Evaluating Lean Manufacturing Proposals through Discrete Event Simulation – A Case Study at Alfa Laval

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ABSTRACT

In their strive for success in competitive markets companies often turn to Lean philosophy. However, for many companies Lean benefits are hard to substantialize especially when their ventures have met success through traditional manufacturing approaches. Traditional Lean tools analyze current situations or help Lean implementation. Therefore productions facilities require tools that enhance the evaluation of Lean proposals in such a way that decisions are supported by quantitative data and not only on a gut feeling.

This thesis proposes how Discrete Event Simulation may be used as an evaluation tool in production process improvement to decide which proposal best suits Lean requirements. Theoretical and empirical studies were carried out. Literature review helped define the problem. A case study was performed at Alfa Laval to investigate through a holistic approach how and why did this tool provide a solution to the research questions. Case study analysis was substantiated with Discrete Event Simulation models for the evaluation of current and future state Lean proposals.

Results of this study show that Discrete Event Simulation was not designed and does not function as a Lean specific tool. The use of Discrete Event Simulation in Lean assessment applications requires the organization to understand the principles of Lean and its desired effects. However, the use of traditional static Lean tools such as Value Stream Mapping and dynamic Discrete Event Simulation complement each other in a variety of ways. Discrete Event Simulation provides a unique condition to account for process variability and randomness. Both measurement of and reduction in variability through simulation provide insight to Lean implementation strategies.

(Keywords: Lean, Manufacturing, Lean Tools, Discrete Event Simulation, Value Stream Mapping)
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<td>Alfa Laval’s Production System</td>
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<td>CU</td>
<td>Component Units</td>
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<tr>
<td>DES</td>
<td>Discrete Event Simulation</td>
</tr>
<tr>
<td>DMAIC</td>
<td>Define Measure Analyze Improve and Control</td>
</tr>
<tr>
<td>DPMO</td>
<td>Defects Per Million Opportunities</td>
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<tr>
<td>ERP</td>
<td>Enterprise Resource Planning</td>
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1. INTRODUCTION

Production sites and manufacturing facilities around the world have implemented principles of Lean manufacturing to reach levels of efficiency and effectiveness satisfactory for their type of industry. The question many a company faces is not whether Lean manufacturing is a path to travel, but how to evaluate whether Lean proposals of improvement will comply with Lean manufacturing principles while at the same time achieve a company’s desired goals.

This thesis proposes Discrete Event Simulation as an answer to the abovementioned problem. A case study approach is undertaken, and the reasons that led the company to its deciding over Discrete Event Simulation are listed. The problem situation at large is narrowed to a group of research questions that bear direct relation to Lean manufacturing and Discrete Event Simulation. Finally, the chapter defines the scope and limitations of the case study.

1.1 Background

Globalization has come to be one of the prominent features of the current trend of evolution of national economies (Requier-Desjardins, Boucher, & Cerdan, 2003). It links companies and customers all over the world and affects industrial activities including final products and inputs such as raw material, intermediate goods, machinery, finance, technology, as well as human resources (Grossman & Helpmann, 1991). The resulting industrial competitiveness forces companies to value production flexibility more than ever as time-to-market has become critical due to shortened product life cycles and variation in customer demand (Zhang, 2010). To benchmark how to manufacture in a more productive and efficient way under Lean Principles, companies have followed the Toyota Way. (Liker, 2004).

The principles of Lean and its documented benefits are enticing. Yet the decision to implement Lean manufacturing is a difficult one because of the substantial differences between traditional production and Lean manufacturing systems in employee management, plant layout, material and information flow systems, and production scheduling/control methods (Detty & Yingling, 2000). There exists a natural resistance to adopt principles that seem to contradict the status quo. Understandably management teams require tools that may provide information regarding the benefits, or lack thereof, of Lean initiatives when compared to traditional methods of production.

If implemented, traditionally Lean initiatives have focused on identifying value adding operations, and waste reduction through the use of tools such as Value Stream Mapping (VSM) that may support the analysis of information and decision making process. VSM is a very effective tool in mapping the current and future state of an organization’s Lean activities. Despite its many benefits VSM may only go so far, and its powers are bounded to technical restrictions such as being time-consuming, its inability to detail dynamic behavior of production processes and to encompass their complexity, have spurred us to turn to simulation (Lian, 2007), or its limitations in calculating variability information that describe system
variations and uncertainty means that more powerful analytical tools are needed (Mahfouz, 2011). Not only is it time consuming to generate a VSM analysis but its outcome might need at least a few months of a continued monitoring to observe the effects of changes and improvements (Hines P. R., 1998).

Tools such as simulation may fill up the void that exists from non-dynamic analysis methods such as VSM. In addition to these benefits, simulation may provide insight into possible outcomes given certain inputs before decisions are made and investments committed. Simulation makes it possible to optimize operations and visualize processes logically or in a virtual environment, outcomes are saved in terms of costs, time, and resources (Heilala, 1999). Thus simulation not only complements Lean concepts but highlights feasible and reasonable initiatives Lean practices.

Early technology adopters viewed simulation as a method of last resort to be employed when everything else had failed (Singh, 2009). The advancement of computer sciences, software access and proficiency in the use of simulation tools by end users has propelled the development of this field. Simulation has witnessed a change of perception in its applicability to the industry, and a refinement is many fields as is the case of Discrete Event Simulation.

Discrete Event Simulation (DES) is used to model systems that are composed of real-world elements and resources that interact when specific events occur. Modeling includes a combination of elements, and a series of logically related activities. All this is organized around events to achieve a specified outcome. Practitioners who engage in DES build comprehensive models of industrial and commercial systems to analyze, design, and document manufacturing, service, and other discrete processes. Whether current operations are modeled or proposed changes are tested, the resulting models make it easy to find operational bottlenecks, estimate throughput, and predict utilization (Imagine That Inc., 2010)

1.2 Company Introduction

Alfa Laval is a leading global supplier of products and solutions for heat transfer, separation and fluid handling though their key products – heat exchangers, separators, pumps and valves. Alfa Laval’s products are used in the manufacturing of food, chemicals, pharmaceuticals, starch, sugar and ethanol, and service the engineering sector, mining industry and water treatment operations. The company is organized into Component Units (CU) and Supply Units (SU) that employ 11,400 people the majority of whom are located in Sweden, Denmark, India, China, the US and France. Alfa Laval is represented in 100 different countries, has over 300 patents, and launches nearly 35 to 40 new products every year.

One of Alfa Laval’s most important sites is its Eskilstuna factory, a Global CU and SU. At its Eskilstuna facility liquid separators are designed, manufactured, assembled, tested and shipped to customers the world over. High quality standards are a rule of law for all the components that make up a separator as the product is custom built for each application.
Amongst a separator’s most critical components are bowl discs, cone shaped metallic artifacts that permit two liquids to be separated from each other through centrifugal forces. The manufacturing of a bowl disc is closer to mass production than any other component in a separator. Bowl discs are produced in cell C6, a small factory in its own right, and encompass the highest volume item in the factory with 75,000 units per year.

Alfa Laval in its acknowledging the importance that quality bestows upon its products has worked with Lean Six Sigma since 2007. In that year the company introduced ALPS (Alfa Laval’s Production System), a production system built upon the philosophies of Lean and Six Sigma. ALPS has been implemented in all factories and distribution centers and is considered the framework for Alfa Laval’s development as a company anywhere from employees’ workplace to global projects.

Based on ALPS, several improvements have been implemented at the Eskilstuna factory such as: new machine investments, introduction of new material flows, SMED (set up time reductions), 5S and visual factory. When new volume forecasts required a production output that exceeded the current capacity of bowl disc production, ALPS was used to provide a solution. The situation of cell C6 was critical; with an increase in demand C6 would become the factory’s production bottleneck. Therefore, management decided to start up a project that would increase capacity and improve quality of cell C6 based on Lean principles.

1.3 Problem Formulation

The concept of Lean production and the principles that encompass its practice are a topic of immediate interest in a growing sector of industrial practices, as well as in a number of service related sectors. One may wonder as to why this concept has expanded from a very punctual agenda in the automotive industry to an expansive system of practices that have an impact anywhere from food industry to health care to product development.

Clearly Lean concepts and principles touch upon critical aspects of any production process and shed light into universal problems. The Lean operations management design approach focused on the elimination of waste and excess from the tactical product flows at Toyota (the Toyota “seven wastes”) and represented an alternative model to that of capital-intense mass production (Hines P. H., 2004), aspects important to any company whatever its end product or activity may relate to. Companies in search for a competent performance have realized the importance of both principles above.

In today’s global market competitiveness is constantly in management’s list of priorities. Literature is indicative of a correlation between the practice of Lean and competitiveness as suggested by Bhasin (2006). Yet despite its storied past and the track record of success in the Japanese automotive industry Lean has been hard to digest for many a western based company.
It is only understandable that change will draw aversion to a new untried method. For companies that have long relied on traditional approaches to their manufacturing systems, it is often difficult to gain from management the commitment required to implement Lean manufacturing (Abdulmalek, 2007). One reason for this is the difficulty in accurately determining the impact of ‘Lean’ transformations, especially when this requires changes in assets (Lian, 2007). When investment is anticipated and clear-cut results are expected the above practices are no longer sufficient for many management teams.

Therefore productions facilities require tools that enhance the evaluation of Lean proposals in such a way that decisions are supported by quantitative data and not only on a gut feeling. Proposal assessment and evaluation are broad enough areas. This thesis report focuses on the evaluation of Lean proposal in a production context.

1.4 Aim and Research Questions

This thesis proposes DES as a tool to evaluate Lean manufacturing proposals through a production perspective. DES complies with a number of parameters upon which to compare a future production state to the current situation. Although many other methods of simulation exist DES is forwarded a solution as it conforms to many of the characteristics that researchers support are necessary to perform a dynamic evaluation of production processes. The aim of this thesis is to analyze how DES may be used as an evaluation tool in production process improvement to decide which proposal best suits Lean requirements.

This thesis will answer the following questions in support of its research aim:

1. What elements are required for DES to work as a tool to analyze different Lean proposals?
2. How do a dynamic tool such as DES and a static tool such as VSM complement each other?
3. What sort of information can DES provide to the analysis of different Lean proposals?

1.5 Project Limitations

Lean thinking and its principles are at the core of this thesis. A succinct overview of its practice and development is presented. This thesis does not explore the methodology, principles, or philosophy of Lean thinking. This thesis elaborates on the idea that current tools for Lean evaluation such as VSM, Load Balance Charts, and production runs may not suffice when a future Lean state is to be implemented. This report describes the benefits and limitations of such tools in the production decision making process.
This research takes upon Lean as one possible solution to reach competitiveness. However, the question at hand is not whether a company should or should not become Lean. The question proposed by this research is how may companies undergoing a Lean transformation evaluate whether any given Lean proposal will be beneficial or not to its production process? This thesis seeks to clarify which tools may be of help for companies to decide which Lean option best suits a given set of requirements.

The literature study presented in this report describes simulation as a tool of Lean Production. A number of simulation methodologies are reviewed to elaborate on the span of simulation as a field of study. DES is defined at large and its relation to Lean Production Systems is explained. A relationship between DES and decision making in production systems is drawn. The principles, cycle, characteristics, benefits, and shortcomings of DES are described.

A case study is presented to support the literature review. The case study was limited to a production improvement simulation of two different Lean scenarios when compared to a current regular production state. The total duration of the simulation project was 20 weeks. The simulation results are restricted by data acquisition, study proposals, time, and the project’s scope.

Data acquisition was supported by the use of Alfa Laval’s Enterprise Resource Planning (ERP) system and validated by Planning, Production, and Lean departments. Simulated data was not supported by on site measurements, but all information was validated by process owners. Simulated data was substantiated with information acquired through process owner interviews.

All future state proposals were generated and submitted by the Alfa Laval Lean Six Sigma project group. Ideation, modification, and changes in the simulation of future alternatives were responsibility of Alfa Laval. The simulation’s scope was defined as that of providing a forecasting tool to compare alternative solutions to a current problem. None of the simulated scenarios, or their results, was meant to follow the principles of optimization. All simulated scenarios, outputted data, and analysis were developed through ExtendSim V8.0 Software.

This project makes extensive use of information collected from organizational records. Simulated scenarios, especially those dealing with current states, were built based on data from VSM analyses. VSMs and their data are taken as pieces of information to support the simulated scenarios. An extensive explanation of how to perform a VSM analysis, its elements, and interrelation is beyond the scope of this thesis.
2. RESEARCH METHODOLOGY

This thesis based its research method on both theoretical and empirical studies. A literature review helped define the problem. Tools for problem solving were described through published research and one in particular was chosen as a solution. The reasons as to why this particular tool was selected were substantiated. A case study was carried out to investigate through a holistic approach how and why did this tool provide a solution to the research questions. Finally an evaluation of the solution was made and results were presented.

2.1 Research Approach

A deductive approach was selected to answer the question of whether DES provides a tool for Lean proposal analysis. This thesis considered necessary the reduction of a larger problem to specific areas of analysis. A group of elements were identified in the evaluation of future state Lean proposal implementation when using DES (research question 1). In addition to this a qualitative comparison between Value Stream Mapping, a traditional tool for Lean production assessment, and DES was made (research question 2). Finally a qualitative analysis was performed in regards to how DES can assist in analyzing different Lean proposals (research question 3).

2.2 Research Method

Because an intensive study of a single unit of analysis was pursued with the purpose of understanding a larger concept, the evaluation of Lean manufacturing proposals through DES, a case study method was selected (Gerring, 2004). In addition to this the authors of the study desired a holistic, in-depth investigation (Feagin, Orum, & Sjoberg, 1991). A small degree of control over the elements that Alfa Laval desired to control was prevalent in the study; thereby, a survey or an experimental approach were discarded as research methods. Furthermore, the method required that the research focus on the contemporary phenomena of Lean production principles established by Alfa Laval in relation to the company’s future production context within the realm of their current real-life shortcomings and needs. Finally the case study was preferred as it is closely linked to its answering the questions of “how” and “why” phenomena occur (Yin, 1993).

The type of case study selected closely followed the design suggested by Yin (Yin, 1993). A single case study variety was selected to narrate and analyze the case. Information provided by the study is augmented by graphic information (VSM, Balance Load Charts, and simulation analysis). A linear analytical structure was established: relevant literature was reviewed, a DES method was used, simulated data was collected and analyzed, and the conclusions and implications of the findings were established. An explanatory case study strategy was selected as the purpose of the case study was not meant to explore a new field of research. The study focused on how could DES be used to evaluate Lean
manufacturing proposals and the manner in which the research questions interrelate to the study’s aim.

2.3 Literature Review

The literature study shortly introduces the concept of Lean Production and gives a brief background on the subject. Tools used in the evaluation and implementation of Lean proposals were reviewed at length. Characteristics of traditional tools in relation to Lean proposal evaluation were described. The blind spots of such tools were defined, and a need for other tools was established.

Simulation was introduced and an explanation of its application and outputs follows. The literature review then built upon this concepts and narrows the subject of simulation into one of its branches that of DES. DES was scrutinized and a section is devoted to researchers´ proposed steps of the model building process. Finally the elements that make DES a useful tool for Lean implementation were clarified.

Literature review was performed through the use of the Internet databases Google Scholar, Discovery, and DiVA. Searched documents cover a span of time between the years 1989 and 2013 and the most recent publications were emphasized. Concepts used to search for articles included: Principles of Lean Manufacturing, Tools of Lean Implementation, Tools of Lean Evaluation, Simulation, and DES.

2.4 Data Collection

Data was collected from week 4 to week 8 of 2013 at Alfa Laval´s Eskilstuna factory on a daily basis from Monday through Friday between 9.00 am and 5.00 pm. Outputted data from two large groups of tools for Lean implementation were categorized: on the one hand, traditional Lean evaluation tools such as VSM, Balance Load Charts, and production runs; on the other hand, DES. Collected data was qualitative in that the type of information gathered from the two groups of tools was described and compared. Data gathered from simulated scenarios was quantitative in as much as forecasts, averaged production volumes, lead times, and batch sizes were measured and analyzed.

Organizational records were used extensively at the start of the project. Value Stream Map results from previous Alfa Laval studies were used and served two purposes. Firstly, VSM output data provided a general idea of the shortcomings of this tool when faced with evaluating a future Lean manufacturing proposal. Secondly, VSM data was used to build a current state simulation model. Although a current simulation model was not required to meet Alfa Laval´s end goal, it was necessary in term of the authors’ comparing future Lean manufacturing proposals to the current production situation.

Data collection required the authors’ corroborating VSM records with Alfa Laval’s Lean and Six Sigma Manager, Production Manager, and machine operators. Machine cycle, change over, planned maintenance, unplanned
maintenance, machine failure, shift scheduling, stock sizes, and queue lengths were accounted for. VSM data was compared to past production records as well as ERP production parameters. The production process was followed and detailed through a month of onsite observation in which the authors got to know the production process, machine sequence of operations, and most common production deficiencies. Discrepancies between VSM data and ERP parameters were subjected to the authors’ questioning of the Lean, Production, Planning, and Maintenance departments through a series of meetings along the duration of the project.

A key element to the models’ providing reliable output data was the simulation’s accounting for a production schedule. Two production schedules were constructed. A current production schedule fed the current state simulation. A future state production schedule was constructed to comply with Alfa Laval’s volume forecast. In addition to this, future state production schedule met product mix, volume, orders, and machine sequence of operations. These two sets of schedules were divided into two separate groups: VSM production schedule, and real life production schedule. Current and future simulated production schedule through VSM was taken from organizational records. Real life production schedule information was taken from historical production logs. In total 5 weeks of production from a year to date were used. Alfa Laval’s Planning department, through its ERP system, provided information of past production. The relevance of the 5 sampled weeks was verified and validated by the Production Manager and Lean Six Sigma Manager.

Planned and unplanned maintenance was accounted for in all simulated scenarios. Data acquired to feed the model was gathered from two sources: Alfa Laval’s maintenance log, and onsite observation. A thorough examination of the maintenance log was performed. The examination encompassed a year’s time of maintenance events. Irrelevant events were discriminated from the list based on inquiries to maintenance personnel and the Production Manager. Once the maintenance log was narrowed down a distribution was made to account for machine failure’s duration and frequency for all machines involved in the process. On site observation was necessary to measure and confirm the existence of micro disruptions in the process that were not entered into the maintenance log. Micro failures were discussed with and validated by operators, maintenance personnel, Production Management, and Lean Six Sigma Manager. Micro failures were accounted for in all simulated scenarios.

