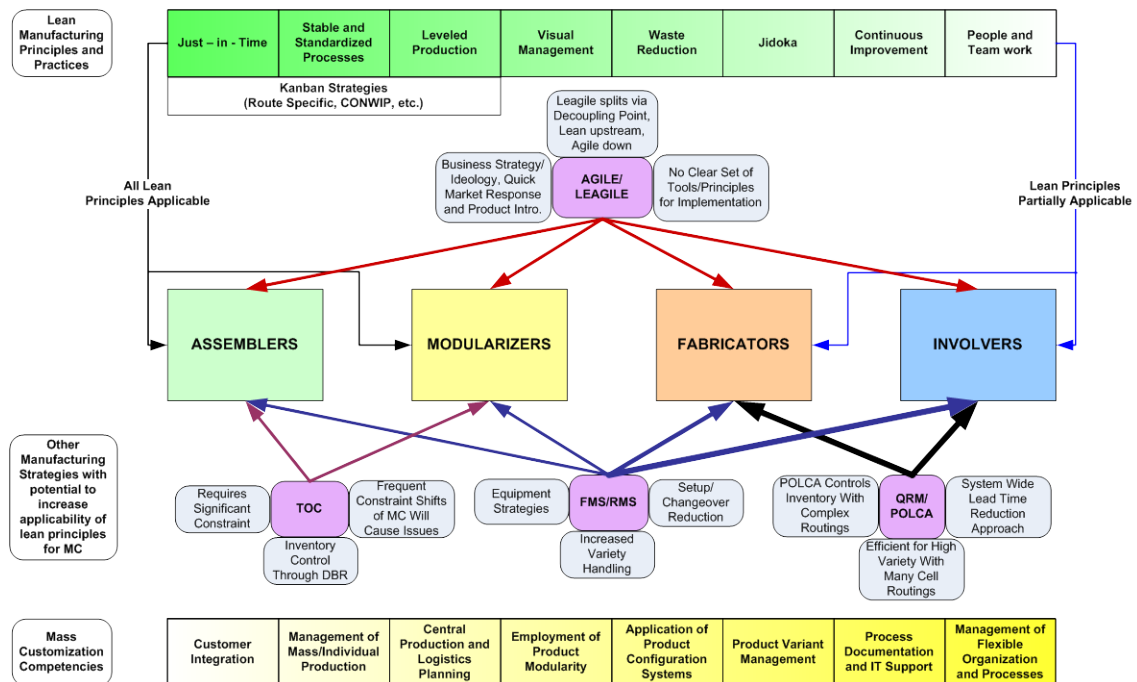


Figure 7.1 Revised Theoretical Framework

The theoretical framework in Chapter 4 stated that Agile, and particularly Leagile strategies, are more likely to be applicable for mass customizers classified as assemblers or modularizers. Leagile manufacturing relies fully on the existence of a logical decoupling point which splits standardized upstream processing from customized downstream processing. Hence, a mass customizer must first have some degree of standardization in the early stages of product manufacture, and also be able to define a specific point in processing at which standardized products become customized. Despite the fact that Skier's Choice is an assembler, it was found through further evaluation that due to their variety explosion occurring very early in the process the implementation of a decoupling point was impossible. This indicates that in fact it may be difficult to define a decoupling point even for low level mass customizers, and the implementation of leagile manufacturing may be just as likely or unlikely in these cases as it is for high level customizers. Based upon this reasoning, the applicability of agile and leagile systems has been represented equally across all types of mass customization as Figure 7.1 shows.

Flexible/Reconfigurable manufacturing systems (FMS/RMS) were indicated in the original framework as being applicable to all mass customizers whose processing is equipment intensive, with increasing degrees of applicability as customer involvement moves up the value chain. The evaluation of the case study company did show that there was little need for these equipment strategies for an assembler, but this is more a result of the particular type of manufacturing taken place and cannot be generalized for all mass customizers. Essentially, the validity of these systems as a tool for mass customization will fully depend on the specific equipment needs of a given manufacturing system. Further research is needed in this area, but it can be speculated that for those manufacturing processes that do require equipment, the need will be greater for robust systems to handle variety as customer involvement moves up the value chain. Thus the applicability of FMS/RMS has remained unchanged in the revised framework.

