Lappeenranta University of Technology
School of Industrial Engineering and Management
Department of Innovation Management

MASTER'S THESIS

LEAN SIX SIGMA IN A MANUFACTURING LEAD TIME IMPROVEMENT PROJECT

Examiners: Professor Ville Ojanen

Associate Professor Kalle Elfvengren

Sampsa Tikkala

ABSTRACT

Author: Sampsa Tikkala

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The objective of this research is to demonstrate the use of Lean Six Sigma methodology in a manufacturing lead time improvement project. Moreover, the goal is to develop working solutions for the target company to improve its manufacturing lead time. The theoretical background is achieved through exploring the literature of Six Sigma, Lean and Lean Six Sigma. The development will be done in collaboration with the related stakeholders, by following the Lean Six Sigma improvement process DMAIC and by analyzing the process data from the target company. The focus of this research is in demonstrating how to use Lean Six Sigma improvement process DMAIC in practice, rather than in comparing Lean Six Sigma to other improvement methodologies. In order to validate the manufacturing system's current state, improvement potential and solutions, statistical tools such as linear regression analysis were used. This ensured that all the decisions were as heavily based on actual data as possible. As a result of this research, a set of solutions were developed and implemented in the target company. These solutions included batch size reduction, bottleneck shift, first-in first-out queuing and shifting a data entry task from production planners to line workers. With the use of these solutions, the target company was able to reduce its manufacturing lead time by over one third.

TIIVISTELMÄ

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Työn tavoitteena on esittää kuinka Lean Six Sigmaa voidaan käyttää tuotannon läpimenoajan parannusprojektissa. Lisäksi tavoitteena on kehittää kohdeyritykselle käytännössä toimivat ratkaisut tuotannon läpimenoajan nopeuttamiseen. Tutkimuksen taustatiedoksi syvennytään kirjallisuuden pohjalta Six Sigma, Lean ja Lean Six Sigma konsepteihin. Kehitys tapahtuu toimimalla yhteistyössä yrityksen sidosryhmien kanssa, seuraamalla Lean Six Sigma DMAIC parannusprosessin vaiheita ja analysoimalla kohdeyrityksen prosessidataa. Tutkimus keskittyy esittämään kuinka Lean Six Sigma DMAIC prosessia voidaan tämän tyyppisissä projekteissa käyttää. Tutkimuksessa nykytilan, parannuspotentiaalin ja ratkaisujen arviointi tehtiin datalähtöisesti käyttämällä apuna muun muassa lineaarista regressioanalyysiä. Näin kaikki päätöksenteko perustui mahdollisimman voimakkaasti oikeaan dataan. Tutkimuksen tuloksena kohdeyritykselle kehitettiin joukko ratkaisuja, jotka implementoimalla tuotannon läpimenoaikaa voidaan parantaa. Nämä ratkaisut olivat tuotantoerien pienennys, pullonkaulan siirtäminen, FIFO jonotus ja erään tietojensyötön siirtäminen tuotannonsuunnittelijoilta linjatyöntekijöille. Näiden ratkaisujen avulla kohdeyritys pystyi nopeuttamaan tuotannon läpimenoaikaa yli kolmanneksella.

FOREWORD

I would like to thank all my coworkers in Cembrit Production Oy for helping me in this project. Especially I would like to thank Jouko Tuuri and Pasi Koskela who made this work possible.

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The journey to the world of Lean Six Sigma has been an interesting one. For this, I want to thank Gregory H. Watson for excellent guidance. This journey is surely just beginning.

Last but not least, I would like to thank Viivi, my family and all my friends for the support during my studies. It still feels like yesterday when the first day in LUT was ahead of me. My studies in the University are over, at least for now, but the years in Lappeenranta won't be forgotten.