All simulated scenarios were built based on proposals generated by Alfa Laval. Alternative proposals were based on a combination of initiatives that tackled different problem areas within cell C6. Process owners realized the need of their modifying, and in some cases discard, the welding, cleaning, and pressing operations. In the brink of a major investment, management deemed necessary to apply a Lean approach.

A Project Group for cell C6 was deployed to include operators, production technicians, maintenance personnel, project owners, and team managers. The Project Group analyzed the production process for bowl discs separators to meet future volume through Lean principles. In addition to this technical capacities of
new equipment were revised by Production Development Steering Committee (SKPU). The result of a 2012 study yielded alternative processes with a Lean perspective.

Two different future state alternatives for Lean manufacturing were evaluated. Through a series of meetings with the Operations Development and Lean Six Sigma managers a number of parameters were established upon which to measure and analyze modeled data. In these meetings variables relevant to production improvement were set, and the criteria for selecting the best possible scenario were established. A current production state was modeled and its results recorded. A total of 64 different simulated scenarios were generated based on the combination of variables established by Alfa Laval. A winning scenario was selected for each Lean manufacturing alternative and tested with real life production demand. All relevant parameters were recorded and analyzed.

2.5 Data Analysis

Simulation ideation, development, and analysis took place onsite for a period of three months. Alfa Laval’s Lean Six Sigma Manager monitored simulation progress on a weekly basis. Different seniority levels within Alfa Laval validated the results of simulation runs. Simulated results were first discussed and presented to the Operations Development, Production, and Lean Six Sigma managers. These presentations served to validate and demonstrate the reliability of the results of the simulated scenarios when different parameters were modified.

Updates on simulation progress and results were presented on a monthly basis to Alfa Laval’s steering committee. The steering committee consisted of project owners, factory management, union representatives and stake holders. During the course of steering committee presentations the authors were asked to answer questions regarding how Lean proposals affected the production process, and what sort of production problems were to be faced according to the simulation of the Lean manufacturing proposals if such proposals were to be implemented.

Final results were presented to Alfa Laval’s steering committee after a period of three months. All modeled scenarios underwent a thorough testing and validating process described in the Empirics chapter of this thesis. Simulated results were limited to a simulation run of 5 production weeks. This shortcoming of the simulation process was discussed with and approved by the Operations Development and Lean Six Sigma managers, and endorsed by Alfa Laval’s steering committee. Validity and credibility of research for the case study was discussed in the Empirics chapter of this report both of which were time and resource consuming processes.
3. THEORETIC FRAMEWORK

This chapter introduces the Lean philosophy and its tools, the basic principles of DES, and ends with a quick look on how these two can come together.

3.1 Lean and Its Tools

Lean encompasses a large body of literature paired with an equally large number of tools to help in its implementation. There are numerous literature reviews that chronicle Lean and its development through the past 70 years. Such a review is beyond the reach of this project. Nonetheless the authors consider Lean’s background an important area of discussion as it is closely linked to competitiveness. Furthermore, Lean directly affects the tools used to implement the Lean philosophy in the context of production processes. Finally the authors consider of great importance the discussion of the available Lean tools, doing so gives insight into the capabilities and shortcomings of these devices when evaluation of Lean proposals is necessary.

3.1.1 Lean Development

Lean has undergone an extensive journey chronicled by numerous researchers. The term “Lean production” was defined in 1990 to describe manufacturing techniques developed over the past 100 years by Toyota Motor Company (Baines, Lightfoot, Williams, & Greenough, 2006). Although the concept of Lean is a recent one, the idea behind its operational and cultural framework is not.

A discussion of Lean production must, at some point, reference the development of Toyota. The two are so closely knit that for many practitioners, Lean production and the Toyota Production System (TPS) are synonymous (Womack & Jones, 1996). TPS was born as a response to the trying needs of an ailing Japanese automaker at the peak of mass production. Faced with a war-torn Japanese economy starved for capital and a meager budget, TPS provided innovative solutions and where each step forward depended on the skill and creativity of shop floor team members (Dennis, 2007).

Initial concept of Lean was more extensively defined and described by five key principles (Womack & Jones, 1996):

1. Specify value – Define value precisely from the perspective of the end customer in terms of the specific product with specific capabilities offered at a specific time.
2. Identify value streams – Identify the entire value stream for each product or product family and eliminate waste.
3. Make value flow – Make the remaining value creating steps flow.
4. Let the customer pull value – Design and provide what the customer wants only when the customer wants it.
5. Pursue perfection
In an over simplified way the Lean thinking paradigm differentiates between waste and value within an organization. Womack and Jones (1996) defined waste as any human activity which absorbs resources but creates no value. Value defined as a capability provided to a customer at the right time at an appropriate price, as defined in each case by the customer. Lean thinking in action is the continuous identification and elimination of waste from an organization’s processes, leaving only value added activities (Rother and Shook, 1999).

The focus of Lean is on reducing the wasteful use of resources and applying a holistic approach when dealing with employees, suppliers, and customers (Maleyeff, Arnheiter, & Venkateswaran, 2008). Liker (2004) describes waste (Muda) at length in his book the Toyota Way. The concept of Muda became one of the most important concepts in quality improvement activities primarily originated by Taiichi Ohno’s famous production philosophy from Toyota in the early 1950s (Dahlgaard & Dahlgaard-Park, 2006). Muda is grouped into 8 different forms: overproduction, waiting, unnecessary transport, over processing, excess inventory, unnecessary movement, defects, and unused employee creativity. Close to the concept of Muda is that of Muri – overburdening people or equipment, and Mura – unevenness that results from an irregular production. Together the three M’s (Muda, Mura, and Muri) are necessary for leveling out the work schedule (Liker, 2004). The concept of waste and its effects on the other three M’s has been the subject of numerous research studies.

Waste reduction and value adding have been closely associated. In the view of Dahlgaard (2006) waste is everything that increases cost without adding value for the customer. Waste removal has been viewed as an occurrence that need be eradicated in the value stream for companies to complete value-adding (and non-value adding) processes (Hines & Rich, 1997). Despite its welcomed addition to a process value is not easily defined when taken within a broad perspective. Defining value in the context of a global enterprise whose goal is long-term sustainability offers a challenge. Although these enterprises pay close attention to short-term financial performance, they act in ways that enhance long-term viability (Maleyeff, Arnheiter, & Venkateswaran, 2008).

From the early mention of “Japanese management” practices to the discovery and dissemination of the TPS into the Lean paradigm it became clear the mass production methods proven successful since the early 1900s were being outperformed by the more modern and flexible aspects of Lean production. While Lean is not void of issues and controversy, the benefits appear to outweigh the investment required to transform from traditional mass production operational methods to a Lean thinking paradigm (Stone, 2010).

3.1.2 Lean Implementation

The importance of Lean implementation is supported by both economic and operational factors. Most companies fear that implementing Lean manufacturing is not only costly and time consuming, but also that the implementation of Lean manufacturing is a strategic activity requiring the support of a firm’s infrastructure, human resources management and technology development departments (Achanga, Shehab, Roy, & Nelder, 2006). One might assume that
Lean implementation will not only tie up a company’s capital but also its resources.

Therefore a company that approaches Lean implementation must be aware of the delicate nature of the decisions and actions that take place. Situation that is supported by the research performed by Karim and Arif-Uz-Zaman (2013), the implementation of inappropriate Lean strategy for a given situation can sometimes lead to an increase in waste, cost and production time of a manufacturer. Because of inappropriate selection of Lean strategies, changes may cause disruptions in the very process it meant to improve. Applying Lean strategies incorrectly increases inefficiencies of an organization’s resources and reduced employee confidence in Lean strategies (Marvel & Standridge, 2009). Furthermore, it is not always easy to justify the implementation of a Lean production program due to productivity decreases in the early implementation stages which are strongly discouraged under the traditional management accounting systems (Karlsson & Åhlström, 1996).

Because of the critical nature of Lean implementation, Lean itself is viewed as a top-down strategy in which company strategy often precludes any operational analysis. Instilling proper organizational values, organization learning and employee empowerment systems, continuous improvement programs, and setting up a consistent organization structure as well as management information systems, are essential, mandatory elements of Lean systems (Detty & Yingling, 2000). Anvari et al. (2010) proposed 11 critical success factors (management and leadership, organizational cultures, goals and objectives, problem solving, skills, continuous improvement, financial capabilities, performance measure, change, education and plan) for effective implementation of Lean strategies. An idea further supported by Roos (1990) is that it is first necessary to change employees’ attitudes to quality, in order to attain a material flow containing only value adding operations. Shah and Ward (2003) are in support of the above as they state that Lean concepts require internalization and adaptation to the circumstances of each company.

In assessing changes towards Lean production it is important to make a distinction between the determinants and the performance of a Lean production system. The ultimate goal of implementing Lean production in an operation is to increase productivity, enhance quality, shorten lead times, reduce cost etc. These are factors indicating the performance of a Lean production system. The determinants of a Lean production system are the actions taken, the principles implemented, and the changes made to the organization to achieve the desired performance (Karlsson & Åhlström, 1996).

Literature is diverse in regard to Lean implementation and no one single structured path exists. The success and implementation of any particular management strategy normally depends upon organizational characteristics, which means that all organizations should not or cannot implement a similar set of strategies in their particular case (Shah & Ward, 2003). The diversity in methods is supported by the many approaches found in literature.
Some authors approach the subject of Lean implementation as a linear process in which a first step is perhaps the most important. Roos (1990) considers that quality and the manner in which employees understand this concept is a necessary first step. Material flow and value added operations are a consequence of quality. Storhagen (1993) declares that continuous improvement is the cornerstone of implementation, and that process factors that support it such as job rotation and team work are critical. Filippini (1998) on the other hand finds a correlation between product variety and implementation: in high variety implementation is secured through technological initiatives, and in low variety should focus on manufacturing organization.

Within this many tier approach Karim (2013) takes upon Lean implementation as a set of areas of opportunity:

1. Production and Process Details - At the beginning, firms need to define their own systems considering production type, order volume and demand quantity since these indicators are highly related to Lean implementation.
2. Lean Team - Based on company policy, management commitment and future plan, Lean culture can be initiated by forming a Lean team in the next phase.
3. Performance Variables - A major part of the proposed methodology is to continuously assess performance before and after Lean implementation. In this process, the first step is to measure the current state of the process in terms of productivity, efficiency, effectiveness, VA time ratio and defect rate using different Lean assessment metrics.

Other authors have chosen to describe Lean implementation as a mesh of activities or a cycle. A good start of point to this approach is Liker’s description of how Toyota, the company who first introduced the concept, deals with Lean implementation. No particular principle is described as a central element of implementation; instead, all principles are necessary for Lean manufacturing to exist.

Toyota’s continued success at implementing Lean stems from a deeper business philosophy based on its understanding of people and human motivation (Liker, 2004). Liker offers a four phase model upon which Lean transformation must be referenced called the Four P’s. The 4P model is, to some degree, hierarchical; the higher levels build on the lower levels. Without a long-term philosophy, a company cannot implement all the actions necessary for the other three dimensions. Furthermore, the processes provide the setting for challenging and developing the employees. This step, in turn, is necessary to create a learning organization (Deflorin & Scherrer-Rathje, 2011).

<table>
<thead>
<tr>
<th>P</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Philosophy</td>
<td>Long term thinking</td>
</tr>
<tr>
<td>Process</td>
<td>Eliminate waste and create flow</td>
</tr>
<tr>
<td>People and partners</td>
<td>Respect, challenge, and grow with those involved</td>
</tr>
<tr>
<td>Problem-solving</td>
<td>Continuous improvement and learning</td>
</tr>
</tbody>
</table>
The question arises as to how the four tenets should be implemented. Åhlström (1998) performed a thorough study of the steps from traditional manufacturing to Lean. In it, he acknowledges the importance of a parallel and sequential implementation, but makes a clear distinction of which steps are to be emphasized: elimination of waste, multifunctional teams, and pull systems. Waste elimination is related to the concept of zero defects, and is viewed as a necessary first step. The importance of achieving zero defects early in the implementation is supported by the idea that to develop lasting improvements in manufacturing capabilities, managers need to devote effort and resources to quality first (Ferdows & De Meyer, 1990). Zero defect, or waste reduction, is also viewed as the first iteration of a future-state map were product designs, process, technologies, and plant locations are given and all sources of waste not caused by these features are to be removed as quickly as possible (Rother & Shook, 2009). Figure 2 illustrates the relationship between the implementation initiatives in respect to time.

Hobbs (2003) offers an alternative first step towards Lean implementation prior to any Lean principles. Fundamentals such as understanding your products and manufacturing processes, their demand, and the real goals of response time, and quality are not to be underestimated. Lean implementation should be methodical and disciplined and to that effect a cyclical procedure, in accordance to the idea of Lean´s continuous improvement, is offered.
Figure 3 illustrates the transformation process from traditional manufacturing to Lean production. While the transformation process should proceed quickly, the pace of implementation must allow the organization and culture time to adapt to the changes being made (Hobbs, 2003). Lean is not about imitating tools in a particular manufacturing process. Lean is about developing principles that are right for an organization and diligently practicing them to achieve high performance that continues to add value to customer and society (Liker, 2004). All process steps are of value when Lean implementation is to follow a continuous improvement cycle, yet factory modeling is closest to evaluating Lean manufacturing proposals and may be traced according to the following steps:

**Choosing the products for Lean**
Determining the products to be manufactured is critical as this decision will impact the processes and material required to produce those products and scope of Lean implementation.

**Establishing capacity to meet demand**
Quantity of demand is important, because it determines both the capacity of the Lean line and the amount of resources required to produce that demand.

**Process flow**
A process in manufacturing can be a combination of resources (people and machines) that perform work to change the form, fit, or function of materials as they are converted toward the completion of the product. Process flow should consider volume variation, rework, and scrap.

**Demand Levels and Takt Time**
When the Lean line operates, all processes complete work at the same rate based on Takt time. Balance is at the heart of every Lean manufacturing line. Processes should be timed to produce at the takt rates (George, Rowlands, Price, & Maxey, 2005).
Calculating Resource Requirements

Because work in every process is balanced using a Takt time derived from required throughput volume, the varying standard times of different processes are of little consequence. The number of resources required to meet the Takt time target goal is the important factor. Lean methodologies seek to achieve Takt at each process. The resource calculation identifies the amount of resources needed to achieve that Takt time goal.

3.1.3 Tools for Lean Implementation

There exists a plethora of different tools and techniques developed for different purposes and waste elimination or reduction (Green and Dick 2001). Tools exist with multiple names, some of them overlap with other tools, and a particular tool might even have a different method of implementation proposed by different researchers. The misapplication of a Lean manufacturing tool may result in the additional wastage of resources such as time and money. It may also result in reduced employee confidence in the Lean philosophy (Pavnaskar, Gershenson, & Jambekar, 2003).

Taylor and Brunt (2001) developed a simple correlation matrix that relates seven different Value Stream Mapping tools to the seven basic types of wastes identified by Ohno and Shingo. Further classifications have been developed to enable matching Lean manufacturing tools to the wastes they eliminate and to the manufacturing problems they solve (Pavnaskar, Gershenson, & Jambekar, 2003). There are an abundant number of tools to identify waste, but these may not apply to the implementation of Lean when a completely new process is developed. Creating the Future State from the current state maps is a considerable challenge. It is relatively easy to take waste out of current systems whilst retaining their essential characteristics, but it is another issue to completely envision a full Lean system (Bicheno, 2004).

Rother and Shook (2009) suggest a list of questions that need be answered before Lean implementation. The information gathered by these questions will provide critical information for the future state.

1. What is the takt time?
2. Will you build a finished-goods supermarket from which the customer pulls, or directly to shipping?
3. Where can you use continuous flow processing?
4. Where will you need to use supermarket pull systems to control production of upstream processes?
5. At what single point in the production chain will you schedule production?
6. How will you level the production mix?
7. What increment of work will you consistently release and take away?
8. What process improvements will be necessary for the value stream to flow as your future-state design specifies?

Bicheno (2004) identifies a group of 6 tools useful in Lean implementation:
Product / Service Family Grid

Helps determine where to focus limited resources on data collection and observation so you can create a complete complexity Value Stream Map with the least time and effort. It is used prior to creating a complexity Value Stream Map to identify representative products or services to include in the map (George, Rowlands, Price, & Maxey, 2005).

<table>
<thead>
<tr>
<th>Collected Volume (Thousands)</th>
<th>Process Flow</th>
<th>Inspection</th>
<th>Credit Check</th>
<th>Appraisal</th>
<th>Service Application</th>
<th>Processing</th>
<th>Raw Material</th>
<th>Waste</th>
<th>Abuse</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,340</td>
<td>Raw Material</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4,210</td>
<td>Waste</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1,150</td>
<td>Raw Material</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4,450</td>
<td>Waste</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>520</td>
<td>Waste</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1960</td>
<td>Waste</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 4 Product / Service family grids

Value Stream Mapping

VSM is a visual representation of every process in the material and information flow. It identifies all actions required to bring a product through the main flow from raw material into the arms of the customer (Rother & Shook, 2009). VSM creates a common language about a production process, enabling more purposeful decisions to improve the value stream (McDonald, Van Aken, & Rentes, 2002).

VSMs are similar to process maps, though a subtle difference is found in their focus. Whereas a process map focuses on a process that can apply across products and items, VSM is product centric and, therefore, likely to span across multiple processes. The specific purpose of the VSM is to identify activities that create: value in the eyes of the customer, no value yet are necessary steps, and no value and are candidates for waste elimination (Womack & Jones, 1996).

Figure 5 VSM example (Rother & Shook, 2009)

Much of the benefit found in VSM is tied to the fact that activities associated with sourcing, making, and delivering product span functional boundaries, and the mapping effort and its output can open everyone’s eyes to the waste created in the
normal scope of business and the opportunities to improve flow. VSM maps are too often devoid of nonoperational influences, perpetuating wastes that could be eliminated through internal collaboration. Additional to this VSM cannot fully represent value in the eyes of the customer without knowing what the customer really needs and is willing to pay to receive a particular service attribute. Finally, the remedy for reducing waste may not reside in simple improvements to the current process. The best solution might be a completely revised process (Goldsby & Martichenko, 2005).