The Theory of Constraints (TOC) was first represented in Chapter 4 as being applicable mainly for low level customizers, and even then to a small degree. In the evaluation of this strategy for Skier's Choice TOC was not considered as a valid means of system control due to the high variation in cycle times which results in the shifting of the constraint. Further analysis, however, has indicated that the assembly line as a whole

could be considered to be a bottleneck. This observation begs the question of how TOC and the *drum-buffer-robe* mechanism could be applied not to a single process, but to a set of processes or a department. It is entirely possible that the TOC system could be adapted to control the system in terms of departments rather than individual processes. For high level customizers, it is still likely that the bottleneck will shift frequently even on a departmental level due to the early customer involvement and very high variation from one design to the next. However, for low level customization it is reasonable to increase the applicability of TOC as shown in Figure 7.1.

Quick Response Manufacturing (QRM) was represented in the original framework as being applicable mainly for high level mass customizers. QRM and the POLCA mechanism offers the ability to efficiently control product routings and inventory between pairs of cells. The existence of many complex routings is more likely to occur when the customer becomes involved earlier in the value chain, and the case study helped to bolster this argument. As an assembler, Skier's Choice has a linear main product line in which product flow while obtaining parts from various feeder lines, thus there are no complex routings to consider. The complexity of operating a POLCA system makes it undesirable to implement unless absolutely needed. QRM also relies on the creation of a cellular structure across the manufacturing system in order to implement POLCA. This system is robust, requires a specific system structure for implementation, and will often be unnecessary for low level customizers as was validated by the case study. Thus no alterations to the original framework have been made in the context of QRM applicability in Figure 7.1.

The theoretical framework enabled the selection of lean manufacturing principles as a means to fully structure and control the system at Skier's Choice. The experimentation with the model of the restructured manufacturing system has validated the use of lean principles in this mass customization environment by showing significant improvements in average lead time and WIP over the system currently in place. Thus it is proven that lean manufacturing can be successfully integrated as a means of systems structure in at least some mass customization settings. While the situation at Skier's Choice is not representative in any way of all mass customizers, it does provide a reasonable

generalization of those mass customizers of the assembler variety as outlined by Duray (2000).

It is apparent that certain lean principles such as continuous improvement, waste reduction, visual management, 5s, etc. can be readily implemented in most manufacturing environments. However what is not known is to what extent principles such as JIT, stable and standardized processes, and load leveling can be applied for mass customization. This research has attempted to investigate these principles further and determine just how applicable they can be for mass customization, and has successfully done so for the assembler variety of mass customizers.

### ***Future Work***

While the objective of validating lean manufacturing for use in mass customization environments has been achieved, there are several limitations of this research that should be the subject of future work. It has been shown that for assemblers lean manufacturing can likely be employed, but the use of lean for the three other mass customizer classifications of modularizers, fabricators, and involvers is still in question and could not be further investigated due to time restrictions.

It is likely that lean can be implemented for modularizers in much the same way that has been shown for Skier's Choice. While the most effective system structure and control mechanisms will vary, the overall application procedure should be similar due to the fact that both assemblers and modularizers involve the customer in the later stages of the value chain. On the other hand fabricators and involvers, who involve the customer very early in the value chain, will likely find that many lean manufacturing principles, especially those that rely greatly on stability, are not readily applicable. It is important that these styles of mass customization be further investigated in order to fully understand to what extent lean principles are applicable in each case.

The second aspect of this research that must be further investigated is the integration of other manufacturing strategies such as Quick Response Manufacturing (QRM), the Theory of constraints (TOC), Agile and Leagile systems, FMS/RMS, and Job Shop Lean in situations where lean manufacturing does not adequately fulfill the needs of mass customizers. While the restructuring of the operations of Skier's Choice required only



lean principles, this will almost certainly not be the case for many mass customizers. The POLCA strategy of QRM is a particularly robust mechanism for controlling inventory and flow in complex product routing situations as will be the case in many mass customization environments. TOC also offers the *drum-buffer-rop*e (DBR) mechanism which is a likely alternative for high level system control for those mass customizers who are able to define a consistent and stable constraint in their system such as a monument process. Also the decoupling point property of leagile systems is of particular interest in those situations where a mass customizer can postpone variety explosion and run upstream processes according to lean principles.

While little has been shown to this point on the actual implementation of agile systems and Job Shop Lean on the manufacturing shop floor, further investigations into the ability of these strategies to aid in mass customization will undoubtedly be required as they become more developed. The strengths and weaknesses of each of these strategies has been critically reviewed and the theoretical framework of the research has laid the groundwork for how and in what situations they can be integrated as a supplement to lean manufacturing for mass customization. However, there is still much work to be completed in this area, and the theoretical framework presented in this work should be used as a base point for conducting further research into the application of lean manufacturing for involvers and fabricators as well as the possibilities for the integration of the other strategies discussed.