November, 17th 2014. Lohja

Sampsa Tikkala

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LIST OF ABBREVIATIONS:

Cembrit = Cembrit Production Oy

CT = Cycle Time

DFSS = Design for Six Sigma

FGI = Finished Goods Inventory

FIFO = First In First Out

LSS = Lean Six Sigma

ROI = Return on Investment

TH = Throughput

WIP = Work In Process

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1 INTRODUCTION

In today's global markets it is increasingly important that companies work smarter rather than harder in order to stay competitive. Current level of technology enables wide range of data to be collected and analyzed efficiently to gain better knowledge of an organization's operations and to recognize potential areas for improvements. However, the data is often not explored deep enough or even worse, the data is analyzed incorrectly, resulting in misleading results. Many organizations lack the proper data analysis skills and as a result, the solutions for complex problems are too heavily based on intuition alone. More data driven decisions are needed.

1.1 Target company and background

The target company of this research is Cembrit Production Oy. Cembrit Production Oy is part of the Cembrit Group which is owned by the FLSmidth Group. Cembrit Group distributes and manufactures fibre-cement products for roofing, interior cladding and exterior cladding as well as offers systems and technical solutions for installation of these products. Cembrit Group is one of the leading companies in fibre-cement products in Europe and employs around 1100 people. (Cembrit 2014; FLSmidth 3rd Quarter Report 2014)

Cembrit Production Oy (referred as Cembrit from this point forward) is located in southern Finland and it is one of Cembrit Group's four factories around Europe. Cembrit manufactures and distributes flat-sheets for both interior and exterior usage as well as supplies installation accessories for these products. Cembrit employs around 200 people and has a revenue of 35 million euros (2011) of which around 70 percent is exported. The flat-sheet products consist of cement (50-70 %), cellulose (5-15 %) and mineral fillers (20-40 %). Products of Cembrit do not contain any asbest or quartz. (Cembrit Oy 2014)

This research was initiated by Cembrit's desire to be able to deliver with lower lead times and with higher on time delivery percentage to ensure high customer satisfaction and enable growth of sales. The research and the related project was at the same time a part of a training project for a Lean Six Sigma Black Belt course held by Gregory H. Watson from Laatukeskus Excellence Finland Oy. Due to this and the company's request, the execution of this project relies heavily on the different ideas and tools combined under the Lean Six Sigma (LSS) methodology.

1.2 Target and scope

This research focused on the manufacturing lead time of interior and exterior cladding products produced by Cembrit Production Oy. This means that other factories of Cembrit Group and other products provided by Cembrit Production Oy are not included in this research. The manufacturing process in question is studied from the point of raw material mixing to the point where the products are in the finished goods inventory ready to be delivered. Due to a request from the target company, the batch sizes and financial benefits presented in this work are not the actual figures but modified numbers.

In this research, the tools and frameworks used are all related to Lean and Six Sigma, in other words Lean Six Sigma (LSS), methodologies. Theories that are not related to these methodologies are not in the scope of this research.

The goal of this research is to demonstrate how these tools can be used in an improvement project that is focused on reducing the manufacturing lead time of an industrial factory and to present a set of solutions for the target company's manufacturing lead time reduction. The research is executed by adapting the presented methodologies.

The goals for this research can be summarized in the following way:

- Demonstrate how Lean Six Sigma can be used in a project focused on manufacturing lead time reduction.
- Create a set of working solutions through which the target company can reduce its manufacturing lead time.
- Illustrate how to base the solution creation on data analysis rather than intuition alone.

As one of the goals of this project is to develop a set of working solutions for the target company to improve its manufacturing lead time, the solutions and the estimates of the performance with these solutions are not theoretical extremes. Instead, the estimates of improvement potential are such that they allow some degree of variation in the manufacturing system. In addition, the solutions are such that they can be implemented in the company with minimal investments and provide more benefits than adverse effects.

1.3 Structure

This work is structured in two parts. First, chapters two and three present the underlying theories of Six Sigma and Lean. As the improvement project is based on Lean Six Sigma methodology, the purpose of this part is to give a solid foundation for the project execution. The second part, which consists of chapter four and five, is focused on the project execution and the benefits the improvement project offered to the target company. Chapter four in the second part rigorously follows the Six Sigma project steps.