Maps should be developed by the area’s people for the area’s people. Maps should be signed off by all the participating mappers, but especially by the people from the area just mapped. Bicheno (2004) suggests the following steps in the VSM process:

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gathering Data</td>
<td>Collect data at factory floor</td>
</tr>
<tr>
<td>Basic Mapping</td>
<td>Walk area and detect Muda</td>
</tr>
<tr>
<td>Current State Data Collection</td>
<td>Collect supporting information before hand</td>
</tr>
<tr>
<td>Current State Workshop</td>
<td>Assemble people, maps, and information</td>
</tr>
<tr>
<td>Short Term Actions</td>
<td>Define a fixed time objective to implement changes</td>
</tr>
<tr>
<td>Detailed Mapping</td>
<td>Collect and support information to bring home the point to management</td>
</tr>
<tr>
<td>Future State Work Shop</td>
<td>Next future state, action plan, and ideal state</td>
</tr>
</tbody>
</table>

**Layout**

Spaghetti charting or diagrams depict the physical flow of work or material in a process, and are used to improve the physical layout of a workspace. Spaghetti diagrams are a floor plan of the area under consideration with lines showing the people movement or the materials movement for a particular process. Through this diagram it is possible to calculate travel time per part produced, and the ways to reduce this travel time. Spaghetti diagrams can be made for material movement or any other type of physical movement that occurs in any area under consideration (Plenert, 2006).

**Takt Time**

Takt boards monitor the output of a process or processes step to judge whether customer demand is met or not. Takt boards should provide at least 3 key pieces of information: work being done, the desired speed (completion rate), and the actual completion rate (George, Rowlands, Price, & Maxey, 2005).
Takt time differs from cycle time, which is the actual time it takes to do the process. The goal is to synchronize takt time and cycle time to the greatest extent possible. Synchronization of these two parameters allows processes integration into cells in support of our goal of one at a time production. Small frequent pulling helps find the pace of production (Dennis, 2007).

\[ (1) \]

In a true one-piece flow process, every step of the process should be producing a part. If the process goes faster it will overproduce; if the process is slower, it will create a bottleneck department. Takt can be used to set the pace of production and alert workers whenever they are getting ahead or behind (Liker, 2004).

**Kaizen**

Kaizen is a method for accelerating the results of process improvement in any setting. It evolved in the application of Lean methods in manufacturing settings, but has since been adapted to the broader Define Measure Analyze Improve and Control (DMAIC) improvement cycle framework. Figure 7 shows the model structures that the Kaizen framework according to its relation to DMAIC (Burton & Boeder, 2003). The process is closely linked to the general structure of the DMAIC. Table 3 based on Burton & Boeder (2003) equates the steps of both Kaizen and DMAIC throughout the duration of both methodologies.
Kaizen involves full time team work for a short period of time with a well-defined problem, where basic data has been gathered already. Kaizen implementation is immediate, and its goal is bounded to obvious identification of waste resources, minimal implementation risks, immediate results are expected, and when opportunities to eliminate obvious waste have been identified (George, Rowlands, Price, & Maxey, 2005).

Table 3 Comparison of Kaizen and DMAIC processes according to Burton & Boeder (2003)

<table>
<thead>
<tr>
<th>Kaizen</th>
<th>DMAIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Develop the Problem Statement and Deliverables</td>
<td>Define</td>
</tr>
<tr>
<td>Select and Educate Team</td>
<td>Measure</td>
</tr>
<tr>
<td>Identify and Measure</td>
<td>Analyze</td>
</tr>
<tr>
<td>Analyze</td>
<td>Improve</td>
</tr>
<tr>
<td>Develop Recommendations</td>
<td>Control</td>
</tr>
<tr>
<td>Implement and Monitor</td>
<td></td>
</tr>
</tbody>
</table>

The techniques and tools considered as the cornerstones for starting to eliminate Muda are thus referred to as “Kaizen building blocks” (Imai, 1997). Standardization, 5s, and waste elimination are implemented through Kaizen methodology. This thinking evolves towards more complex techniques and tools that are considered to be part of Lean thinking, such as: just-in-time (JIT) manufacturing (producing for transfer to the next customer only what is needed, when it is needed), kanban, poka-yoke (error-proofing), andom (visual display boards and lights), single minute exchange die, total productive maintenance, and heijunka (leveling production batch size and variety) (Lewis, 2000).

**Cardboard Simulation**

Bicheno (2004) describes a method to provide a set of building blocks and scheduling concepts that can be slotted together, Lego style, to construct almost any pull system. Blocks are combined to make up any factory. This procedure is not optimal but helps with fine tuning and operator buy in. The Lego simulation...
should include the operation of the cell full scale by using the minimum operators and proposed new layout.

3.2 Simulation

The authors’ intention is to give an introduction of the simulation field to the reader. It is not the aim to provide a tutorial on how to thoroughly build models or how to use the chosen software. Merely, it is supposed to demonstrate when to apply simulation, what to expect out if it, and comprehensively explain the very basic steps in model building.

3.2.1 Appliance of Simulation

Simulation is the imitation of the operation of a real world process or system (Banks, Carson, Nelson, & Nicol, 2004). The behavior of a system as it evolves over time is studied by developing a simulation model. The model naturally takes the input of assumptions and gathered information concerning the operation of the system. The assumptions and information are represented by mathematical, logical and symbolic relationships between the entities or objects of the system. Once the model has been validated and verified, it can be used to investigate a wide variety of “what if” questions about the real world process. Potential changes or disruptions of the system can first be simulated in order to see the effects and impacts on the system’s outcomes. In addition, simulation can be applied in the design phase of a process, before it is actually built. Therefore, simulation can used as an analysis tool for predicting effects on the system as well as a design tool for predicting the performance of such (Fishman, 2001).

Banks et al. (2004) describe purposes in which simulation is an appropriate tool in operations research and systems analysis and when it is not:

**Appropriate**

1. Simulation as a study of internal interaction of a complex system or of a subsystem within a complex system
2. Informational changes can be simulated and the effects of these changes on the model can be observed
3. The knowledge gained during a designing of a model can be used to suggest improvements in the system
4. Changing of inputs and observing the impacts on the outputs can lead to understanding of which variables are most important and how they interact
5. Simulation can be used to reinforce analytical solution methodologies
6. It can be used to experiment with new designs before implementation to prepare for what might happen
7. Simulation can be used to verify analytical solutions
8. Simulating different capabilities for a machine can help determine its requirements
9. Simulation models make learning possible without the costly on-the-job constructions
10. Behavior of the model can be visualized
11. Modern systems are mostly so complex that the internal interaction can be treated only through simulation

**Not appropriate**

1. When a problem can quickly be solved by common sense
2. When a problem can quickly be solved analytically
3. When it is easier to perform direct experiments than simulating
4. When costs of simulation is likely to exceed possible savings
5. When resources or time are not available to perform the simulation
6. When necessary data or estimations are not available for modeling
7. When there are no possibilities to validate and verify the model
8. When the systems behavior is too complex or cannot be defined

(Banks, Carson, Nelson, & Nicol, 2004)

### 3.2.2 Information that Simulation Provides

Managers are likely to jump on the simulation wagon as it delivers what happens in a real system or what is perceived to happen in a system that is in a design stage. Thus, simulation is often used as the technique of choice in problem solving. Given a set of inputs and model layouts, the model is run and its behavior is observed. What follows is the process of changing the inputs and the layouts and the effects they have on the results, which are evaluated. A good solution can then be recommended for implementation (Hoover & Perry, 1989).

As this it still rather general in terms of possible beneficial information outcomes, Pegden et al. (1995) listed a more detailed overview:

1. New policies, procedures, and flows can be tested without interrupting the ongoing process of the real system
2. New physical layouts and transportation systems can be tested without their costly acquisition
3. Hypotheses about what effects what and why things occur can be tested for feasibility
4. Time can be compressed or expanded to allow for a speed-up or slowdown of the system under investigation
5. Interactions of variables and their importance can be observed
6. Bottleneck analysis can be performed
7. It provides an understanding of how systems operate rather than how people think they operate
8. “What if” questions can be answered

(Pegden & Shannon, 1995)

Whilst seeing these points as great opportunities, it must be considered that they come at a “cost” and caution is advised before jumping into simulation. Model building requires training and can be seen as an art that is acquired over time and through experience. It is also unavoidable that if two models are constructed by two different users, the setup and results might be similar but most likely be different. Thus, results may be difficult to interpret. Most outputs of a model are random outputs as they are often based on random inputs. Therefore, it might be
hard to distinguish if results occur based on interrelationships or randomness (Banks, Carson, Nelson, & Nicol, 2004).

Simulation modeling and analysis can be time consuming and expensive. However, advances in information technologies suggest that simulation today is cheaper and faster than yesterday and will be tomorrow as well (Pegden & Shannon, 1995).

Additionally, simulation may also provide a means to validate a future state. Validation is the process that ensures that the simulation model mimics the real system (Law and Kelton, 1991). Validation grants credibility to a future state proposal and helps minimize the time required for the cell to achieve production capabilities at the required throughput level (Grimard & Marvel, 2005). According to Adumalek (2007) the availability of the information provided by the simulation can facilitate and validate the decision to implement Lean manufacturing and can also motivate the organization during the actual implementation in order to obtain the desired results. Marvel and Standridge (2009) describe the manner in that simulation modeling is proposed as the primary validation tool of Lean transformation in their relying on a series of iterations to modify the system until performance is satisfactory.

3.2.3 Systems and System Requirements

To model a system it is necessary to understand its meaning and boundary. Banks et al. (2004) defines a system as a group of objects that are joined together in some regular interaction or interdependence toward the accomplishment of some purpose. Automotive production is a good example; the machines, parts and workers operate together to produce a vehicle.

A system is often affected by change that occurs outside the system. The world outside the system is known as system environment. The dimensions of a system and its environment are important first step questions that will weigh heavily on a model’s outcome. Recalling on the automotive example, if orders for vehicles were to be outside the influence of production they would become part of the environment. A number of terms are defined before starting to build systems, which are displayed in table 4.

<table>
<thead>
<tr>
<th>Table 4 Components of a system (Banks, et al., 2004)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
</tr>
<tr>
<td>Entity</td>
</tr>
<tr>
<td>Attribute</td>
</tr>
<tr>
<td>Activity</td>
</tr>
<tr>
<td>State</td>
</tr>
<tr>
<td>Event</td>
</tr>
<tr>
<td>Resource</td>
</tr>
</tbody>
</table>
3.2.4 DES and ExtendSim

Systems can be categorized as discrete or continuous. Although few systems are entirely one or the other, one type usually dominates and thus classifies the system. A discrete system is one in which the model state changes occur at discrete points of time (Brailsford, Desai, & Vianna, 2010). For example every time a new part comes to the assembly station. A continuous system is one in which the state variables changes continuously over time. For example when simulating how water flows from a lake through a dam to make electricity and you might have a constant change in pressure.

In general, both models have similarities as they both represent a simulation of a certain process. They have variables to grasp the state of the system, both show how these variables change in interaction with others, and they have constants, random number generators, equations and other math blocks in them to model uncertainty and variability.

There are significant differences between the two types of models. When a system is modeled through discrete event all changes are bounded to system changes, in other words simulation steps only occur when certain events take place in the system. Time itself has no direct effect on the model. Time is directly related to the occurrence of events. Thus, the simulated time between events is unlikely to be the same. On the other hand, in continuous models time advances in equal intervals, and the values of the model change as a function of time. Hence, in a continuous model the state of the model is represented at any particular time.

Production systems fit the model of discrete event systems. DES models are analyzed by numerical methods. Numerical methods employ computational procedures to solve mathematical models. In the case of simulation models, an artificial history of the system in generated from the model assumptions and observations are collected for analysis and estimation of the system performance.

ExtendSim was selected as the program of choice for the model and simulation purposes of the thesis. ExtendSim is a “drag and drop” simulation program, and was the first graphical simulation tool to embody the concept of modeling components as objects (Krahl, 2009). ExtendSim encloses libraries of blocks containing their own behavior, responses to messages, interface, and data, that allow the user to create and model in a flexible way. Programming know-how is not necessary for model building and simulation. Complex processes are modeled through the combination of pre-defined blocks. Each type of block has its own functionality, help, icon, and connections. Each instance of a block has its own data. Blocks perform a number of functions in a simulation model that include:

- Simulating the steps in a process (Queue, Activity)
- Performing a calculation (Math, Random Number)
- Interfacing with other application or data storage (Read, Write)
- Providing a model utility (Find and Replace, Count Blocks)
- Plotting model results (Plotter, Histogram)
- Generating tools for interface creation (Popup, Buttons)
The source code for all of these blocks is available and can be viewed or modified by the end user. Creation of entirely new blocks is also possible. ExtendSim includes a relational database for organizing and centralizing simulation information. The use of a database in a model allows the modeler to separate the data from the model structure. According to Krahl (2009), even the newest simulation tools are merely variations on the basic theme developed by Imagine That Inc. in 1989. In addition, ExtendSim is one of the most popular simulation programs with over 20,000 full commercial licenses (Krahl, 2009).

3.2.5 Steps in Model-building

The simulation model-building process can be broken down into 12 steps (Banks, Carson, Nelson, & Nicol, 2004). The first three steps are a period of discovery and orientation. The second phase (Steps 4 to 7) is related to model building and data collection. Model running takes place in step 8 to 10 while implementation occurs in steps 11 and 12. A continuing interplay is required amongst these steps.

1. **Identify and formulate problem**
   The nature of the problem is determined: design of a new process, optimize an existing process, improve a process’ understanding, diagnose a problem through a model, or simulate for operator training.

2. **Set objectives and overall project plan**
   The objectives give insight into the questions that the simulation model is due to answer. At this point a decision need be made, is simulation the appropriate methodology for the problem at hand? If so, the overall project plan should include a statement of the alternative systems to be considered and of a method to evaluate their effectiveness. In addition, the plan should include the number of people involved, the cost of the study, and time frames for each phase of the study with expected results.

3. **Model conceptualization**
   Literature indicates that there are no step-by-step instructions to build a successful and appropriate model for every problem, yet general guidelines do exist that may help achieve a model’s end goal. Building towards complexity is desirable, model creation becomes an easier task when a very simple model is initially built and layers of complexity are added in time. A model should be as simple as possible as long as the model achieves its intended purpose; in other words, overly complex model are cumbersome. A model need not be a one-to-one copy of the real system, the essence of a real system may suffice. The model user is to be included in the conceptualization phase as his contribution will give valuable advice, enhance the quality of the results, and increase the user’s confidence in the model.

4. **Data collection**
   At this stage there is a constant interplay between the construction of the model and the collection of input data required for the model. As the complexity of the model increases so do the required data elements. Data
collection is a laborious and time consuming task; hence, data should be collected as early as possible if possible in parallel with the earliest stages of the model building process.

5. Model translation
Complex models require a great amount of data storage and computing. Models must be entered into a computer-recognizable format whenever software simulation is to play a part of the process. For purposes of this thesis ExtendSim software was used. Software selection was based on the availability of software resources on both university and at Alfa Laval.

6. Verified?
Verification pertaining computer programs occurs when the model is prepared for simulation. If the input parameters and logical structure of the model are correctly represented, and the interrelation between these elements is confirmed then verification is complete. A verified model does not provide an end solution, but a certain degree of accuracy is necessary. For the most part, common sense is used in completing this step.

7. Validated?
Validation is normally achieved by comparing the model against the actual system behavior and using the discrepancies between the two to improve the model. Validation is an iterative process and is repeated until the accuracy of the model is judged to be satisfactory. This step is perhaps the most critical one as an invalid model leads to erroneous results, which – if implemented – could be costly mistake.

8. Experimental design
A base level to depart from exists once a model is verified and validated. From this base layer a model may provide different possibilities from where to move to. For simulation to move forward in any of these intended paths alternatives must be determined. For each design that is simulated, decision need to be made concerning length of initialization period, the length of the runs, and number of runs.

9. Production runs and analysis
These are used to estimate measures of performance for the system designs that are being simulated.

10. More runs?
The analysis in the preceding step determines whether more runs are necessary and which changes in design are necessary.

11. Documentation
Experts distinguish between program and progress documentation. Program documentation is necessary when the program is to be used again by the same or different analysts. Parameters may be modified at any point of the simulation process, documentation is important as it helps learn and establish the relationship between parameters and their interrelation in
regard to optimization performance. Progress documentation such as project reports gives a chronology of work done and decisions made that might be of great value in its keeping the project at course. A project log might be helpful. A log book may include records of accomplishments, change requests, key decisions and other important aspects. The result of all analysis should be documented clearly in a final report.

12. Implementation
The success of this step depends on how well the previous eleven steps have been carried out. Implementation plays an important role on the degree of involvement the model user has immersed him or herself in during the course of the project, and the degree to which the nature of the mode and its inputs are comprehended.
Figure 8 Steps in a simulation study (Banks, et al., 2004)
Data output validation

The validation of the data gathered from the model is an essential part of simulation. The model user takes the model output as an aid to make recommendations to managers or third parties, whereas those third parties look at the model and its results with skepticism. Therefore, the reason for validation is to produce a model that behaves like the real system and allows analyses of the real system’s performance. In addition, validation entails the acknowledgement and corroboration of the model and its outcome, which increases the credibility of the model.

Model validation is defined as the substantiation that a computerized model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model (Sargent, 2008). Often the validation process is considered to be too costly and time consuming to determine an absolute validity of a model, thus tests and evaluation are conducted to obtain sufficient confidence that a model is valid for its intended application. The process of validation is mostly twofold: to build a model that has high face validity; and to validate its obtained data.

Face validity

Individuals, mostly process owners and model users, are asked whether the model and/or its behavior are reasonable. In the best case scenario, the model user is involved from the conceptualization to its implementation, to ensure that the highest degree of realism is built into the model through reliable knowledge, assumptions, and provided data. Besides assisting in the creation of the model, these individuals may also evaluate the output for reasonableness and aid in identifying the model deficiencies. Moreover, the user’s involvement increases the model’s perceived credibility when results are being presenting to a larger audience.

Sensitivity analysis can assist in face validation. Users are asked what – based on their experience – will change if certain parameters are changed. From working with the real system, the user would probably have some notion on how the output variables will be affected. Large simulations often comprise an equally large number of variables, and selection of critical variables for test purposes is often necessary.