In closing, this research has proven that lean manufacturing is not simply a tool for companies with stable demand and a strict definition of takt time. Lean manufacturing is a very strong and robust strategy that when properly applied can and will increase the performance of at least some types of mass customizers, and while some classifications of mass customization present great obstacles to the application of lean manufacturing, many of its principles hold true for all manufacturers. However, mass customizers must pay careful consideration to the individual properties of their system when contemplating the application of lean manufacturing. One cannot simply reach into the lean toolbox and pull out the answers to their manufacturing woes. Many consider the very idea of mass customization to be an oxymoron, but with the increasing fragmentation of markets and desire for individualization by consumers, there is no doubt that it is here to stay. Those

companies that are able to offer this individualization with short lead times while maintaining system efficiency will gain a profound competitive advantage in their market, and this research has shown that for at least some classifications of mass customizers lean manufacturing can be the answer.

## List of References

1. Agarwal, A., Shankar, R., Tiwari, M.K., (2006), 'Modeling the metrics of lean, agile and leagile supply chain: An ANP-based approach,' *European Journal of Operational Research*, Vol. 173, pp. 211-225
2. Alves, T. da C. L., Tommelein, I. D., Ballard, G., (2005), 'Value Stream Mapping for Make-to-order Products in a Job Shop Environment,' *2005 ASCE Construction Research Congress, San Diego, CA, April 5-7, 2005*
3. Badurdeen, F., Masel, D., (2007), 'A genetic algorithm-based approach to design minicells for mass customization manufacturing,' *International Journal of Mass Customization*, In press
4. Badurdeen, F., Masel, D., (2007), 'A modular minicell configuration for mass customization manufacturing,' *International Journal of Mass Customisation*, Vol. 2, Nos. 1/2, pp. 39-56.
5. Badurdeen, F., Thuramalla, S., (2006), 'Establishing Rules to Design a Minicell-based Manufacturing System for Mass Customization,' Submitted to *International Journal of Agile Systems and Management*, October 31, 2007
6. Barnett, L., Rahimifard, S., Newman, S., (2004), 'Distributed scheduling to support mass customization in the shoe industry,' *International Journal of Computer Integrated Manufacturing*, October-November 2004, Vol. 17, No. 7, pp. 623-632
7. Berman, B., (2002), 'Should your firm adopt a mass customization strategy?', *Business Horizons*, Jul/Aug 2002, Vol. 45, No. 4, pp. 52-60
8. Bicheno, J., (2000), 'The Lean Toolbox', second ed., England: PICSIE Books
9. Boynton, A.C., Victor, B., Pine, B.J. II, (1993), 'New competitive strategies: Challenges to organizations and information technology,' *IBM Systems Journal*, Vol. 32, No. 1, pp. 40-64
10. Brink, T., Ballard, G., (2005), 'Slam-A Case Study in Applying Lean to Job Shops,' *2005 ASCE Construction Research Congress, San Diego, CA, April 5-7, 2005*
11. Clarke, C., (2005), 'Do you want to be lean or agile?,' *Manufacturing Computer Solutions*, Vol. 11, No. 3, pp. 14-15

12. Co, H. C., Jacobson, S. H., (1994), 'Kanban assignment problem in serial just-in-time production systems,' *IIE Transactions (Institute of Industrial Engineers)*, Vol. 26, No. 2, pp. 76-85
13. Da Silveira, G., Borenstein, D., Fogliatto, F. S. (2001) 'Mass Customization: Literature review and research directions' *International Journal of Production Economics* Vol. 72, No. 1, pp. 1-13
14. Duray, R., Ward, P. T., Milligan, G. W., Berry, W. L., (2000), 'Approaches to mass customization: configurations and empirical validation,' *Journal of Operations Management*, Nov. 2000, Vol. 18, No. 6, pp. 605-625
15. Fernandes, N. O., Carmo-Silva, S., (2006), 'Generic POLCA-A production and materials flow control mechanism for quick response manufacturing,' *International Journal of Production Economics*, Vol. 62, No. 1-2, pp. 119-132.
16. Ford, H., (1988) 'Today and Tomorrow' Oregon: Productivity Press
17. Framinan, J.M, Gonzalez, P.L., Ruiz-Usano, R., (2006), 'Dynamic card controlling in a Conwip system,' *International Journal of Production Economics*, ' January/February 2006, Vol. 99, No. 1, pp. 102-116
18. Gilmore, J. H., Pine, J. B., (1997) 'The Four Faces of Customization', *Harvard Business Review*, January-February 1997, pp. 91-101)
19. Goldratt, E. M., (2004), 'The Goal: A Process of Ongoing Improvement,' Minnesota: Highbridge Company
20. Goldsby, T. J., Griffis, S. E., Roath, A. S., (2006), 'Modeling Lean, Agile, and Leagile Supply Chain Strategies,' *Journal of Business Logistics*, Vol. 27, No. 1, pp. 57-79
21. Hirano, H., (1995), '5 Pillars of the Visual Workplace', Oregon: Productivity Press
22. Huang, C., Tseng, T., Chang, H., (2005), 'A Novel Approach to Lean Control,' *IIE Annual Conference and Exposition 2005*
23. Huang, M., Wang, X., Wang, D., (2007), 'Simulation study using system dynamics for a CONWIP-controlled lamp supply chain,' *International Journal of Advanced Manufacturing Technology*, Vol. 32, No. 1-2, pp. 184-193
24. Johnson, D., Harrison, V., (2004), 'Enabling quick response manufacturing,' *Circuits Assembly*, Vol. 15, No. 12, pp. 36-38