Chapter six presents the conclusions of the work which includes observed benefits and challenges of the Lean Six Sigma methodology as well as an assessment of the project's execution. Summary of the work is presented in chapter seven, giving a

compact description of the main points of this work. Figure 1 presents the structure of this work in more detail.

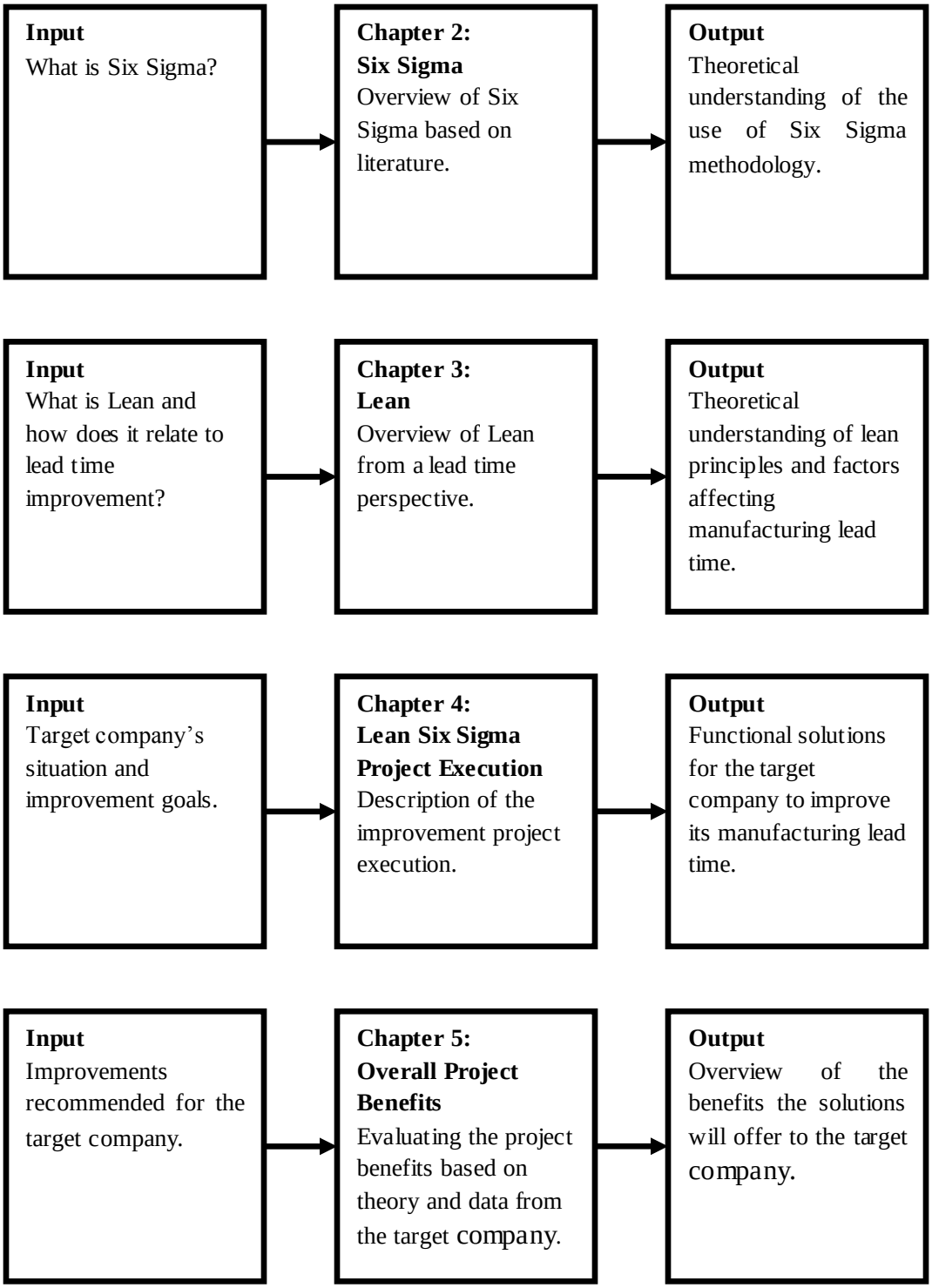

Figure 1. Structure of this work.