(Banks, Carson, Nelson, & Nicol, 2004)

Data validity

Output data should be compared to the actual system performance whenever possible. When new processes are designed comparison between a real life system and a simulated model are hard to come by as no real data will likely be available. To choose the best results, validating data from a sample consists of three steps:
1) Identify an appropriate probability distribution.

To start off, a frequency distribution or histogram is useful in identifying the shape of the data distribution. It is a quite simple process, in which the range of the data is divided into intervals, the frequency of occurrences within each interval is found, and then plotted with intervals on the horizontal and frequencies on the vertical axis. The number of intervals depends on the amount of data and the dispersion within it. Literature suggests choosing the number of intervals approximately close to the square root of the sample size.

Once the shape of the distribution is identified, a family of distribution is selected “on the basis of what might arise in the context being investigated along with the shape of the histogram”. Common distributions such as exponential, normal, and Poisson are frequently encountered and not difficult to analyze. A quick introduction to these probability distributions is explained below:

Normal: A bell-shaped symmetrical frequency distribution curve. Often used where two or more variables have direct relationship and high predictability (low variation). In normal distribution, extremely-large values and extremely-small values are rare and occur near the tail ends. Most-frequent values are clustered around the mean. (Web Finance, Inc., 2013)

Exponential: Widely used to describe the time between independent events, or a process time that is memory less. For example, the times between the arrivals of customers who act independently. (Banks, Carson, Nelson, & Nicol, 2004)

Poisson: Unlike normal distribution, it is not symmetrical but instead is skewed to the left of the median. Good for inspection sampling, it is employed where the probability of an event is small and the number of opportunities for the event is large, such as the number of misprints in a book. (Web Finance, Inc., 2013)
2) Estimate the parameters of the hypothesized distribution.

After choosing an appropriate family of distributions, the next step consists of establishing the parameters of the distribution. Most commonly, the sample mean and the sample variance is calculated. If the observations in a sample of size \( n \) are \( X_1, X_2, \ldots, X_n \), the sample mean is defined by

\[
\bar{X} = \frac{1}{n} \sum_{i=1}^{n} X_i
\]

and the deviation, \( \delta \), is defined by

\[
\delta = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (X_i - \bar{X})^2}
\]

(Banks, Carson, Nelson, & Nicol, 2004)

3) Validate the assumed statistical model by a goodness-of-fit test, such as the chi-square test.

Goodness-of-fit test provide helpful guidance when evaluating the suitability of a potential sum of data, and to test whether the right distribution family was chosen. The Chi-Square test is popular for this purpose. This test formalizes the idea of comparing the histogram of the data to the shape of chosen distribution and mostly applicable for large sample sizes. The procedure begins by arranging the \( n \) observations into a set of \( k \) class intervals. The function is given by

\[
X = \sum_{i=1}^{k} \left( \frac{O_i - E_i}{E_i} \right)^2
\]

Where \( O_i \) is the observed values in the \( i \)-th class interval and \( E_i \) is the expected values in that class interval. The quantity \( X \) is therefore a measure of the deviation of a sample from expectation. The way that this method works is that it either rejects or confirms the null hypothesis, which is stated as follows:

\( H_0: \) There is no significant difference between the observed and the expected values.

The decision maker sets the value for the significance, most often 0.01 or 0.05. To answer the hypothesis, the chi-square table is used (Appendix B). For that the degree of freedom must be known, which is \( k-s-1 \), where \( s \) represents the number of parameters of the hypothesized distribution. Knowing the significance and the degree of freedom, the critical value can be read from the table. If \( X \) is lower than the critical value, the hypothesis is accepted. If it is higher, the hypothesis is rejected and the distribution family chosen is not suitable.

(Banks, Carson, Nelson, & Nicol, 2004)
3.3 Lean and Simulation

The fusion of Lean and DES is not common in the manufacturing field (Robinson, Radnor, Burgess, & Worthington, 2012). Often simulations are played out only manually to visualize Lean principles or sometimes computerized games are carried out for training purposes. However, nothing really comes close to the DES models and these attempts cannot represent the actual system.

3.3.1 Reason for Fusion

The decision to implement Lean manufacturing is often not an easy task as there is a big step from traditional to the Lean manufacturing when employee management, plant layout, material and information flow systems as well as production scheduling and control methods are considered. As changes are enormous, companies and managers in charge find it difficult to grasp the magnitude of the benefits than might come along. Thus, the decision whether to implement the Lean techniques or not is often based on faith in the philosophy, rule of thumb on anticipated results, and experience from other parties. It comes to no surprise that a decision based on this basis might be difficult for management to justify. (McDonald, Van Aken, & Rentes, 2002)

Therefore a tool is required during the design, planning and evaluation phase that is capable of assisting management in quantifying the expected benefits from implementing Lean. Furthermore this tool should adapt to each unique system and generate resource requirements and performance statistics for the current state of the process as well as the proposed future one. With this information, management has the required information to see differences in production efficiency and productivity regarding old and new system.

Detty and Yingling (2000) argue that Discrete Event Simulation is such a tool. Simulation can “quantify the performance improvements that can be expected from applying the Lean manufacturing shop floor principles of continuous flow, just-in-time inventory management, quality at the source, and level production scheduling.” (Detty & Yingling, 2000, s. 431)

The way that DES supports decision making varies from case to case. Often DES has been applied to establish specific parameters of a Lean system such as product mix, batch size, number of kanban etc. or to design, test and improve systems on a bigger scale, for example to test different layouts and flows. Furthermore, simulation has been used to assist in the early stages with the decision to replace an existing manufacturing process with a new Lean one. Detty and Yingling (2000) took this approach and found that simulation can provide creditable estimates of the savings in shop-floor resources and the improvements in time-based performance statistics that are achievable with Lean manufacturing. Their research showed the impact of Lean principles in terms of improvements and reductions in inventory, floor space, transportation, manpower, and equipment requirements. In addition to the latter, positive developments in time-based performance measures such as model changeover time and order lead time were discovered.
Information for future systems both facilitate the decision to adopt Lean principles and strengthen the organization’s commitment during the implementation phase. DES makes possible the comparison of an actual plant to simulation results provides, this examination provides means through which benchmark a company’s implementation effectiveness.

### 3.3.2 DES complementing Lean

A reason that might support the distance between simulation and Lean is that simulation is time consuming. It is the perception that creating, running and analyzing a simulation model is a lengthy and time-consuming process, not well aligned with for example a quick VSM creation process (McDonald, Van Aken, & Rentes, 2002). Companies may be inclined to rearrange a production line, check for feasibility, and switch back to the previous state, in case of need, in the same time window as it would to develop a simulation model. However, especially with the use of recent simulation software, actual programming time is often held to a minimum, in consequence a shorter –complexity withstanding– model development time ensues.

In addition, VSM is mostly used to evaluate current processes under a Lean perspective. A different approach is often necessary for the analysis of a future state. While in some cases future state mapping might be possible with modest effort, other situations require arduous work or may be impossible to solve with such a tool altogether. Because a static model cannot observe how inventory levels vary for different scenarios tracking inventory levels throughout the production process and predicting inventory outcome in future processes is practically impossible through VSM analysis. Thus a tool that may account for quantity variation, such as inventory levels, and compliment VSM is needed.

DES is capable of generating resource requirement and performance statistics whilst remaining flexible to specific organizational details; moreover, DES handles uncertainty and creates dynamic views of inventory levels, lead-times, and machine utilization with a high degree of flexibility. Most production lines have a wide variety of product families, different processing and change-over times, elaborate shift and personnel interrelations, as well as intricate product flows. All this creates a complexity that VSM alone cannot cope with (Abdulmalek, 2007).

Although VSM allows users to see the desired process in a static sense, simulation provides a dynamic visualization over time. DES software has a graphical interface that allows the user to see the system operating on the screen, almost like watching a movie (Brailsford, Desai, & Vianna, 2010). Items are created, batched, stored, and moved along the process in the model. The dynamic representation of items enriches process understanding and is not to be taken lightly. Plus a consensus on improvement possibilities is achieved when bottlenecks become visible and lead times vary.

Despite the many benefits of interplay between VSM and DES, McDonald et al. (2002) suggests that VSM should not be complimented through simulation in
every case, but that simulation be an integral part of the tool set. The above is especially true when there is product complexity, parallel processing steps, and different shifts.

To go beyond just the VSM, Robinson et al. (2012) discuss in their paper how the key methodology assumptions of DES fit the concept of Lean. In particular the seven original wastes (Muda) are seen as well-fitting to DES usage. The table below shows the principles of Muda and how DES is able to assist.

Table 5 Comparison of Muda and DES

<table>
<thead>
<tr>
<th>Seven Original Wastes</th>
<th>Role of DES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transportation: moving products that are not actual required for the process</td>
<td>Modeling process flow and measuring transportation times</td>
</tr>
<tr>
<td>Inventory: all components in process</td>
<td>Modeling queues</td>
</tr>
<tr>
<td>Motion: extra movement of people or equipment that is not necessary for the process</td>
<td>Modeling the interconnection between resources and the process</td>
</tr>
<tr>
<td>Delay: Waiting for next production step</td>
<td>Modeling queues that evolve as a result of variability in interconnected processes</td>
</tr>
<tr>
<td>Overproduction: Production ahead of demand</td>
<td>Modeling the interconnection between variability in demand and production</td>
</tr>
<tr>
<td>Over processing: Resulting from poor tool or product design creating activity</td>
<td>Modeling the process flow and measuring utilization of resources and activities</td>
</tr>
<tr>
<td>Defects: effort in inspecting and fixing defects</td>
<td>Modeling of activity breakdowns</td>
</tr>
</tbody>
</table>
4. EMPIRICS

An overview of the Lean methodology at Alfa Laval, problem situation, and pre study is forwarded. A detailed description of the current and future production process follows. The simulation model’s setup and runs are outlined as part of the Case Study performed at Alfa Laval.

4.1 Alfa Laval and Lean

In its implementing Lean principles, Alfa Laval developed its own Production system closely following the principles of Toyota’s production system. Alfa Laval named its production system ALPS (Alfa Laval’s Production System). The system is based on Lean and Six Sigma philosophies and was first deployed in 2007.

ALPS targets all of Alfa Laval’s organization and entails a structured procedure with milestones and measurable instances. The local implementation of ALPS follows a six months plan to close local performance gaps. ALPS scorecards are reported every month to ensure quality and speed in problem resolution and improvement activities.

Alfa Laval’s Eskilstuna facility is no exception to the realm of its production system. The areas of ALPS implemented in the Eskilstuna factory has so far included leadership and culture, organization, 5S, standard operation procedure, 7 wastes reduction, status boards, problem resolution process (DMAIC-light), and Total Productive Maintenance (TPM).

As problems occur on different levels and with different magnitudes, improvements need to be addressed in different ways respectively. Problems are reported and then distributed in accordance to their impact and importance. Problems of simple complexity are dealt with in status board meetings, “24 hours problems” (problems whose solution should not exceed 24 hours), internal audits of ISO 9001:2008 and ISO 14000:2004, claims, 5S audits and daily problems. These problems are fist discussed and solved on weekly improvement meetings. If a problem exceeds this time frame or if the problem entails greater complexity then a DMAIC-light method (problem resolution process) approach is put in effect.

Even more complex problems will generate a Green belt, Black belt project or a Project Management Alfa Laval (PROMAL) project. A Green belt project must generate a Defects Per Million Opportunities (DPMO) reduction of 25% or a yearly cost saving of at least 5k€. The requirements for a black belt are a DPMO reduction of 50% or a yearly saving of at least 50k€. PROMAL projects entail an organizational initiative that targets specific areas of the company’s structure but that may affect many functional departments.
PROMAL projects describe a process, employee relation to a project, roles and responsibilities of participants, and entail lengthy documentation. During the PROMAL process, different gateways are scheduled along the project’s life cycle. Milestones may signal project progress, important events or project status such as: project continuation, put in on hold, or shut the project down. These decisions are taken by a Steering Committee. Depending on the area the project belongs to there are different Steering Committees to report to such as: Purchase and supplier development, Quality, and Production development. Every month a Steering Committee meeting is held where all project managers present the status of their on-going projects. A Steering Committee consists of project owners, factory manager, representatives of the union and stakeholders.

The increase of capacity in any of Alfa Laval’s structure falls under the category of a PROMAL project. In 2012 Alfa Laval’s Eskilstuna factory foresaw an increase in the production of its separators. The only production cell that would not be able to cope with the forecasted volume was Cell C6. A PROMAL project that would ideate a solution to this problem was launched.

Cell C6 project is under supervision of the Production Development Steering Committee (SKPU). The project started as an umbrella project that housed many modifications to the process under its span, for instance: new washing method for bowl discs, new welding line, and developing a new layout. The end goal of the project was to create a new flow that would meet the new demand.

The project started off with a VSM analysis of the current process to get a better picture of the situation and pinpoint problem areas. Process bottlenecks were discovered after comparing current machine cycle times to the future takt time. Brainstorming and discussion brought a number of possible solutions.

Two suggestions for a new flow were proposed. The new process flows required the investment of new and faster equipment, but most importantly a change from

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**Figure 11 PROMAL project methodology framework**

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traditional batch production (batches of 170-220) to a few-piece-flow production. The decision to invest in new equipment made sense to experienced personnel from different seniority levels for they were too familiar with the day-to-day operations of the process. Implementation of a one-piece flow concept was harder to grasp.

To educate the project team and get a better understanding of the Lean principles, the Lean Six Sigma manager implemented a number of Lean activities amongst which was a Lean game. The Lean game is a simulation of a factory in which Lego parts are produced. In the game the participants are able to try the different Lean principles and see how it affects the outcome and the flow.

The game was both educational and demonstrative, participants gained a sense of batch size reduction (one-piece flow), 5S, takt times/cycle times, bottlenecks, communication, SMED, pull/push flow, customer value, waste reduction, and Lean layout. In addition to the above, the Lego simulation offered a visual representation of what a new flow would look like, and what new possible bottlenecks would be encountered. The Lego simulated tried to represent as closely as possible the new process layout, cycle times, and production steps.

Usually an increase in capacity is verified by calculating cycle times, possible down times and the availability of the machines. In this case, the proposed solutions entailed a complex flow with a very diverse product mix, cycle and change over time modifications from the current production process, material recirculation loops that were not previously occurring or the elimination of such loops were present, new batch size, and newly introduced processes. Despite the many benefits of a Lego simulation its shortcomings were substantial when assessing a holistic overview of the process. Therefore, Discrete Event Simulation was proposed to evaluate the possible changes and the new flow.

4.2 The Product

The authors refrain from a detailed description of separators’ inner workings, or a bowl disc’s function. For general understanding it can be pointed out that a separator is a centrifugal device that separates liquids from other liquids, solid particles from liquids, and recently particles from gases through the use of centrifugal forces (Alfa Laval, 2013). A separator will stack an average of 200 bowl discs per unit. Bowls are responsible for the separation process that takes place between each disc. Bowl discs require separation from each other within the stack; such separation is achieved through welded stainless steel insert called caulks. Centrifugal forces sort fluids from particles, and expel one or the other, as a result of density, into the outer periphery of the separator bowl. Fluid phases are then discharged through separate outlets. Separators are
commonly used in processing of liquids in food, pharmaceutical, chemical and petrochemical processes, as well as in extraction and treatment of crude oil. Further appliances include treatment of fuel and lubricating oils in vessels and electric power plants and cleaning of crankcase gases from truck and ship diesel engines.

4.3 Process Descriptions

Alfa Laval realized the need to modify its current process to meet future demand. A new process meant a new Lean process were Muda reduction, quality, and flow were prioritized. A multi-disciplinary team was formed to tackle the issues. The team’s activities were supported by the use of Lean tools and procedures.

4.3.1 Current Process

Bowl disc manufacturing entails a complex process that starts long before single machine is operated. When a new order for a separator is placed, the production planner aligns all the different production cells in order to have all components ready for assembly at the same time. Two weeks before assembly start, Cell C6 gets its production schedule thus allowing two weeks from the pickup of raw material to the transport, and then to the assembly cells. In addition to the orders, bowl discs are manufactured every week for a safety stock.

The process of manufacturing the bowl discs starts when the operator of the cutting machines picks the raw material – large steel plates - from stock. In the first machine the material is cut into squares. After one order is complete, the stack is moved to the second cutting machine and the same operator cuts them into circles. The order then moves to the metal spinning operations. It is important to mention that the bowl discs move to the next operation once the entire order in completed. At metal spinning the metal circles are formed into cones. Depending on technical restriction, metal spinning is performed in either the manual flow, where an operator is in charge of new setup after each item, or an automatic flow that makes use of a robot cell.

Figure 13 Current bowl disc production process at Cell C6
Once these steps are completed, the orders go to either a safety stock or the welding lines, where caulks are spot-welded onto the cone. Again based on technical requirements and capacity availability, the items make their way through one of the four welding options. Current distribution shows 50% of bowl discs to be welded pass through the Svets 2000 station, 40% through A and B welding lines, and the rest through C welding line.

The four flows converge into one path at the press adjustment station. The press station shapes the caulks in line with the disc. After the washing of the items, the order goes back into the press adjustment machine, in this second stop at the press station a top hole is punched onto the bowl disc. Once all these steps are fulfilled, the bowl discs make their way into the separator assembly lines.

**4.3.2 Current Process Analysis**

The current process analysis was carried out by the C6 Project Group over the duration of two months. The Project Group was constituted by a project manager, the team manager of cell C6, operators of C6, members of production technology and service, and maintenance personnel. Main tools used for the analysis were VSM, spaghetti diagrams, and balance load charts.

![Figure 14 VSM analysis of the current production process](image)

Figure 14 shows the final version of the VSM chart. In addition to the traditional data (processes and times) acquired through VSM analysis post-it notes were included to illustrate where problems and restrictions occur. An analysis of the current state of the process is beyond the scope of this thesis, however the current VSM may be found in Appendix C.

Time values were taken by stop watch measurements, assumptions based on experience, and calculations of average process cycles. Table 6 summarizes the operations in the process per data gathered through VSM analysis. VSM analysis
was valuable in its understanding the proportion of time in the process that is Value Adding and the proportion of time that is Non-Value-Adding. This ratio is quantified in Table 6 as Ratio VA / LT, its low percentage tells of the improvement opportunities in existence for the process.

Perhaps the most important figure in the table is the comparison between current and future takt time. The differential between the current and future takt time signals the lack of responsiveness from the current production process to meet future demand. The takt time figures show the importance of a new process if the future demand of 120,000 bowls discs were to be met.