25. Kadipasaoglu, S., Xiang, W., Hurley, S., Khumawala, B., 'A study on the effect of the extend and location of protective capacity in flow systems,' *International Journal of Production Economics*, 2000, Vol. 63, No. 3
26. Klusewitz, G., Rerick, R., (1996), 'Constraint Management Through the Drum-Buffer-Rope System,' *IEEE/SEMI Advance Semiconductor Manufacturing Conference and Workshop*, 1996, pp. 7-12
27. Koren, Y., Heisel, U., Jovane, F., Moriwaki, T., Pritschow, G., Ulsoy, G., Van Brussel, H., (1999), 'Reconfigurable Manufacturing Systems,' *Annals of the CIRP*, Vol. 48, No. 2, pp. 527-540
28. Krishnamurthy, R., Yauch, C. A., (2007), 'Leagile manufacturing: a proposed corporate infrastructure,' *International Journal of Operations & Production Management*, Vol. 27, No. 6, pp. 588-604
29. Kumar, S. C., Panneerselvam, R., (2007), 'Literature review of JIT-KANBAN system,' *International Journal of Advanced Manufacturing Technology*, Vol. 32, No. 3-4, pp. 393-408
30. Lampel, J., Mintzberg, H., (1996), 'Customizing Customization,' *Sloan Management Review*, Vol. 38, No. 1, pp. 21-30
31. Lee, H. L., Feitzinger, E., (1995), 'Product configuration and postponement for supply chain efficiency,' *Industrial Engineering Research Conference Proceedings*, May 24-25, 1995, Nashville, TN USA
32. Liker, J. K., (2003), 'The Toyota Way', Wisconsin: McGraw-Hill
33. Mabin, V., Balderstone, S., (2000), 'The World of Theory of Constraints: a Review of the International Literature', Florida: St. Lucie Press
34. Mason-Jones, R., Naylor, B., Towill, D. R., (2000), 'Lean, agile, or leagile? Matching your supply chain to the marketplace,' *International Journal of Production Research*, Vol. 38, No. 17, pp. 4061-4070
35. Mehrabi, M. G., Ulsoy, A. G., Koren, Y., (2000), 'Reconfigurable manufacturing systems: Key to future manufacturing,' *Journal of Intelligent Manufacturing*, Vol. 11, pp. 403-419
36. Meyer, M.H., Lehnerd, A.P., (1997), 'The Power of Product Platforms: Building Value and Cost Leadership,' New York: Free Press