2 SIX SIGMA

The term "sigma" comes from the Greek letter σ which is the symbol for standard deviation of a population in statistical mathematics. When a process is running at a 6σ level it means that the process is six standard deviations away from the customer specification limits, in other words only average of 3.4 defects are produced per million products (Table 1). This Six Sigma level is therefore a near perfect quality level for the specific process. (Watson 2005, p. 34-37; Watson 2009, p. 1-10)

Table 1. Sigma Performance Scale. (Watson 2005, p. 34-37)

Sigma Performance Level	Defects per Million Opportunities	Process Yield	Estimated Cost or Poor Quality (% Revenue)
1.0σ	670 000	33%	>40%
2.0σ	308 537	69.2%	30-40%
3.0σ	66 807	93.32	20-30%
4.0σ	6 210	99.38%	15-20%
5.0σ	233	99.9767%	10-15%
6.0σ	3.4	99.99966%	<10%

Roots of Six Sigma lie in the late 1980s when Motorola started to systematically reduce variation in its processes to better compete with the Japanese competitors. The CEO of Motorola at that time, Bob Galvin, set a goal of 10-fold improvement of all product and service qualities for every 2 years period. As a result of this program, aggressive reduction of process variation started and the improvement process quickly took the shape of measure, analyze, improve and control (MAIC). The effort

paid off and in 1988 when Motorola was awarded with the Malcolm Baldridge National Quality Award. (Hopp & Spearman 2008, p. 171-172)

After Motorola the Six Sigma methodology was further developed by such companies as ABB, AlliedSignal, General Electric (GE), DuPont, Nokia and Toyota. For example, the CEO of GE Jack Welch initiated a companywide program in 1995 to make GE the "greatest company in the world". This was to be done by implementing Six Sigma to all areas of GE. Furthermore, to boost up the program, Six Sigma training became mandatory for promotions. Overall the program at GE was a great success and their annual reports estimated the savings from Six Sigma to be 1 - 2 billion dollars per year during the years 1996 - 1999. (Hopp & Spearman 2008, p. 172; Watson 2009, p.1-10)

By the start of the 21st century the Six Sigma methodology had evolved and in addition to several new tools, the basic improvement process got an additional step "define" meaning that the old MAIC was now DMAIC. Furthermore, a new methodology was shaped under the basic Six Sigma and it was called Design For Six Sigma (DFSS). The difference was that DFSS focused on new product and process design rather than improving the existing products and processes. DFSS also has its own process which consists of steps define, measure, analyze, design and verify (DMADV). (Hopp & Spearman 2008, p. 172)

In addition to the new "define" step a new orientation called "Lean Six Sigma" (LSS) also emerged. LSS is an integration of both Lean and Six Sigma philosophies and the reasons behind LSS creation mainly lie in the synergies these two distinct methods offer for each other. LSS has the same DMAIC improvement process as the original Six Sigma, but in addition to Six Sigma tools, Lean tools are also incorporated into the different steps. Whereas Six Sigma mainly focuses on defect and variation reductions, Lean adds more focus on process standardization and simplification as

well as waste reduction. (Pepper & Spedding 2010, p. 144-145; Tenera & Pinto 2014, p. 913)

In general Six Sigma can be thought as a business-improvement approach that focuses on finding and removing causes of errors or defects in any process. This is done by identifying process outputs that are important to the customer and focusing on those inputs that affect the specific output. This kind of outside-in focus guarantees that the results will be felt as an improvement of one or more of the following: lead time, product and process costs, process yields, and customer satisfaction. (Watson 2004, p. 3; Watson 2005, p. 34-37)