<table>
<thead>
<tr>
<th>Table 6 Sample of data acquired through VSM analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Current Process</strong></td>
</tr>
<tr>
<td>----------------------</td>
</tr>
<tr>
<td><strong>Lead Time with Stock</strong></td>
</tr>
<tr>
<td><strong>Lead Time without Stock</strong></td>
</tr>
<tr>
<td><strong>Value adding Time</strong></td>
</tr>
<tr>
<td><strong>Ratio VA / LT</strong></td>
</tr>
<tr>
<td><strong>Takt Time 2 Shifts</strong></td>
</tr>
<tr>
<td><strong>Takt Time 3 Shifts</strong></td>
</tr>
</tbody>
</table>

In addition to VSM analysis, Balance load charts were used to analyze the current process as well as how the current process would respond to future demand. Current rate of production of every station was compared to future takt time as seen in Table 6. Future demand affected the current process in two ways: firstly, takt time was to be reduced by half; secondly, machine cycle times would not be able to cope with the future rate of production.

One example of such balance load charts (others to be found as Appendix D) underlines the need of a new production approach, especially in regards to the welding lines, the process bottlenecks. The impact of the bottleneck on the volume output of the process was expected to be even greater in the future, as 50% of all items make their way through the faster Svets 2000 welding station, a machine that is utilized close to its full capacity. Because of their constant need for corrective maintenance A, B, and C lines were also regarded as troublesome equipment. The constant production problems in lines A, B, and C alone justified the investment in new equipment.
Once the bottle neck, welding stations, was identified a technical analysis was performed. The analysis resolved the need for a faster welding process. Welding cycle times were estimated to cope with future demand, and a search for a new welding station that could cope with future demand began.

In process quality was also revised. The washing process was subject of concern as clients had submitted complaints in regard to the cleanliness of separators. A new washing method that would comply with both quality and production needs was studied.

Finally, C6 Project Group identified and wished to eliminate Muda in the process. The spaghetti diagram illustrates that the current flow of the product is not a flow to be wished for. Particularly the last steps, in which the product goes from the pressing station to washing station and then back to the pressing machine, for the top hole punch, a clear example of unnecessary transportation that should be avoided.
4.3.3 New Proposed Process

After their analyzing the weak points of the system, the Project Group came up with improvement suggestion for process and flow according to Lean thinking.

Figure 17 Future bowl disc production process at Cell C6

The new process allows for a stock after the cutting station. Cutting steps are fast operations that work on one shift and share one operator but still have more capacity than the rest of the system. One of the most vital differences follows afterwards: two flows are created. One leads through the manual metal spinning and the Svets 2000 welding station, whereas the other one runs through the automatic metal spinning and a new welding machine, called Ny Svets. In between the steps, the flows are shortly reunited when they run through the same washing machine. The ratio of distribution for product flow between this to paths was unknown at the time of ideation; however, the Project Group desired to have the majority of the items run through the automatic metal spinning and the new welding.

In addition to the separation of flows, orders are split as well. Following the Lean idea of a one-piece flow, one order is broken down into several batches after the metal spinning operation. These batches move through the entire process until the last step. Because of the cross over flow at the washing station batches from each flow may be mixed; hence, a prioritizing sequence is conceived.

The washing station can hold an entire batch at once and does not require set up time. The pressing station however would have 30 minutes set up every time a batch with a different product was to arrive. The time differential would defeat the purpose of a fast flow. Thus, every last batch of an order that approaches from the Ny Svets was marked (see figure 18) to inform the operator. When the last batch has been pressed an entire order is taken from the Svets 2000. After pressing an order, the operator goes back to take batches from the Ny Svets flow. The prioritizing system works when small volumes and high cycle time of items flow through the Svets 2000 flow. The prioritizing setup allows the Svets 2000 to gather stock but up to a limited quantity.

The last step included a top hole punch, or laser station. The acquisition of a laser is part of one alternative that includes the replacement of the traditional top hole
punch system to improve accuracy and thus less rework. After the last step, the entire order was collected and sent to assembly.

Figure 18 Alternative processes based on Lean principles

4.3.4 Need for Simulation

Cell C6 Project Group analyzed the current state, ideated solutions to current waste problems, and conceived a new process flow based on Lean principles. All the ingredients for an effective solution were in place. Despite the creative ideation, Alfa Laval did not know whether any of the proposed alternatives were to work, or in what quantity amount would concepts like batch and stock size were to create flow. Production runs were out of the question as new machines, layout, and processes had not been implemented. Alfa Laval required a tool to test whether the proposed Lean alternatives were to meet their goals.

Despite the vast experience of team members in the production of bowl discs there were a number of parameters that neither experience nor traditional Lean tools could answer in regard to Lean proposals. Figure 19 illustrates the parameters defined by Alfa Laval’s Lean Six Sigma Manager that the simulation was due to answer. These parameters were important in terms of process functionality, evaluation of “Leaness” in the proposal, and physical space assigned to each proposal. Although no conditions of optimality were required from the simulated models, simulation was expected to provide the best solution possible within a given range of values.

Figure 19 Variables for which models were required to provide a solution for
In regard to its productive, physical, and technical capabilities all production variables illustrated in figure 19 were subject to a lower and upper boundary of values. Simulated models were to trace, evaluate, measure, and determine the best possible outcome for these combinations. Table 7 shows the range of values for which production variables could select from.

**Table 7 Variety of production values**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Minimum Value</th>
<th>Maximum Value</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lot Size</td>
<td>15</td>
<td>30</td>
<td>Increments of 5</td>
</tr>
<tr>
<td>TVA &amp; Weld Distribution</td>
<td>20%</td>
<td>80%</td>
<td>Increments of 10%</td>
</tr>
<tr>
<td>Shifts</td>
<td>2</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>WIP</td>
<td>0</td>
<td>10</td>
<td>Increments of 1</td>
</tr>
</tbody>
</table>

Lot sizes were to have a minimum value of 15 items up to 30 items per order with increments of 5 additional pieces for each evaluated scenario. Two possible paths existed associated to the TVA and Welding stations. Each path could have as little as 20% and as much as 80% of the volume running through it. All operations were to be performed with two or three shifts respectively for all production operations. Finally, work in progress (WIP) was to be reduced as much as possible and any value between no work in progress up to 10 lots was considered viable. Evaluation of these variables was to be judged by the total number of bowl discs produced.

Furthermore simulation was required to track production parameters that Alfa Laval considered factors upon which to judge each proposal other than volume alone. Figure 20 illustrates these parameters.
The variety of variable combinations, information to track, process variability, and product mix were all reasons that contributed to Alfa Laval’s deciding upon a DES approach to Lean proposal evaluation.

**4.4 Discrete Event Simulation Approach**

The steps in section 3.2.5 ‘Steps in model-building’ were followed to model all DES scenarios. The current production process was modeled first. The reason for this choice was that this first model served as a framework to compare blocks, processes, flows, and information from real life production to those of a simulation model. On a second instance, the future desired states were evaluated based on the applicability of Lean principles. First off the input and output data is explained.

### 4.4.1 Model Data

Data used for the current model’s input made use of historical information, interviews, and field observations. The authors relied heavily on the use of organizational records to substantiate the model’s validity. All information used for the purpose of simulation was approved and validated by Alfa Laval’s Planning, Production, and Lean Six Sigma departments. Data used in the current state model may be classified as: input data to feed the production schedule, and data affecting the production process performance.

**Input Data to Feed Simulation Model**

Input data was mainly gathered from an existing VSM performed by the Project Group beforehand. A production schedule based on VSM data was elaborated once the information was gathered and approved by Alfa Laval’s Lean Six Sigma manager. The production schedule included a number of orders to be produced in a week’s time. All items within the order were labeled with its standard production characteristics for every operation in the process.
A standard order with 170 bowl discs was used for all VSM orders. Every time had equal production parameters when compared to all other items in the production schedule. Two different sets of production schedules were generated on the one hand a schedule that complied with current demand of 75,000 bowl discs per year; and on the other hand, a production schedule that complied with a future demand of 120,000 bowl discs per year. The only difference between both schedules was the quantity of items to be produced in the same amount of time.

![Figure 21 Data distribution and quantity split based on VSM analysis](image)

One of the most critical operations for bowl disc production is the welding operation. Products are distributed to different welding stations based on their physical characteristics, functionality, and machine availability. A randomized probability distribution was selected to direct the bowl disc welding station on the VSM models. This randomized probability distribution was calculated and approved by Alfa Laval’s Lean Six Sigma department. Table 8 shows the welding line distribution of bowl discs. As all items in the VSM production schedule were “standard products” their physical characteristics and functionality were ignored.

<table>
<thead>
<tr>
<th>Svets 200</th>
<th>Line A</th>
<th>Line B</th>
<th>Line C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Welding Distribution</td>
<td>47%</td>
<td>20.5%</td>
<td>20.5%</td>
</tr>
</tbody>
</table>

VSM production schedule was useful yet limited. A far more complex model, closer to real life production settings that tested the capacity of the current production process through new demand with real order size, change over, cycle time, and product mix was necessary. Historical data was used to build a production schedule that simulated a week of production at a time. Data from Alfa Laval’s ERP system (Movex) fed machine production parameters. Gathering, sorting and registering real life production data to feed the system was perhaps the most cumbersome of activities throughout the project’s duration.

Data used to build the production schedule was acquired from Alfa Laval’s Planning Department log. Data was collected in weekly batches according to production requirements were orders, products, quantities, and processes to follow were detailed. Revised data considered for the analysis comprehend a year’s time...
of information. Weeks with low production volume, holidays, or special circumstances were discarded.

Table 9: Production data with variation of order quantity between products

<table>
<thead>
<tr>
<th>Order Number</th>
<th>Product</th>
<th>Quantity</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>245801</td>
<td>500</td>
<td>cut</td>
</tr>
<tr>
<td>2</td>
<td>245802</td>
<td>500</td>
<td>cut</td>
</tr>
<tr>
<td>3</td>
<td>245277</td>
<td>-</td>
<td>cut</td>
</tr>
<tr>
<td>4</td>
<td>245647</td>
<td>100</td>
<td>cut</td>
</tr>
<tr>
<td>5</td>
<td>245646</td>
<td>5</td>
<td>cut</td>
</tr>
<tr>
<td>6</td>
<td>245201</td>
<td>240</td>
<td>weld</td>
</tr>
<tr>
<td>7</td>
<td>244882</td>
<td>240</td>
<td>weld</td>
</tr>
<tr>
<td>8</td>
<td>245633</td>
<td>8</td>
<td>weld</td>
</tr>
</tbody>
</table>

After discriminating certain weeks based on the criteria above, the Planning Department was asked to select 5 weeks of production for Cell C6 that were representative of Alfa Laval’s weekly production targets. After the Planning department delivered the list of times to be produced in the course of the 5 weeks of simulation; the Production Manager, operators of Cell C6, and the Lean Six Sigma Manager corroborated these weekly schedules. In all 500 different products were included in the simulated production schedule distributed along 5 weeks. No random distribution of items were followed, all items were placed for production according to Alfa Laval’s selection.

After a production schedule was generated, the products in the list were linked to their production parameters for every stage of the process. Real production parameters for orders and products encompassed in the above schedule were collected. The use of Alfa Laval’s ERP system (Movex) made it possible to receive cycle and change over times for all 500 product numbers and for every operation. Time differences did exist between real life production measurements and information provided by the Movex system. The use of Movex data, and its selection over onsite measurements, was analyzed and approved by Alfa Laval’s steering committee. All data for production settings was entered into a database developed by the authors of the thesis from which to draw information from.

Welding distribution criteria was embedded into the production order based on its schedule. No random distribution was used to funnel bowl discs through the welding operation. This was an important modeling decision and a tradeoff. A randomized welding distribution adds variability to the process, a desirable characteristic of DES; however, the custom made characteristic of separator production greatly affects the order size quantity of items to be produced. The difference between production quantity sizes is exemplified in table 9. An unrestricted randomization of products yielded production situations that would never occur in real life. Production planning at Cell C6 is categorized in such a way that a balance between larger and low order quantities is maintained. Therefore, items were handpicked to follow a particular route in the system. Microsoft Excel as used extensively to classify, tag, and manage data that was put
into the production schedule. The total amount of items to be processed using this method was validated by the Production and Lean Six Sigma managers.

**Data Affecting Production Performance**

The simulated model complied with the logical sequence of production, items scheduled for production were ready, and parameters registered. Notwithstanding its operational capacities, the model had to account for those events that affect production such as: planned maintenance, machine failures, and shifts. Information was collected, skimmed, and arranged into probabilistic distributions to account for variability in the events.

Alfa Laval’s maintenance log was consulted for unplanned maintenance. A universe of all events that took place in Cell C6 was comprised into an Excel spreadsheet. The search included all events triggered in a year’s time. The table included the operation affected by the failure, time of repair, and a brief description of the event. No failures were excluded from the analysis. All failures whose repair time exceeded one shift were labeled for further analysis.

![Figure 22: Unplanned maintenance represented as distribution](image)

Operators, maintenance personnel and the Production Manager were questioned and asked to discriminate between those events tagged that were representative and likely to repeat, and those that were unique instances and unlikely to happen again. After the register was cleared of events that were unlikely to happen failures were separated into machine operations. A mean average for Time Between Failures and Time To Repair were calculated. A triangular distribution was selected, per ExtendSim’s user guide suggestion, to represent unplanned machine failures.

Shift changes were critical for the purpose of simulation. The number of shifts necessary to reach a yearly goal was an initial question of concern for Alfa Laval. Time for shift start and stop had a direct impact on the place and time material had to wait in process, a machine’s utilization rate, and the maximum amount of items to hold in queue between workstations. Alfa Laval’s production procedure was consulted to account for all of Cell C6 shifts’ start, pauses, and end. Two and Three shift options were created based on the aforementioned data. All operations included in the simulation were linked to the use of these shifts. All operations
were executed based on either a two-shift work schedule or a three-shift work schedule. No mixed schedules were employed.

**Evaluation Data**
Evaluated data comprehended all variables in Figure 20. All parameters were tracked throughout the duration of each simulation run. All parameters were evaluated on a 5 run cycle per simulation run were each run included 5 weeks of production. Data was recorded and measured with ExtendSim’s tool suit. Parameters were defined as follows:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Volume</td>
<td>Total number of finished bowl discs at the end of a 5 week period</td>
</tr>
<tr>
<td>Off Duty %</td>
<td>Week time not assigned to production</td>
</tr>
<tr>
<td>Lead Time</td>
<td>Total hours it takes for a product to be processed from the end of the cutting operation to finished good stock</td>
</tr>
<tr>
<td>Machine Utilization %</td>
<td>Proportion of time in which a machine is busy be that as a result of its producing or holding material for the next operation</td>
</tr>
<tr>
<td>Work In Process</td>
<td>Maximum amount of items to be held as work in progress in queue before each operation.</td>
</tr>
</tbody>
</table>

It is worth noting that the Work in Progress parameter is meant to evaluate the maximum minimum amount of items necessary to produce material flow and comply with yearly production. Alfa Laval’s management decided to limit the maximum number of lots to hold in stock to 10 lots as part of an operational initiative that sought to reduce Work in Progress inventory. Work in Progress parameter is no the addition of all material in process, but the upper limit that results after evaluation through DES analysis.

**Output data validation**
Recommendations to SKPU and the Project Group were made upon simulation results. Simulated results were to be trustworthy pieces of information; therefore, it was necessary to validate data and provide mean figures that represent the simulation outcome representatively. Statistical data validation procedure was followed closely per a Chi-square method.

First outcome data was gathered and plotted in a histogram. Then a distribution family was chosen and validated by the chi-square method. Once this was achieved, the mean was considered to be representative. To exemplify, the results from the Laser (Three shifts, Movex) are validated below. To obtain enough sufficient data, each scenario was run 1000 times. As this type of validation is time consuming, the authors chose their showing the example below alone. However, all final simulated results followed the same producer and principles of statistical validation.
The shape of the distribution equals the shape of the normal distribution, thus it is chosen as the family of distribution.

Due to equations (2) and (3), the parameters for this case came to:

The detailed calculation of the chi-square test was done in excel and can be comprehended in Appendix A.

H0: There is no significant difference between the observed and the expected values.

6.65 and

As is lower than the critical value, the hypothesis is accepted and the distribution family chosen is suitable.

This validation process was followed for all of the final future state models:

- Two Shift Laser
- Two Shift Top Hole
- Three Shift Laser
- Three Shift Top Hole

After this process the results for the validated simulation output for Volume through Chi-square method are found in the Results chapter of this report (5.1)
4.4.2 Current State Modeling

First Phase: discovery and orientation (Identify and formulate problem / Setting of objectives and overall project plan / Model conceptualization)

Beyond process understanding and improvement, the current model addressed two problems:

a) The current state model was related to the desired future state model. The current state model would serve as a framework upon which to build the future state. Construction and validation of this base level framework scenario was necessary.

b) Although VSM analysis delivered lead time, WIP, etc., these datum were built upon average calculation and/or assumptions. In order to compare a future Lean concept to the current state, the performance of the actual system with future demand must be known.

Thus, the purpose of this model was to serve as a basis and framework for the future state model and confirm that the results of the obtained simulation matched the actual system.

Questions that the simulation sought to answer were:

1. What would the yearly bowl disc production output be when based on the current production capacity and processes having to comply with the future expected production schedule forecast?
2. What lead time exists for a future production schedule based on the current state capacities?
3. Would it be possible to increase the current system’s capacity while its taking into account future production schedule forecast?

As this simulation enables the study of a complex production system and confirms most other points listed in section 3.2.1 ‘Appliance of Simulation’, it is an appropriate methodology to apply and capable of answering the questions noted above.

The system was contained within C6 manufacturing cell and comprehended all production steps from the start of the cutting operation until items leave for assembly. Activities and processes were not a function of time. Time was a function of the events that occurred between activities. The state of the system and its changes were bounded by events such as the arrival of a new item to a station, or completion of a production step. The system was defined DES appropriate based on the above characteristics.