37. Michel, R., (2002), 'Multiple paths to lean,' *MSI*, Vol. 20, No. 11, pp. 54-57
38. Monden, Y., (1998), 'Toyota Production System', Third Ed., Georgia: Engineering and Management Press
39. Moser, K., (2007), 'Mass Customization Strategies-Development of a competence-based framework for indentifying different mass customization strategies'
40. Naylor, J. B., Naim, M. M., Berry, D., (1999), 'Leagility: Integrating the lean and agile manufacturing paradigms in the total supply chain,' *International Journal of Production Economics*, Vol. 62, pp. 107-118
41. Ohno, T., (1988), 'Toyota Production System: Beyond Large-Scale Production', New York, Productivity Press
42. Pine, J. B., (1993), 'Mass Customization: The New Frontier in Business Competition'
43. Sanderson, S.W., Uzumeri, M., (1997), 'Managing Product Families', Chicago: Irwin
44. Selladurai, R.S. (2004), 'Mass customization in operations management: oxymoron or reality?' *Omega*, Aug. 2004, Vol. 32, No. 4, pp. 295-300
45. Shingo, S., (1988), *Non-Stock Production: The Shingo System for Continuous Improvement*, Oregon: Productivity Press
46. Shingo, S., (1986), 'Zero Quality Control: Source Inspection and the Poka-yoke System', Oregon: Productivity Press
47. Steele, D. C., Philipoom, P. R., Malhotra, M. K., Fry, T. D., (2005), 'Comparisons between drum-buffer-rope and material requirements planning: a case study', *International journal of Production Research*, Vol. 43, No. 15, pp. 3181-3208
48. Stratton, R., Warburton, R.D.H., (2003), 'The strategic integration of agile and lean supply,' *International Journal of Production Economics*, Vol. 85, pp. 183-198
49. Suri, R. (1994), 'Common misconceptions and blunders in implementing quick response manufacturing,' *Technical Paper – Society of Manufacturing Engineers.*, 1994, pp. 1-23
50. Suri, R., (1998), 'Quick Response manufacturing: A Company Wide Approach to Reducing Lead Times,' Oregon: Productivity Press

51. Swaminathan, J. M., (2001), 'Enabling Customization Using Standard Operations', *California Management Review*, Vol. 43, No. 3, pp. 125-135
52. Takahashi, K., Myreshka, H., Daisuke, (2005), 'Comparing CONWIP, synchronized CONWIP, and Kanban in complex supply chains,' *International Journal of Production Economics*, Vol. 93-94, Jan. 2005, pp. 25-40
53. Towill, D., Christopher, M., (2002), 'The Supply Chain Strategy Conundrum: To be Lean or Agile or To be Lean And Agile?,' *International Journal of Logistics: Research and Applications*, Vol. 5, No. 3, pp. 299-309
54. Tseng, M. M., Jiao, J., (1996), 'Design for Mass Customization,' *Annals of the CIRP*, Vol. 45, No. 1, pp. 153-156
55. Tsutsui, W. M., (1998), 'Manufacturing Ideology', New Jersey: Princeton University Press
56. Ulrich, K., Tung, K., (1991), 'Fundamentals of Product Modularity,' *Issues in Design Manufacture/Integration*, Vol. 39, pp. 73-79
57. Wantuck, K. A., (1989), 'Just In Time for America', Michigan: Edwards Brothers Inc
58. Womack, J. P., Jones, D. T., (1996), 'Lean Thinking', New York: Simon & Schuster
59. Womack, J. P., Jones, D. T., and Roos, Daniel (1991) 'The Machine That Changed the World' New York: HarperCollins Publishers
60. Yusuf, Y.Y., Adeleye, E.O., (2002), 'A comparative study of lean and agile manufacturing with a related survey of current practices in the UK,' *Modeling, Planning and Scheduling of Manufacturing Systems*, Vol. 40, No. 17, pp. 4545-4562
61. Zipkin, P., (2001), 'The limits of Mass Customization,' *Sloan Management Review*, Vol. 42, No. 3, pp.

## Vita

Gregory Brandon Stump was born on January 6<sup>th</sup>, 1985 in Louisville, Kentucky. He completed secondary school at Spencer County High School in Taylorsville, Kentucky. He received his bachelor's degree in mechanical engineering from the University of Kentucky in December, 2008, and entered the graduate program in mechanical engineering in January 2007 via the University Scholars Program to pursue a master's degree in mechanical engineering. During the course of the Master's Degree he served as a teaching assistant and research assistant.

### Scholastic and Professional Honors

GAAN Fellowship, January 2007 – August 2007  
University of Kentucky, Lexington, Kentucky

### Publications and Conferences

1. H. Metta, A. Goyal, B. Stump, Kundana Inala, Smitha Thuramalla, Fazleena Badurdeen, "A Simple Simulation Model to Demonstrate Mass Customization Strategies," 2007, Third World Conference on Mass Customization & Personalization, October 07-11, 2007, Boston, MA
2. F. Badurdeen, H. Metta, B. Stump, (2007), "Simulation Models to Demonstrate Mass Customization Strategies," Advances in Mass Customization and Personalization, Vol. 3, World Scientific Publishing, in press (W\*)
3. F Badurdeen, B. Stump, (2008), "Integrating Lean and Other Strategies for Mass Customization: A Case Study," *Journal of Intelligent Manufacturing*, submitted (W)