2.1 Variation

Stable processes are much easier to manage and streamline than unstable processes. This means that in order to be able to control the flow of production, the processes should be as stable as possible. Unstable processes cause extra work, material losses, high inventory and high cycle times. All of which are counterproductive for improving operations. (Rother 2010, p. 285-286)

Every process in the world has some kind of variation in its inputs and outputs. Thus, it is not possible to produce two exactly identical products, some level of difference will always occur. Variation leads to problems that result in defected products; a process without variation should always have a 100% yield. Reducing variation is therefore an important aspect of lowering process costs and one of the most highlighted parts of Six Sigma methodology. (Magnusson et al. 2000, p. 22-28)

In terms of Six Sigma, variation is further divided into two categories which require different approaches for analysis and reduction. First category is the common cause variation. Common cause variation includes all the variation that is impossible to get rid of as well as some that can be reduced. It can sometimes follow a bell shaped

normal distribution as some of it is caused by natural randomness. To reduce common cause variation, changes to whole system are often required. (Magnusson et al. 2000, p. 22-23)

Second category of variation is called the special cause variation. These events are not random, often few in numbers, but large in contribution to total variation. Events that often result in special cause variation could be for example machine malfunction, raw materials from different supplier or non standardized work procedures. Best combination of improvement potential in relation to resources needed for improvements are often found in these special causes. Thus it is important to be able to distinguish common cause variation from special cause variation. (Magnusson et al. 2000, p. 22-23)

2.2 Six Sigma Project Team

One of the differences between Six Sigma and other quality programs is that the Six Sigma project team is well structured and several of the roles in the team require a certain level of training and certification in the field of Six Sigma. This chapter will introduce these roles in a top to down order, as it is typically the same order in which the implementation of Six Sigma is done in companies. These roles are: Executive Sponsor, Champion, Master Black Belt, Black Belt and Green Belt. (Kamrani & Nasr 2008, p. 48-49; Pham 2006, p. 959; Snee 2005, p. 2; Wasage 2012, p. 24-25; Watson 2004, p. 17-19)

Executive sponsor is often part of the company's top management and well aware of the strategic direction the company is heading. Therefore, the executive sponsor should be involved in project selection. Furthermore, because the executive manager is most likely part of the top management, he also possesses the authority to ensure that the projects have the required resources. (Pham 2006, p. 9593; Watson 2004, p. 17-19)

Champions act as projects' business and political leaders. Responsibilities of an champion include tasks such as reporting to the executive sponsor, project supervision and ensuring that the project stays aligned with the company's strategy. Most suitable personnel for the role of the champion are those in the company's senior management. (Kamrani & Nasr 2008, p. 48; Pham 2006, p. 959; Snee 2005, p. 2; Wasage 2012, p. 26-27; Yang & Hsieh 2009, p. 7597)

Master black belt acts as an technical leader providing support on data analyzes and coaching and training for both green belts and black belts. They also work with the champion on project selection and ensure that the project proceeds rigorously according with the Six Sigma problem solving process DMAIC (explained in the following chapter). Master black belt has at least the same level of technical knowledge in Six Sigma than black belts, as well as similar leadership and managerial skills than champions. (Kamrani & Nasr 2008, p. 48; Pham 2006, p. 959; Snee 2005, p. 3; Wasage 2012, p. 26; Watson 2004, p. 131-136)

Black belt is the Six Sigma project manager and leader. They work on the projects full time and handle most of the detailed work. Furthermore, black belts provide training and guidance for team members and green belts in statistical tools and Six Sigma methodologies. The role of black belts is often the most visible one in a Six Sigma implementation and therefore black belts are critical for a successful Six Sigma implementation. The black belt training consists of four to five weeks of training that are spread over a period of four to five months. During the training the black belt completes a project that can be finished within a six months period of time and gives at least 175 000 - 250 000€ yearly savings to the bottom line. After the training, fulltime black belts can complete four to six black belt projects per year. (Pham 2006, p. 959; Snee 2005, p. 3; Wasage 2012, p. 25-26; Watson 2004, p. 67)