Two people worked on the conceptualization, programming, execution, and troubleshooting of all simulated scenarios. Due dates of milestones were weeks in year 2013:

1. Start of project week 4
2. Analyze and gather data, process, and interviews week 6
3. Modeling the current state week 8
4. Simulation and analyzing results week 9
5. Review with Project Team and Steering Committee week 10

The model building started on a simple scale and slowly built up to a more complex one. As the model increased in complexity its results were validated. Those parameters that were added in different layers of complexity included a production schedule, change-over times, batching / unbatching, shifts, breakdowns, distributions, and tracking of information. The model user (Lean Six Sigma Manager) was actively involved throughout the construction of all models. Her understanding of the process and revisions were necessary to verify the model, and fine-tune the model.

Figure 24 illustrates an example of increase in model complexity in the welding operation. What started as an inconsequential fixed cycle time activity block evolved to a multi machine welding operation whose products included different cycle times, change over times, order quantities, machine failures, and planned maintenance stops.

Figure 24 Model complexity increased to meet the project’s objectives

Second Phase: model building and data collection (Data collection / Model translation / Verified and Validated?)

Data collection and its use were detailed described in section 4.4.1. All models were created and run in the ExtendSim V8.0 Software.

The input parameters and the logical structure were correctly represented in the ExtendSim. Thus, the model has been verified. Validation was achieved by comparing the model against the actual system behavior (see section 4.4.1).
Third Phase: Model running (Experimental design / Production runs and analysis)

In regards to the problem statement, two different scenarios were simulated: one with the current production demand and one with a future production demand. The current demand model was fed with two different inputs: VSM data and ERP data (Movex). Other than the reasons stated in the section above the model’s having two different production schedules corroborated the veracity of the simulation. It was hypothesized that although different, simulation results through VSM or Movex data were to yield similar results.

The future demand model based on the current state of production was simulated with two and three shifts on all machines and with Movex data. Even shift distribution in all machines helped compare future demand through current state production to Lean proposals scheduled with future demand. Lean proposal models’ number of shifts was one of the variables affected by simulation analysis as described previously. A standard time for simulation governed all simulation runs. All simulations considered a 5 day work week for a period of 5 weeks. Simulated time amounted to over 17,000 hours of production.

A great amount of information was tracked along the process, but to keep information visible and easy to comprehend for the reader, only key parameters are shown in the tables below. Each table is connected to one problem statement.

a) The current state model was related to the desired future state model. The current state model would serve as a framework upon which to build the future state. Construction and validation of this base level framework scenario was necessary.

The results show that simulations runs with Movex and VSM data deliver similar information in the key categories ‘Lead Time’ and ‘Total Yearly Output’. As the yearly output of the actual system is around 75,000 bowl discs per year, these results validate the accuracy of the model, regardless of the input data selected for the production schedule (VSM of Movex).
A lead time of over 80 hours might seem high at first compared to the 36 hours calculated in the VSM. However, the VSM option does not account time spend in queues, which was an important aspect when bottlenecks are taken into consideration. Moreover, the process runs in three shifts during the week but not on the weekend. This means that every week items spend over 48 hours in the progress without being processed. That time was also not considered in the VSM.

The only significant difference lay on the Svets 2000 utilization. The difference in utilization at the welding station was a result of the distribution of bowl discs that circulate through the different welding lines. The VSM data determines that the distribution is 47% Svets 2000, 20.5% A-line, 20.5% B-line, and 12% C-line. As the Svets 2000 was the fastest line and capable of welding most article numbers, the goal was to send the most items through that line, this situation explains the high utilization of 94%. As the Movex data was based on a randomly chosen five weeks period of production the utilization was different. Models with Movex data were based on real life production schedules, and the difference between Movex and VSM models in terms of utilization is a result of the technical requirements of products and their orders at the time of production. This difference in utilization was not of concern for Alfa Laval as it demonstrated the normal operational circumstances of bowl disc production. A lower distribution of items through Svets 2000 welding station would have led to a lower utilization rate of that machine. This also explains the slightly higher lead time and lower output as a result of the other welding stations’ having higher cycle times.

As the yearly production of the model met the actual production volume and the lead time was considered to be close to reality by the project team, it can be concluded that problem statement a) was solved. After evaluation of results and approval by the project team, this model functioned as a framework for the future model. Within this framework, flows were altered, operations moved, and parameters modified.

b) Although the VSM delivers lead time, WIP, etc., these data are built upon average calculation and/or assumptions. In order to be able to compare a future Lean concept to the current state, the performance of the actual system with demand must be known.

Key idea was to gain results, which may be used to compare the future state model with. This enables Alfa Laval to evaluate the Lean concept and if implementing a new manufacturing process for C6 is going to pay off.
Table 12 Current Layout Future Demand

<table>
<thead>
<tr>
<th>Future Demand (120,000 with Movex)</th>
<th>Welding Utilization Svets 2000</th>
<th>Lead Time</th>
<th>Total Output</th>
<th>Yearly Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two Shifts</td>
<td>96%</td>
<td>150 h</td>
<td>63,000 items</td>
<td></td>
</tr>
<tr>
<td>Three Shifts</td>
<td>95%</td>
<td>110 h</td>
<td>77,400 items</td>
<td></td>
</tr>
</tbody>
</table>

The Movex data as an input was chosen as it delivers actual cycle times per product and was thus recommended to use by the project team. The production schedule was slightly adapted in two ways: more items were created to ensure that the new demand could be met; the distribution of the welding lines was set to average values (47% - 20.5% - 20.5% - 12%) since this apportionment is the standard aim of the production planner.

The outcome of the simulation provided expected results. The lead time is significantly higher since the model is “fed” with more items due to a higher demand. The cutting operation coped with the increase but the bottleneck welding lead to a pile up of products which consequently spent more time in the process.

The current demand scenario works on three shifts. Due to later comparisons, two and three shifts are evaluated separately in the future demand scenario. Two shifts delivered less output since less actual production time is available. Three shifts delivered slightly more than the current demand scenario. However, this shows that cell C6 runs on high capacity and if an increase in output is needed, it will not help to increase input but the process needs to be altered.

To sum up, the current demand scenario delivered a confident framework for future adjustment and at the same time helped to understand the system. The future demand scenario supplied data that the future model performance may be compared with.

**Fourth Phase: Documentation and Implementation**

Every new version of the model was saved separately, as well as each scenario with different input. The project team was introduced to the software and shown how with little adjustments consequences could be visualized. Progress documentation was done informally to the project leader on a weekly basis. The final results were then documented in this report. The purpose of this simulation was to gain understanding and gather data for future comparison. Thus, no implementation was required.
4.4.3 Future State Modeling

First Phase: discovery and orientation (Identify and formulate problem / Setting of objectives and overall project plan / Model conceptualization)

The problem is the lack of certainty in what the future system is able to deliver. Is it capable of meeting the future demand of 120,000 discs per year and is it thus worth investing in new process, layout, and machines or will the effects be insignificant? The design and simulation of the new process is necessary to answer this question.

Questions that the simulation is supposed to answer: What is the yearly production output regarding two and three shifts? What is the lead time? What distribution is needed between the two flows? What batch sizes are best suited? How much buffer is allowed in between the operations?

As this simulation enables the study of a complex production system and confirms most other points listed in section 3.2 ‘Appliance of Simulation’, it is an appropriate methodology to apply and capable of answering the questions noted above. The system and its category is the same as in the current state model.

Two people will work on the simulation. Due dates of milestones are weeks in year 2013:

1. Gather new input data and changes of current state system  
   week 11
2. Modeling future model  
   week 13
3. Review with Project Team  
   week 13
4. Developing scenarios  
   week 14
5. Simulation and analyzing the results  
   week 15
6. Present Project Team and Steering Committee  
   week 15

The existing and verified current state model served as a framework for the future state model. Thus, the proposed new layout was implemented in the framework. This involved a change of washing machine, replacing three welding lines with one new one, dividing and reuniting the flow, and – for one scenario – replacing the top hole punch with a laser.

Second Phase: model building and data collection (Data collection / Model translation / Verified and Validated?)

Most data could be taken from previous model. The new cycle and change-over times of welding, washing, and laser were provided by the other subproject within the PROMAL-project. As before, all models were created and run in the ExtendSim V8.0 Software.
The input parameters and the logical structure were correctly represented in the ExtendSim. Thus, the model has been verified. Comparing the model against the actual system behavior was not possible. Validation was achieved by ensuring that the framework and overall structure of the previous model was applied and that project team and steering committee agreed with the functionality of the implemented operations and flows.

Third Phase: Model running (Experimental design / Production runs and analysis)

Two different layouts were modeled: one with the top hole punch as last operation and one with a new implemented laser. Each layout is run with two shifts and three shifts for comparison. Each shift setup is run with VSM and Movex data. Reason for this purpose lied in the complexity of the following scenarios. The flow distribution varied from 50/50 to 80/20 (80% of volume through Ny Svets, 20% Svets 2000) in 10% steps. In addition, each of those alternatives was run with different batch sizes varying from 15 items per batch to 30 items. As the order quantity in the VSM setup is equal amongst all orders it is easier to simulate with a scenario manager. Having done this with Movex data would have required hours of manual programming. It was therefore decided to run the overall evaluation of best scenarios with the VSM data and subsequently test the results with Movex data. For better understanding is the evaluation of the result explained in the next step. All possible scenarios were run with the new expected demand of 120,000 per year.

For each scenario and setup the initialization period accounts for one day and the simulation duration for five weeks. In total, 68 scenarios were run with five repetitions each. This amounts to over 290,000 hours of simulation.

Tracked information of all 340 runs included the total production output (winning criteria), the lead time, work-in-progress, machine utilization of the welding and metal spinning machines, and the scheduled downtime. Illustration 27 gives insight into the analysis stages. After all 64 scenarios were run with VSM data for two and three shifts, for the Top Hole Punch and Laser Layout and for variation in flow distribution and batch sizes, the results were exported to Excel for analysis purposes. Winning criteria of tracked information was the production volume as
the problem statement concerned the capacity of the system. The best results for two and three shifts for each layout were highlighted. The winning scenarios with their setup (flow distribution and batch size) were then run again but with Movex data for validation purposes. Consequently, the Movex results were analyzed.

Figure 27 Analysis Stages of Future State

The two tables below show the four best results from the VSM volume selection. For all of them were the best results based on a 70/30 distribution and 30 items per batch. The lead time and the yearly output delivered better results with three shifts than two shifts as could have been expected. The increase in lead time from Laser to Top Hole Punch layout was also logical as two operations are performed by the one pressing machine in the Top Hole Punch layout. Thus, waiting time in front of it was longer and consequently fewer items pass through the model.

Table 13 VSM Volume Selection

<table>
<thead>
<tr>
<th>VSM Data Two Shifts</th>
<th>Distribution of Flows</th>
<th>Batch Sizes</th>
<th>Lead Time</th>
<th>Total Yearly Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser Data</td>
<td>70 / 30</td>
<td>30 items</td>
<td>44 h</td>
<td>90,300 items</td>
</tr>
<tr>
<td>Top Hole P. Data</td>
<td>70 / 30</td>
<td>30 items</td>
<td>61 h</td>
<td>85,000 items</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>VSM Data Three Shifts</th>
<th>Distribution of Flows</th>
<th>Batch Sizes</th>
<th>Lead Time</th>
<th>Total Yearly Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser Data</td>
<td>70 / 30</td>
<td>30 items</td>
<td>39 h</td>
<td>119,600 items</td>
</tr>
<tr>
<td>Top Hole P. Data</td>
<td>70 / 30</td>
<td>30 items</td>
<td>48 h</td>
<td>111,000 items</td>
</tr>
</tbody>
</table>

As a result, these setups were applied again but with Movex input. Table 14 shows the results of the simulated future state scenarios for a 2 shift yearly work pattern. Both Laser and Top Hole scenarios were evaluated with the same input parameters. The total expected yearly demand of bowl discs was 120,000 units. The Welding utilization differential between Laser and Top Hole in Svets 2000 exists as a result of the new technical capacities of the Laser equipment. A Laser option would save 40 seconds per processed bowl disc in Svets 2000. Hence, Svets 2000 in the Laser alternative has more available time.
Because of the product distribution funneled through the Ny Svets welding station, and because of no variation in the cycle times or process for this station in either alternative there is an equivalent utilization of 95% for both scenarios for the new welding station. The large proportion of bowl discs processed in the new welding station sets the pace for product lead time. The faster welding process in Svets 200 for the Laser option bares no significance on product lead time with the final parameters of the simulation. The total amount of items produced through both alternatives in a 2 shift work schedule is roughly 92,000.

The table 15 shows the same figures as table 14 in the utilization columns and can be explained in the same way. The lead time however is approximately 16 hours shorter than in the two shift simulation. As more production time is available it makes sense that items pass through the process quicker. Consequently, the output is higher too and matches the demand with 120,000 items per year.

**Table 14 Two Shifts Future Demand Movex**

<table>
<thead>
<tr>
<th></th>
<th>Two Shifts Future Demand Movex</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Future Demand</strong></td>
<td>(120,000 units)</td>
</tr>
<tr>
<td><strong>Two Shifts</strong></td>
<td></td>
</tr>
<tr>
<td>Laser Data</td>
<td></td>
</tr>
<tr>
<td>Welding Utilization</td>
<td>Svets 2000</td>
</tr>
<tr>
<td>Ny Svets</td>
<td></td>
</tr>
<tr>
<td>Lead Time</td>
<td>57 h</td>
</tr>
<tr>
<td>Total Yearly Output</td>
<td>91,600 items</td>
</tr>
<tr>
<td>Top Hole Data</td>
<td></td>
</tr>
<tr>
<td>Welding Utilization</td>
<td>95%</td>
</tr>
<tr>
<td>Ny Svets</td>
<td></td>
</tr>
<tr>
<td>Lead Time</td>
<td>57 h</td>
</tr>
<tr>
<td>Total Yearly Output</td>
<td>92,700 items</td>
</tr>
</tbody>
</table>

**Table 15 Three Shifts Future Demand Movex**

<table>
<thead>
<tr>
<th></th>
<th>Three Shifts Future Demand Movex</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Future Demand</strong></td>
<td>(120,000 units)</td>
</tr>
<tr>
<td><strong>Three Shifts</strong></td>
<td></td>
</tr>
<tr>
<td>Laser Shifts</td>
<td></td>
</tr>
<tr>
<td>Welding Utilization</td>
<td>Svets 2000</td>
</tr>
<tr>
<td>Ny Svets</td>
<td></td>
</tr>
<tr>
<td>Lead Time</td>
<td>41 h</td>
</tr>
<tr>
<td>Total Yearly Output</td>
<td>120,600 items</td>
</tr>
<tr>
<td>Top Hole Shifts</td>
<td></td>
</tr>
<tr>
<td>Welding Utilization</td>
<td>94%</td>
</tr>
<tr>
<td>Ny Svets</td>
<td></td>
</tr>
<tr>
<td>Lead Time</td>
<td>40 h</td>
</tr>
<tr>
<td>Total Yearly Output</td>
<td>119,700 items</td>
</tr>
</tbody>
</table>

**Fourth Phase: Documentation and Implementation**

Every new version of the model was saved separately, as well as each scenario with different input. The project team was introduced to the software and shown how with little adjustments consequences could be visualized. Progress documentation was done informally to the project leader on a weekly basis and formally to the project team as presented in the milestones schedule. The final results were then documented in this report and presented to the steering committee. The information that was gained from this report will help to make decisions for changes in the current process. The actual implementation will take until 2014 and is not within the scope of the thesis.
5. ANALYSIS

Case study results through DES simulation are presented, and interpreted. Functional aspects as to why such results were obtained are elaborated. Empirical results are then linked to the research questions proposed at the beginning of this thesis. Simulated data as well as literature is used to support the authors’ findings.

5.1 Comparison of Results

Assessment of future state model required its comparing to the current state. A fixed number of inputs were selected to run all models on equal basis: production schedule, quantity of items in the schedule, and shifts; production parameters such as off duty percentage, machine utilization, finished products, and lead time were tracked for the purpose of the model’s evaluating general production. Tracking data for each model was equivalent for all simulation models. The results of the analysis are presented in tables 16 and 17.

Table 16 Overall Comparison Two Shifts

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Lot Size</th>
<th>Lead Time</th>
<th>Utilization Svets 2000</th>
<th>Utilization Ny Svets</th>
<th>Off Shift</th>
<th>Yearly Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser</td>
<td>30</td>
<td>57 hrs</td>
<td>71%</td>
<td>95%</td>
<td>49%</td>
<td>91,600</td>
</tr>
<tr>
<td>Top Hole</td>
<td>30</td>
<td>57 hrs</td>
<td>78%</td>
<td>95%</td>
<td>49%</td>
<td>92,700</td>
</tr>
<tr>
<td>Current State</td>
<td>Order</td>
<td>150 hrs</td>
<td>96%</td>
<td></td>
<td>52%</td>
<td>63,000</td>
</tr>
</tbody>
</table>

Table 17 Overall Comparison Three Shifts

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Lot Size</th>
<th>Lead Time</th>
<th>Utilization Svets 2000</th>
<th>Utilization Ny Svets</th>
<th>Off Shift</th>
<th>Yearly Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser</td>
<td>30</td>
<td>41 hrs</td>
<td>71%</td>
<td>95%</td>
<td>33%</td>
<td>120,600</td>
</tr>
<tr>
<td>Top Hole</td>
<td>25</td>
<td>40 hrs</td>
<td>78%</td>
<td>94%</td>
<td>33%</td>
<td>119,700</td>
</tr>
<tr>
<td>Current State</td>
<td>Order</td>
<td>110 hrs</td>
<td>95%</td>
<td></td>
<td>33%</td>
<td>77,400</td>
</tr>
</tbody>
</table>

Results for two and three shift simulation alternatives are presented separately. The number of production shifts was considered from the start of the project as a variable were one or another option would be selected. Hence, tables 16 and 17 should be viewed as an evaluation of the same parameter, namely production shift. In addition to this, these tables present not only the total amount of finished
good products, but also the simulation variables that led to the corresponding finished bowl discs produced in a year.

Total expected volume of 120,000 bowl discs was met through the use of alternative Lean scenarios. Results showed no major difference in the number of bowl discs produced between Laser and Top Hole alternatives. Hence factors other than number of finished good products ought to be considered a decision factor for Alfa Laval’s selecting between Lean proposals of Top Hole or Laser.

The yearly expected volume of 120,000 units was not possible to achieve under the current production state that resulted in a simulated total of 77,400 bowl discs per year. Alfa Laval’s historical production data of 2012 recorded a yearly production of 75,000 bowl discs.

The slight increase of 2,000 units is a result of a larger quantity of items to be processed by Cell C6. The current production process having a longer list of items scheduled for production is over worked and machines are never left idle. This situation is supported by the high percentage of machine utilization in welding station Svets 2000 for two and three shift variables, 96% and 95% of machine utilization correspondingly, show in tables 16 and 17.

The increase in production volume as a result of a longer list of items enumerated for production is not to be considered an improvement. Work in progress quantity would increase as a result of production schedule. This situation is further supported by simulation results in the current state models were the following increase in WIP is observed prior to the Svet2000 welding station as show in figures 28 and 29. Svets2000 was tracked for this parameter since the welding stage is the operational bottleneck and the largest proportion of welded material passed through this welding station.

![Figure 28 WIP Increase in 2 Shift Current State Model](image-url)
A result of lower levels of Work in Progress is the reduction of production lead time. An item waiting in stock waits for a shorter period of time when there are fewer items ahead of it. New layouts, both Laser and Top Hole options, reduced lead time by more than half the number of hours when compared to the current state model. A similar proportion in lead time reduction was observed when comparing two-shift Lean options to current production setting to three-shift Lean options to current production settings. The lead time proportion ratio was expected to remain the same as no other variables affecting the simulation of two and three shifts is available (i.e. machine failures, line disturbances, etc.). There is however a difference in lead time when different shifts come in to play. Lead time of three shift options was less than that of two-shift options in all simulated scenarios. This reduction is a result of a larger amount of production available time. Shift starts and stops were an operational factor in terms of production flow.

In terms of product flow, the welding process remained the production bottleneck for both Laser and Top Hole alternatives. As a result of a new and improved flow in the alternative scenarios and a different distribution of processed items through the welding stations, Ny Svets welding station was kept idle for 5% of the time. The low percentage of idle time is directly related to the distribution of items that flow through the Ny Svets welding station.

Machine utilization at the welding station operation is directly related to the proportion of items that pass through either Ny Svets or Svets 2000 welding station tables 16 and 17 show machine utilization as a function of bowl disc distribution in the welding stations. It is worth mentioning that distribution of bowl disc welding is not related to product characteristics or client specifications. Distribution of bowl discs at the welding station is related to machine cycle time and total finished product quantity. Svets 2000 welding station had to wait for material lots to process in both Laser and Top Hole layouts.

Finally simulation results confirm that shift quantity was an important operational variable that impacts on the finished good yearly goal. Although both Top Hole and Laser options provided a benefit when compared to the current state it is only through a three-shift work schedule that volume expectations are met.
5.2 Research Questions

5.2.1 What elements are required for DES to work as a tool to analyze different Lean proposals?

Simulation in general, and DES in particular, was not conceived as a Lean specific tool. Characteristics inherent to simulation make its use desirable to pursue a Lean state in the field of manufacturing. Despite its many benefits the amount of information that DES models provide to decision makers may be overwhelming. There is a need to identify the elements required for DES to work as a Lean assessment tool both prior and subsequent to the planning, conceiving, designing, or modeling of simulated states.

Lean implementation at Alfa Laval exemplifies the introductory stages of DES as a Lean evaluating tool. Lean as a concept and methodology had to be introduced to Project Group members involved in the development of solutions for Cell C6 project. Organizational values were a prerequisite to understand, talk, and think in Lean terms. Once the inner workings of Lean methodology were in effect, waste detection and measurement was necessary for process improvement. Process owners, operators, and managers identified waste and thought of solutions that would reduce non value adding operations. Finally, once DES models are finalized their results must be verified and validated.

*Lean in Organization first*

Many of the benefits of Lean manufacturing cannot be quantified with simulation modeling. As mentioned in the Theory chapter of this report, researchers are quick to point out the need for an organizational perspective in the application of Lean principles.

Authors such as Anvari and Roos have pointed out the importance that implementation of principles takes upon the nature of the obtained results as approaches often starting and ending with misguided efforts initiated by “companies that use only the toolbox without embracing the underlying philosophy [and] are unlikely to gain more than limited and temporary results (Seddon & Caulkin, 2007).”
Development of Lean initiatives at Cell C6 in Alfa Laval is in support of the need for an organizational deployment that substantiates specific company needs. Figure 30 shows the Lean road travelled by Cell C6 Project Group participants that led to the use of DES as a tool for Lean assessment. DES was not the beginning of the Lean assessment journey but a tool that substantiated knowledge acquired through the Lean production improvement process.

As depicted in Figure 30 Alfa Laval first presented its Lean initiative through the ALPS methodology. A Lean production improvement strategy was launched upon Alfa Laval’s realizing a need for improvement in bowl disc production. The current state process was assessed through VSM analysis, and based on the results of such analysis resources were approved for project deployment. A Project Group was conformed and its members trained. Based on Lean training members ideated Lean solutions and gauged proposal characteristics upon which to judge the effectiveness of Lean proposals. Lastly a simulation initiative was deployed to evaluate the effectiveness of Lean proposals.

Diversity in Project Group participant background tells of the holistic approach Alfa Laval undertook to implement an organizational approach to Lean. Simulation was only deployed once the process was understood, analyzed, and evaluated by Project Group participants. The validation process of current state models evidenced the organizational importance that Lean plays in steps prior to any future state simulation. Because Lean existed as an organization framework prior to the conception of a model, Project Group and Steering Committee members evaluated the validity of simulated models.

In other words, DES models were not used to support the idea of Lean but to evaluate characteristics with which Alfa Laval employees were already familiar with. The success of any particular management strategy normally depends upon organizational characteristics, which implies that all organizations should not or cannot implement a similar set of strategies in their particular case as pointed out by Shah and Ward (2003) in the Theory chapter.
To this effect field data gathered and analyzed by Alfa Laval throughout the duration of the project is indicative of the importance of the identification of Lean concepts when evaluating a problem and suggesting a solution. Data variety and tools with which Project Group participants evaluated the current state prior to simulation demonstrates understanding of Lean concepts as portrayed in Figure 31.

Simulation parameters did not win face over Project Group or Steering Committee members because of the manner in that information was presented, gathered, or forecasted in a model. Simulation parameters were tailor made to Alfa Laval’s specifications based on the needs and requirements that employees thought of as critical for the process. Figure 31 represents the correlation between tools and Lean criteria that members of Cell C6 Project Group based the simulation parameters from. Simulation in itself did not provide a list of parameters to identify or improve the value adding process.

Alfa Laval’s approach to Lean implementation was parallel to that suggested by Karim in such a way that process, resources, and outputs were taken into account for Lean implementation of the Cell C6 Project.

Identifying Waste

Researchers suggest that one of the closest links that exist between DES and Lean is waste identification. The manner in that DES and Lean complement each other from a theoretical perspective can be investigated by considering how the key assumptions of DES fit the three key concepts of Lean: Muda, Mura and Muri. The need to model variability is a key assumption of DES since this is a major source of process inefficiency. As reviewed earlier, Mura argues that unevenness in demand (which is a key source of process variability) leads to process inefficiency (Robinson, Radnor, Burgess, & Worthington, 2012).

This report identifies waste classification as a necessary condition for DES to work as a Lean assessment tool. DES simulation is a flexible tool in the range and depth of information it can provide. However, the amount of data is often overwhelming. Development of the present case study suggests that a necessary requirement for DES as a Lean assessment tool is the need for decision makers to have a clear idea of the type of information they wish to extract from a model prior to its construction. Although the use of traditional tools such as VSM is not
necessary for DES model parameterization, waste identification is facilitated by such tools.

![Diagram of waste and related factors](image)

**Figure 32 Process variability and waste**

Figure 32 shows production affecting elements used for DES assessing variability in production. This case study provides evidence of the importance that variability holds in terms of waste reduction and waste quantification through DES as was evidenced by production system behavior with and without the inclusion of data affecting production. The effects of different cycle times, change overs, machine break downs, and shift changes were impossible to judge through paper and pencil tools, as were any increase or reduction in these variables.

<table>
<thead>
<tr>
<th>Table 18 Significance of model variability inclusion</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Model Type</strong></td>
</tr>
<tr>
<td>Process Variability</td>
</tr>
<tr>
<td>No Process Variability</td>
</tr>
</tbody>
</table>

The importance of process variability was best observed when running a current state model with and without parameters that affect bowl disc production. Table 18 shows the described effect. Current state model that includes process variability factor have a 1.5% difference in regard to yearly production volume. Models that do not include process variability over produce yearly production volume and have an error margin of 8% in regard to yearly production volume.

The percentage of error that exists between a model and its validation objective is of course subject to the requirements of each project. Process owners ought to identify how much is good enough. Regardless of this, the proportion of error impacts on the finesse with which a simulated model may provide a solution for; in the present caste, waste reduction as a result of process variability.

DES provides the means with which to measure waste reduction. ExtendSim in particular possess a wide array of functions that permit a tight control over any modification of parameters. Regardless of the many systems to track information with any decision that affects evaluation variables, such as waste in any of its forms, is based on functional principles of Lean and process experience.
Validation

Validation is often considered from the perspective of a simulation model whose results must comply with real life behavior. In such cases it is the real system or any of its parameters that grants validity to the model. According to Standridge & Marvel (2005) the future state must be validated before it is implemented to minimize or eliminate the period of trial and error adjustments.

When DES is used as a tool to analyze different future Lean proposals a different approach is needed. The validity of the outcome of a system depends on what is included in the system description. Therefore, it is important to construct a conceptual model so that the model may be verified prior to investing resources in the development of a computer model. A “valid” model can be used to make decisions similar to those that would be made if it were feasible and cost-effective to experiment with the system itself (Law, 2005). An invalid model may lead to erroneous conclusions and decisions (Manuj, Metzer, & Bowers, 2009).

Literature on the subject of validation for DES models indicates that models require validation to demonstrate fidelity of results to real life circumstances. Reality validates the outcome of a simulated model. Literature also suggests the possibility of simulated models’ validating future state Lean proposals. There exists a double validation path from current states to simulated models and from simulated models to Lean proposals.

![Figure 33 Validation process of DES models at Alfa Laval](image)

Figure 33 reflects the validation process at Alfa Laval’s Cell C6 Project and compares the validation of the current state model (left hand side) to that of the future state model (right hand side). Validation of current and future states pursued different objectives, confirmation of model process and frame work for Lean assessment respectively. Notwithstanding the validation’s end goal the process paralleled the objectives supported by Marvel & Standridge (2009) that of simulation’s providing quantitative validation evidence that system requirements an objectives will be met by the first system transformation.

In the current state process models (left hand side of figure 33) the process was mapped, measured, and its logic described. Based on VSM analysis, Project Group member experience, historical data, and field observations a DES model was built. The output of the simulated model was then validated with real life
production data. The DES current model served as a frame work for the future state simulation.

In the future state models (right hand side of figure 3) future state Lean proposals were built based on a validated current state model. Lean proposals were classified based on the output of the simulated future state DES models. Future state outputs served in the assessment of Lean proposals and validation of future Lean proposal results.

Validation is an important element to include in DES for the analysis of Lean proposals because evidence is obtained if the simulation demonstrates that the system operation corresponds to its design as reviewed in the Theory section of this report. This evidence includes comparing both detailed system behavior and performance measure values to those stated in the design (Grimard & Marvel, 2005). Through this evidence it is possible to make an educated guess on the outcome of implementation of Lean proposals.

Validation is a unique characteristic of DES as a tool of Lean analysis and very different from any other quality provided by Lean assessment tools such as VSM charts. Since a VSM is a descriptive model, there is no mechanism for analyzing it to see if the specifications it contains will produce the desired system behavior or achieve performance targets (Standridge & Marvel, 2005). DES validation enables decision makers the possibility of foretelling or evaluating a decision before the final word has been said.

5.2.2 How do a dynamic tool such as DES and a static tool such as VSM complement each other?

The statement that both tools gain something from the use of the other one was an assumption based on prior knowledge and due to literature suggestion. This part divides the results obtained from the simulation into how the DES benefits from the VSM and vice versa.

**DES from VSM**

The key necessity for modeling in DES is possessing an understanding of the process. Without knowing which activities are preceding or successive, it is impossible to even model the simplest version of the process. The VSM visualizes for the first time the value stream and thus the product flow. This is of great assistance when taking the first steps in simulation. Alfa Laval’s organizational records were used for VSM data acquisition. The authors of this study did not perform a VSM analysis of their own as this information was already available. This available information made it easy to create a first simple simulation draft for comprehensive purposes.

The second issue for modeling is data that feed the simulation. Input data provide the driving force for a Discrete Event Simulation model. Collecting data from the real system of interest often requires a substantial time and resource commitment. Alfa Laval’s C6 Cell bowl disc production is a customized manufacturing process. Over 500 different items are produced in a year and most of these items have
The simulation of such vast universe of items required not only registering the information to feed the system, but also managing the interrelation between items to be produced within a schedule.

Manually labeling all items with ERP data and tagging them to take a unique flow through the model was inconvenient in terms of the simulation performance: the system’s manual feed was time consuming, and the quantity of data the model processed increased its execution time. Execution time was a critical factor as all possible scenarios required several runs to account for data validity.

Had all possible scenarios been evaluated with real life production data then the project would have exceed its time frame. For the purpose of the models’ gaining validity while doing so within the project’s time frame a compromise was made. Initially, all scenarios and models would first make use simpler and more even VSM data as input data to feed the model.

VSM data gathered by Alfa Laval delivered information on average order quantity, cycle and change-over times. VSM data served the purpose of its providing a quick, even, and pre-approved set of data upon which to develop a model were process and logic of the system was prioritized over production order complexity.

Table 19 shows VSM data according to the production process. The complete table with VSM values may be found in Appendix C. VSM data represents a standard order size composed of the average of quantities and production parameters of bowl discs produced in Cell C6. A capture from the creation block in ExtendSim shows how the information from the VSM has been translated into the model (figure 34).

<table>
<thead>
<tr>
<th>Bowl Discs / Order</th>
<th>Cutting</th>
<th>Manual TVA</th>
<th>Top hole Punch</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cycle Time</td>
<td>Change Over Time</td>
<td>Cycle Time</td>
</tr>
<tr>
<td>VSM Data</td>
<td>170 items</td>
<td>0.002</td>
<td>0.017</td>
</tr>
</tbody>
</table>

Table 19 VSM data used for current state model

As VSM data was uniform, the complexity of the model was held to a minimum, especially in regards to the distribution on the welding lines. Products are distributed to different welding stations based on their physical characteristics,
functionality, and machine availability. A randomized probability distribution was selected to direct the bowl disc welding station on the VSM models. This randomized probability distribution was calculated and approved by Alfa Laval’s Lean Six Sigma department. As all items in the VSM production schedule were “standard products” their physical characteristics and functionality were ignored. If ERP data had been used instead, each item would have to been tagged manually to secure the correct distribution. As one key need of Alfa Laval was to establish the correct distribution, each setup (50/50, 60/40, 70/30, 80/20) would had to be done in each scenario and once again had exceeded the time frame.

One reason often mentioned in the literature is that simulation is time consuming in contrast to a VSM creation (McDonald, Van Aken, & Rentes, 2002). Although for most parts this might be true, it is overlooked that the VSM can be seen as a presudy for the DES. All the basic data is made available and a comprehensive product flow is provided. This shortens the lengthy and time-consuming process of model conceptualization and data collection. Without the existence of the VSM information at Alfa Laval, the authors assume that gathering this information and grasping the flow would have taken at least two weeks more before being able to start simulating.

Moreover, DES in itself cannot provide a list of parameters from which to select waste occurring activities or processes. Waste identification for bowl disc production required Alfa Laval’s Project Group narrowing down from a list of possibilities a manageable number of parameters to keep track of. Parameter identification in relation to waste was closely paired with VSM analysis and Lean concepts of Waste.

A close relationship between Waste, VSM, and simulation parameters existed in the development of this project. Such relationship may be observed in Table 19. The concept of waste was first introduced to the Project Group. On a second instance VSM analysis was presented and areas of opportunity were observed as a result of the analysis. Once the general concept of the problem evolved was there a clear understanding of what parameters were the most meaningful to track production improvement and waste reduction.

<table>
<thead>
<tr>
<th>Waste Type</th>
<th>VSM Parameter</th>
<th>Simulation Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inventory</td>
<td>Finished Goods Inventory</td>
<td>Total volume</td>
</tr>
<tr>
<td>Overproduction</td>
<td>Uptime</td>
<td>Off Duty %</td>
</tr>
<tr>
<td>Delay</td>
<td>Production Lead Time</td>
<td>Lead Time</td>
</tr>
<tr>
<td>Over processing</td>
<td>Uptime</td>
<td>Machine Utilization</td>
</tr>
<tr>
<td>Inventory</td>
<td>Buffer or Safety Stock</td>
<td>Work in Progress</td>
</tr>
</tbody>
</table>

VSM from DES

Even though VSM provides a first visual aid in comprehending a process, it is still in an abstract form. No items are moving, no stock is varying, and no figures are
changing over time. On the other hand, the DES software has a graphical interface that allows the user to see the system operating on the screen, almost like watching a movie (Brailsford, Desai, & Vianna, 2010). The visualization of the welding C-Line of the bowl disc process is used as an example to comprehend the differences between VSM and DES (figure 35). The VSM box on the left is filled with the “hard facts”, such as cycle time, change over, and work in progress. The capture from the simulation on the right demonstrates the visual dynamic of the tool. The queue alters over time, the information of current product number and order size in the process is for direct reading, the shutdown block indicates whether there is maintenance in process, and the item changes color after the welding line to realize track ability throughout the following process.

Moreover, the DES provides extra information on the WIP on every machine, or any other information that would like to be observed. The VSM delivers this data either by average or taken at a specific point in time, which allows no or little inference on the overall behaviour, such as occurring bottlenecks. The DES on the other hand allows tracking statistics and displaying them over time. This assists in identifying peaks and idle times, which again contributes to evaluate the root causes of the occurrences. Displayed here on the right are the queue statistics of the Svets 2000 welding line in the current state. If a VSM was to be performed at the end of a simulation run, the WIP would state 46 items. However, the DES statistics show an average of 158 items and a peak of 484 items after about one week of simulation time. This information might be vital for decision making and is lost when only relying on VSM figures.