Green belts are trained in the use of Six Sigma methodology and tools. The training for green belts is typically couple of weeks in length and includes a Six Sigma project that is done alongside the training and should give a minimum of 50 000 - 75 000€ yearly savings to the bottom line. In Six Sigma projects green belts can either be team leaders under the supervision of a champion or master black belt, or they can assist black belts on their projects. While working on projects, one major difference between green belts and black belts is that green belts typically work on their projects only part time. In addition, projects led by a green belt are often more locally focused than black belt projects. The number of projects per year is typically around two to three. Because green belts work only part time on their projects, it also means that they have other work activities to perform. Gradually they will bring Six Sigma methodology in their other work activities, which will in the long run help in shifting the organizations culture. (Kamrani & Nasr 2008, p. 49; Pham 2006, p. 959; Snee 2005, p. 2-3; Wasage 2012, p. 25)

In addition to the Six Sigma trained roles mentioned above, process owners should also be involved in the project. Process owners are those responsible for the processes under the scope of the project. As they are responsible for the processes, it is vitally important to involve them in order to ensure sustained gains. (Watson 2004, p. 99-122)

2.3 Problem Solving Process DMAIC

DMAIC is the basic problem solving process of Six Sigma. It includes five steps which are: Define, Measure, Analyze, Improve and Control (Table 2). This problem solving process can be described as "A rigorous, step-by-step, logical discipline for defining the most critical business improvement issues, converting them into statistical problems, and then resolving them as standardized daily work practices.". (Watson 2004, p. 93-98)

Table 2. DMAIC steps. (adapting Watson 2004, p. 97)

Step	Y=f(X)	Explanation
Define	Identify Y	Identify and choose most critical business issues and concerns.
Measure	Characterize Y and identify X's	Eliminate factors that are not controllable from the analysis.
Analyze	Translate Y into X's	Eliminate factors that do not contribute much to the overall performance.
Improve	Optimize X	Identify the critical factors that drive the desired state of the process.
Control	Manage X and monitor Y	Set the process under control and implement management and monitoring tools that ensure future control.

2.3.1 Define

The first step of DMAIC process is called Define. This step starts with problem identification. The problem can for example be related to any of the following: financial concern, customer problem, process inefficiency, product failure or flow bottleneck. It is important to understand and define who the customer of the project is so that the goals can be set appropriately. In addition, the scope of the project and resources needed have to be defined. Project resources include the personnel for the project as well as other costs that can be seen at this stage. Well estimated costs and benefits enable the team to critically evaluate the project's potential. (Pham 2006, p. 961; Watson 2004, p. 71-72, 99-103; Watson 2005, p. 52)

During this step a project charter is created to keep relevant information up to date and easily available for all involved participants. This charter includes basic information about the project, scope and description of the project, project team

structure, key measures and project milestones. The charter is created during the define phase, but it will be updated during the project and after the project is finished, it will act as a part of the documentation of the project. (Pham 2006, p. 961; Watson 2004, p. 71-72, 99-103; Watson 2005, p. 52)

Some of the most commonly used tools at the Define phase (Kamrani & Nasr 2008, p. 50; Pyzdek 2003, p. 240; Watson 2004, p. 100):

- Theory of Constrains
- Problem Statement
- Operational Definitions
- Customer CTQ Characteristics
- Competitive Analysis
- Process Map
- SIPOC

2.3.2 Measure

Once the business problem is defined the project proceeds to the measure phase. During this phase the work processes related to the problem are identified by the project team. After identification of related processes, the flow, feedback loops, measurement-control points, and hand-offs across organizational groups are mapped for the processes. Using this information the processes can then be divided into logical models that provide quantitative understanding of the process. Process evaluation can then be executed using actual process data to ensure reliable process evaluation. (Watson 2004, p.105-106)

Process evaluation also means that data about the processes' performance is needed. A major part of the measure phase is focused on ensuring that the data needed is available and accurate. It is not uncommon that the data needed has not been

measured or collected before the project or the data is simply not accurate enough. Thus, sometimes the project requires setting up a new measurement system or improving the existing one. All this is done to ensure that the improvement efforts are focused to those areas that exhibit the greatest improvement potential for the chosen business problem. This also means that the decisions will be based on data and facts rather than guesswork. (Pham 2006, p. 961; Pyzdek 2003, p. 238, 277-278; Watson 2004, p. 105; Watson 2005, p. 52-53)

Once the current performance level is known, it will then be compared to the best performance possible without major investments. The best performance baseline can for example be a historical best performance, benchmarking with similar process or engineering maximum capacity calculations. When the current performance and ideal performance are known, the potential benefits for the project can be estimated more precisely. (Pham 2006, p. 961; Watson 2004, p. 106-109; Watson 2005, p. 52-53)

Some of the tools used at measure phase (George 2003, p. 285-286; Watson 2004, p. 106) :

- Process Analysis
- Failure Analysis
- Performance Baseline
- Capability Analysis
- Measurement System Analysis
- Pareto Chart

2.3.3 Analyze

After the first two steps of DMAIC the business problem has been defined, related processes identified and current performance evaluated. The objective of the analyze step is to locate the greatest sources of controllable variation from the identified

processes, after which the improvement opportunities and root causes of the problem can be determined. In other words this means that now the output performance of the processes' is know and the focus will shift on studying the inputs that drive the output performance. (Kamrani & Nasr 2008, p. 51-53; Watson 2004, p. 111)

Great amount of the work done during this step is based on statistical analysis tools. These tools are used to calculate the amount of variation added by each individual factor to the overall process variation. Thus this helps to determine which inputs are the most crucial ones for the overall performance. Possible interaction effects between the factors will also be quantified. Sometimes the number of factors is really high and in this situation for example a Pareto chart can be used to prioritize the hypothesis testing. (George 2003, p. 289; Kamrani & Nasr 2008, p. 51-53; Watson 2004, p. 111-114)

Some of the most commonly used tools at analyze phase (Kamrani & Nasr 2008, p. 52-53; Pham 2006, p. 961; Watson 2004, p. 112):

- Hypothesis Testing
- Multi-Vari Analysis
- Cycle-Time Analysis
- Regression Analysis
- Analysis of Variance
- Brainstorming

2.3.4 Improve

As a result of the previous steps, the improvement focus has been agreed-upon. During the Improve phase the factors that drive the process towards the statistical solution are identified and validated, the statistical solution being either variation reduction, mean shift or both. The solution is not validated before the desired change

is actually observed as a result of changing the factors. The validation is often done through some type of testing, often referred as design of experiments (DOE). After the solution has been validated, the critical factors will be controlled in a way that ensures robust performance. It should also be noted that not all changes come without negative effects. Thus it is important to evaluate the solution effects on the whole system's performance. (George 2003, p. 292-299; Pham 2006, p. 961-962; Watson 2004, p. 115-118; Watson 2005, p. 52-53)

Some of the most commonly used tools at the Improvement phase (Watson 2004, p. 116):

- Shainin Methods
- Taguchi Methods
- Simulation Analysis
- Design of Experiments (DOE)
- Tolerance Analysis

2.3.5 Control

The last step of DMAIC is called control. Now that the solutions have been found and validated they need to be implemented and maintained. This means that the critical inputs need to be set under control and process outputs monitored. Monitoring will ensure that the process does not drift back to the old performance. (Pham 2006, p. 962; Watson 2004, p. 119-122)

The goal of the control phase is to ensure that the improvements stick and become part of the normal way of doing things. Only reason why the improvements should be revoked is if an even better way of doing things is found and validated. (George 2003, p. 303-304)

Some of the most commonly used tools at the Control phase (Pham 2006, p. 962; Watson 2004, p. 120):

- Mistake Proofing
- Lean Production
- Work Standardization
- Preventive Maintenance
- Statistical Process Control (SPC)

3 LEAN

In this chapter the main principles behind lean are presented. In addition, some extensions such as Little's Law are presented to help illustrate the effects and dependencies between different manufacturing parameters.