Figure 35 Difference of Visualization between VSM and DES

Figure 36 Queue Statistics
It becomes clear that the DES provides more detailed information to the initial VSM information. One might argue that it is not the VSM’s main purpose to display WIP, however the same is valid for a core part of the VSM: the lead time. As seen in table 6, the lead time of the current state process was calculated to be 35.5 hours, which was achieved by simply adding the average calculated cycle times of every machine in the process. When running the simulation a lead time of over 80 hours evolved. The VSM option does not account time spend in queues, which was an important aspect when bottlenecks are taken into consideration. Moreover, the process runs five days per week but not on the weekend. This means that every week some of the items spend over 48 hours in the production without being processed. That time was also not considered in the VSM.

As much as the DES benefits from the simplicity of the VSM information, the VSM is complemented by the complexity of the data that the DES can provide. As mentioned in the theoretical part, most production lines have a wide variety of product families, different processing and change-over times, elaborate shift and personnel interrelations, as well as intricate product flows. (Abdulmalek, 2007). The figure 37 illustrates how the complexity of data varies. The top information show once again the create block and how four different products belong to different order with different quantities and thus have different cycle and change-over times in the C-Line, all taken from Alfa Laval’s ERP system. Below that capture is the information of the VSM which proposes a range of data (cycle time), an average (change-over), and a current observation (WIP). Depending on how complex information is needed, the DES can support the VSM.

5.2.3 What sort of information can DES provide to the analysis of different Lean proposals?

DES is advantageous in that the methodology provides customized information for concrete circumstances. For organizations considering implementing Lean manufacturing, DES has the significant advantage of reflecting site specific circumstances, as well as comparing the performance of the Lean system with the present operation (Detty & Yingling, 2000). This report identifies three areas where DES may help in the analysis of Lean proposals. These areas are divided into characteristics inherent to DES, representation of future states, and those associated to the use of software models.

Variability and randomness are intrinsic qualities of DES models. The inclusion of these distinguishing traits into Lean evaluation methodology is only desirable, and the information that variability and randomness provide to proposal assessment is advantageous. Simulation provides a method for including random and structural variations in models, identifying at least a very good solution to
production system issues before implementation by examining a variety of alternatives, and assessing the effects of the interaction of system components (Standridge & Marvel, 2005).

In the present case study production affecting events were included to comply with real life circumstances such as machine breakdowns, batch size differences, and change overs. Additionally, production variables that would maximize bowl disc output were evaluated. The approach taken by Alfa Laval was that of evaluating productive waste through WIP and production Lead Time. A relation between production affecting elements and production variables was established.

Although other methods could have been used to establish the abovementioned relationship, DES provided a tool that could sweep through a range of possible outcomes while at the same time adding variation to the process. This effect is observed in Figure 38 were a fixed amount of items were produced when production variables were stationary and yet variability of production affecting elements was included. DES is capable of not only measuring the effects of such variation but also changing the proportion of variation on the fly and with relative ease.

Understanding of the interrelation between elements within the production system is easily accessible through DES as a result of its event based nature. As DES is not a continuous simulation method were elements are a function of time, but a method were simulation only occurs when events are triggered then actions occur on a cause and effect procedure. Causality in simulation provides Lean assessment a tool to reason which elements and under what circumstances do Lean affecting parameters such as overproduction burden the manufacturing operation.

Robinson (2012) provides further insight by his stating that DES during a Lean event provides a means for debating alternative views and providing an evidence base for reaching an accommodation of ideas. In particular, simulation brings to life lessons about process flow and helps to be a ‘myth buster’ regarding the beliefs held regarding the system. This is best exemplified in the presented case study by Alfa Laval’s open range of Lot Size quantity that would provide the best few-piece-flow solution without strangling the manufacturing process downstream.

One of DES’s strongest assets as a Lean assessment tool is its ability to represent future state models. A desirable characteristic when shortcomings of traditional Lean tools are considered. As pointed out by Strandridge (2005) Lean is a necessary but not a sufficient approach to analyzing production system issues. Deficiencies in the Lean approach arise because it is a deterministic method and it uses only descriptive VSM to model production operations.
In its capacity to represent future states, DES provides the basis for comparison between current practices and future improvements. The information that management can gather by applying simulations enables a comparative analysis of the current and future state of the system, with all performances significant for making decisions concerning whether the system satisfies the initiation of changes; and database as such, represents a significant foundation before Lean philosophy is implemented (Bozickovic, Radosevic, Cosic, & Sokivc, 2012). As DES models future state scenarios the simulation of such scenarios aids in establishing specific parameters of a system, and in doing so decision makers may quantify the impact of system improvements (Detty & Yingling, 2000).

The authors of this thesis report identify 5 characteristics of information provided by DES future state model as exemplified by the reviewed case study. Characteristics of future state information are presented in Figure 39. Information is described as follows:

- **Relevant** – Information is relevant to the problem at hand, and was custom fitted to the problem statement. DES as a tool of Lean assessment enables users of the method to fit measurements and parameters to case specific circumstances that may fall outside traditional systems of Lean measurement.

- **Complete** – Information was sampled evenly for all parameters of evaluation and for all scenarios. A very complete database of Lean assessment parameters was created. Historical information may be retrieved, manipulated, and compared to data from other simulated models, or to different cases altogether.

- **Accurate** – Accuracy of output data from DES models is subject to the validity and verification of the model itself. The current case study was verified by Alfa Laval’s Project Group and Steering Committee. Furthermore all data used for analysis underwent Chi-Square tests to grant statistical validity.

- **Current** – A characteristic of software simulation parameters is the quickness with which parameters are modified once the logic of the process is established. That a system is responsive does not necessarily mean that this trait is made us of, yet such a possibility is desirable and encouraged when the evaluation of Lean initiatives is at stake.

- **Factual** – Information is succinct and gives answer to specific questions once parameters are established. No explanation or analysis is required to interpret output data from the system in cases such as: What is the lead time of products in
Cell C6? How many items are been held along the production process as WIP? Etc.

That DES is a simulation method constructed upon the use of software purports models with the possibility of variation within the same system provided that a range of values is available. Figure 40 shows the use of factorial analysis evaluation in the future state models of Alfa Laval’s case study.

Figure 40 Software characteristics provide information for Lean assessment

Factorial analysis within a simulated model runs through a series of variations within one or more simulated parameters. All possibilities are evaluated under the same circumstances. Information is registered after simulation. Information can then be stored, analysed, and evaluated upon Lean parameters. This method of parameter evaluation enables calculation of a number of possibilities within the execution of a single model.
6. DISCUSSION AND CONCLUSIONS

In this chapter the authors subjectively discuss the findings and draw conclusions. Part two focuses on the overall thesis aim and research questions, whereas the first part suggests measures to Alfa Laval regarding its Lean proposals.

6.1 Case Study Related Recommendations

Aim of Alfa Laval’s latest PROMAL project was to increase production capacity for bowl discs in Cell C6. A Lean proposal was developed to cope with this challenge. The proposed solutions entailed a complex flow with a very diverse product mix, cycle and change over time modifications, new batch sizes, and newly introduced processes. In addition, parameters that steer the flow and affect the output performance were unknown. Therefore, DES was introduced to model the current state, the future state with the Lean proposal, and to determine which parameters deliver the best results.

After running over 300,000 hours of simulation in different models and through different scenarios, the results shown in section 5.1 were obtained. Based on these results the authors draw the following conclusion:

- With the current flow and production layout, Alfa Laval is unable to meet the desired future demand of 120,000 – regardless of number of shifts
- Attempts to run the future demand in the current layout will result in a lead time of 110 to 150 hours
- When implementing the new process, the variances of performance between Laser and Punch layout is insignificant – this goes for yearly volume as well as for lead time, set-ups, and utilizations of machines
- Best results in future layout were achieved with following parameters:

<table>
<thead>
<tr>
<th>Table 21 Ideal Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Lot Size</strong></td>
</tr>
<tr>
<td><strong>Flow Distribution</strong></td>
</tr>
<tr>
<td><strong>Shifts</strong></td>
</tr>
<tr>
<td><strong>Max. WIP</strong></td>
</tr>
</tbody>
</table>

- Three shifts will achieve the desired 120,000 bowl discs per year in the new proposed Lean layout – two shifts will not
- Lead time is cut to 57 hours on two shifts, respectively to 41 hours on three shifts
- Welding stations are utilized to their full capacity and are yet the process bottlenecks

Consequently, recommendations were made to the PROMAL project group and the Production Development Steering Committee. The results as well as the following recommendations are wholly based on given data provided by the VSM and/or the ERP system. Cycle times of new machines were supplied by SKPU members and can be seen as expectations more than actual future performance...
rates. In addition, corrective and preventive maintenance for new machines were not considered. The performance differences of Laser and Punch Press were based on cycle times and change over only; possible quality impacts were disregarded. Considering these limitations, the authors propose to

- Start implementing new proposed flow and layout,
- Refrain from investing in Laser, keep deploying the Punch press instead,
- Apply parameters as stated in table 21 with the exception of ‘Shifts’,
- Start with two shifts as this will result in an 20% increase of production,
- And switch to three shifts once the actual demand of 120,000 is conceivable.

In conclusion, the DES assisted in its evaluating the Lean proposals by Alfa Laval. The current production system was translated into a simulation model and its performance for future demand was recorded. Based on Lean proposals the future state was built and desired parameters were combined and tested for best outcome. The best scenarios were analyzed and hence recommendations could be made.

**6.2 Research Findings**

The aim of this thesis has been achieved by proposing DES as a tool to evaluate Lean manufacturing proposals through a production perspective. A group of elements were identified in the evaluation of future state Lean proposal implementation when using DES (research question 1). In addition to this a qualitative comparison between Value Stream Mapping, a traditional tool for Lean production assessment, and DES was made (research question 2). Finally a qualitative analysis was performed in regards to how DES can assist in analyzing different Lean proposals (research question 3).

*What elements are required for DES to work as a tool to analyze different Lean proposals?*

DES was not designed and does not function as a Lean specific tool. The use of DES in Lean assessment applications requires the organization to understand the principles of Lean and its desired effects. Therefore, DES’s first requirement to works as a tool for Lean analysis is understanding the principles of Lean philosophy, so that users pair the general concepts of Lean to the tool’s capacities. Within the concepts of Lean waste identification is perhaps the most important one when pinpointing to a Lean principle when DES is used as a tool of evaluation. Note must be taken that the assessment of future Lean proposals to DES is closely followed by validation of information. Developing a simulation model is a first step towards Lean implementation, simulation helps direct expected results of factory settings once machines and production processes are modified.
How do a dynamic tool such as DES and a static tool such as VSM complement each other?

The static VSM and the dynamic DES complement each other in a variety of ways. Visually the VSM gives a good first look on how the system works and the products flow. This provides an excellent foundation to build the first steps of a DES model. On the other side, the DES software has a graphical interface that allows the user to see the system operating on the screen. This is especially beneficial in visualizing changes in future layouts and product flows.

Secondly, the two tools complement one another by collecting and providing data. When building a VSM cycle times, change overs, and stocks are amounted, which can once again set the basis for DES. Once this information need detailed depth and portray changes over time, DES statistics take over. Lean related waste identification work in a similar fashion. DES can track any information desirable but if all are tracked, the amount of data becomes overwhelming and difficult to analyze. The simplicity of the VSM allows highlighting the key waste issues that need to be looked at. Once these parameters have been established, they are implemented and tracked in the DES model.

In conclusion, literature as well as the empirical findings suggests that a static tool, VSM, and a dynamic tool, DES, complement each other. The simplicity of a VSM identifies the key critical issues and at the same time sets the data basis for modeling in DES. The simulation then delivers in-depth performance data over time and functions as an add-on to the VSM.

What sort of information can DES provide to the analysis of different Lean proposals?

Although many other simulation methods exist, DES provides a unique condition to account for process variability and randomness. Since variability and randomness occur in everyday production processes representation of such events is desirable. Both measurement of and reduction in variability through simulation provide insight to Lean implementation strategies. Since DES makes use of visual elements to represent events its simulation method helps understand the interrelation of elements within a system. Finally the characteristics of DES as a tool for simulation enable users to represent future process without real implementation.

6.3 Discussion

This report should not mislead the reader into his believing that DES is a straightforward tool that is easily implemented. DES requires understanding in the concept of event-based simulation as well as technical capacities to develop a software based model. Although modern simulation software do not require high level programming a technical learning curve is necessary. In addition, the selection of DES projects is important. DES is a resource consuming activity as models require a long time for conception and adequately trained personnel to develop the models. Furthermore, the use of DES should not impair the use of traditional Lean assessment tools that may be better suited for Lean evaluation.
The authors of this report find a very large gap between development of simulation models for Lean assessment and the use of DES as an everyday Lean assessment tool. There exists an area of opportunity for developments of technically sound yet user-friendly applications that may bring DES methodology to every day production problems were engineers, production personnel, and company managers gauge the state of their process, foresee solutions to problems, or diagnose manufacturing issues.

In regards to the Case Study, Alfa Laval objectives were satisfied within the specified time frame and the results for the study were used to select a Lean alternative for implementation. Case study data was used in support of its providing an answer to research questions that apply to larger problems in Lean manufacturing. Building a model that was used not only for the purpose of evaluating Lean alternatives for a future state but also for refining production parameters in the future production process. This thesis managed to show what elements are necessary for DES to work for Lean assessment, and the type of information that may be extracted from DES models for Lean evaluation.

There is a need to point out however that this report and its results were based on the assumption that all proposals were Lean proposals to begin with. Evaluation of proposals was never contemplated as part of this report for reasons of timeliness. In addition, the authors of this report suggested no Lean proposals for future state improvement on their own. Also, this report did not evaluate the existence of optimal solution for evaluated production variables. All results for production variables were selected from a range of possible values suggested by Alfa Laval.

The authors of this report realize that models built in this thesis for evaluation of Lean parameters were based on requirements stipulated by Alfa Laval. The execution and evaluation of these parameters does not guarantee that a Lean state is achieved. The authors suggest that a further evaluation of parameters and critical production circumstances is reviewed.

DES is a complex method for simulation that allows for a very broad flexibility in design and evaluation of models; models that may reach beyond the scope of Lean production and into new paradigms in manufacturing. Further studies on this subject would be beneficial for the fields of simulation and manufacturing. The development of simulation models at Alfa Laval evidenced the need for simulation in general, and DES in particular, to reach down to companies and their needs. Further studies are necessary to understand the reasons as to why DES is viewed as a consultancy experience rather than an everyday tool. The authors of this report have witnessed the manner in that DES is developed within companies as a selective tool that is not accessible to all employees in an organization. DES proficient employees take their skills and knowledge with them once their work relation with an organization is terminated. Further studies are necessary to understand the reasons why DES is not a tool of common use. Lastly, it has been realized that DES is an obscure and unknown subject to many organizations although companies easily grasp the benefits of its use. Further studies could focus on discovering the reason why simulation’s knowhow is not widespread.
7. REFERENCES


APPENDICES

A Laser Chi-square Calculation Volume Output Results

Ho: Gathered results are normally distributed

Step1: Compute mean and standard deviation of the 1000 runs
Mean 120604.716
Deviation 804,1027276

Step2: Compute standardized values of the 1000 runs
= (value - mean)/stddev

Step3: Count the frequencies of standardized values

<table>
<thead>
<tr>
<th></th>
<th>-1</th>
<th>0</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cumulative</td>
<td>149</td>
<td>512</td>
<td>867</td>
</tr>
<tr>
<td>Count</td>
<td>149</td>
<td>363</td>
<td>355</td>
</tr>
</tbody>
</table>

Step4: Compute expected values under condition of Ho

<table>
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<th>-1</th>
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<th>1</th>
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<tbody>
<tr>
<td>Cumulative</td>
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<td>500</td>
<td>841,3447</td>
</tr>
<tr>
<td>Count</td>
<td>158,6552539</td>
<td>341,3447</td>
<td>341,3447</td>
</tr>
</tbody>
</table>

Step5: Compute squares, degrees of freedom, and the chi square value

<table>
<thead>
<tr>
<th></th>
<th>0,587588032</th>
<th>1,373831</th>
<th>0,546269</th>
<th>4,148568</th>
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</thead>
<tbody>
<tr>
<td>df</td>
<td>3</td>
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<td></td>
<td></td>
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<tr>
<td>Chi Square</td>
<td>6,656255496</td>
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<td></td>
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</table>

Step6: Table Value of $X_{0.05}^2$

<table>
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<tr>
<th></th>
<th>7,81</th>
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</table>

Conclusion: Calculated Value is smaller than table value -> Ho is not rejected
B Chi-Square Distribution

The table below gives the value $x_0^2$ for which $P[x^2 < x_0^2] = P$ for a given number of degrees of freedom and a given value of $P$.

<table>
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<tr>
<th>Degrees of Freedom</th>
<th>Values of $P$</th>
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<tr>
<td></td>
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</tr>
<tr>
<td>1</td>
<td>0.011</td>
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<tr>
<td>2</td>
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<tr>
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<td>4</td>
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<td>5</td>
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<tr>
<td>6</td>
<td>0.989</td>
</tr>
<tr>
<td>15</td>
<td>5.142</td>
</tr>
<tr>
<td>18</td>
<td>6.844</td>
</tr>
</tbody>
</table>
D Balance Load Chart
Load Balance Chart for Three Shifts

Load Balance Chart for Welding Station Svets2000
Load Balance Chart for A/B Line Welding Stations

Load Balance Chart for C Line Welding Station
# E Cycle and Change over Times According to VSM Analysis for Entire Cell C6 Process

<table>
<thead>
<tr>
<th>Bowl Discs / Order</th>
<th>Cutting</th>
<th>Round Cutting</th>
<th>Manual TVA</th>
<th>Svets2000</th>
<th>Press Adjust</th>
<th>Washing</th>
<th>Tophole Punch</th>
</tr>
</thead>
<tbody>
<tr>
<td>VSM Data</td>
<td>170 items</td>
<td>0.003</td>
<td>0.017</td>
<td>0.004</td>
<td>0.667</td>
<td>0.050</td>
<td>1.5</td>
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</table>

<table>
<thead>
<tr>
<th>Auto TVA</th>
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</thead>
<tbody>
<tr>
<td>Cycle Time</td>
<td>Change Over Time</td>
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<td>0.043</td>
<td>2</td>
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</table>

<table>
<thead>
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<th>Line B</th>
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</thead>
<tbody>
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<td>Cycle Time</td>
</tr>
<tr>
<td>0.167</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Line C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cycle Time</td>
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</table>