The Toyota Production System (TPS) is the basis that the current lean philosophy is built on. Most recognized contributor to the creation of TPS was a Toyota motor company employee called Taichi Ohno who worked nearly sixty years at Toyota, starting from 1932. Main idea behind TPS was to eliminate all waste, which was defined to be "anything other than the minimum amount of equipment, materials, parts, space and time which are absolutely essential to add value to the product". (Modig & Åhlström 2013, p. 75-76; Pepper & Spedding 2010, p. 138-140)

First time the term "lean production" was used in an article was in 1988 by John Krafcik. The article was called "Triumph of the Lean Production System" and it was based on comparing the production systems of different car manufacturers. Conclusion of that article was that production systems, such as Toyota's, that had simple technology, low inventories and low buffers could reach high productivity and quality. This finding was in conflict with the idea that economies of scale and advanced technologies were necessities for high productivity and quality. (Modig & Åhlström 2013, p. 76-77)

3.1 Wastes

Main principles behind lean thinking are based on the idea of waste removal. Different type of wastes throughout a company should be continuously reduced, the goal being zero waste. Originally seven wastes were presented, but later on many

have added an eighth waste that takes into consideration the utilization of peoples' capabilities. These eight wastes presented by Alukal and Manos (2006, p. 3-4) are:

1. **Overproduction.** Making more, earlier, or faster than is required by the next process.
2. **Inventory.** Excess materials or more information than is needed.
3. **Defective production or service.** Production requiring inspection, sorting, scrapping, downgrading, replacement, or repair. This also affects information, if it is not accurate and complete.
4. **Over processing.** Extra effort that adds no value to the product (or service) from the customer's point of view.
5. **Waiting.** Idle time for staff, materials, machinery, measurement, and information.
6. **People.** The waste of not fully using people's abilities (mental, creative, skill, experience, and so on).
7. **Motion.** Any movement of people (or tooling/equipment) that does not add value to the product or service.
8. **Transportation.** Transporting information, parts or materials around the facility.

As stated by Modig and Åhlström (2013, p. 40-42) and Magnusson et al. (2000), some level of variation will always occur. Some of it will be related to manufacturing processes and some to customer demand. This variation will inevitably result in increase of at least one of the eight wastes presented by Alukal and Manos (2006). The increase of these wastes will result in a buffer that dampens the variation effects. Hopp and Spearman (2008, p. 202) present that this buffer can have three forms:

- **Inventory** - Be it in raw materials, work in process (WIP) or finished goods.
- **Time** - If enough inventory is not held, then there is a delay between customer request and product delivery.

- **Capacity** - To be able to answer to high demand spikes, extra capacity is needed.

3.2 Little's Law

Little's law offers a way of evaluating the efficiency of a manufacturing process from a perspective very similar to the concepts of lean. Some authors present Little's Law outside the scope of lean (Hopp & Spearman 2008, p. 239) while others use it to clarify the underlying theory behind lean (Modig & Åhlström 2013, p. 34-37). Thus it can be said that Little's law is not always considered to be part of lean, but for illustration purposes Little's Law is presented here under the lean methodology.

$$WIP = TH \times CT \qquad (1)$$

Little's law links together work in process (WIP), throughput (TH) and cycle time (CT) as can be seen in formula 1 presented by Hopp and Spearman (2008, p. 239). WIP is the production between start and end of the manufacturing process, TH tells how many items the production system can produce in a given time unit and CT is the average manufacturing lead time. John D. C. Little proved mathematically that Little's law holds true for any manufacturing system when time goes to infinity. Thus, Little's Law is not exact for real life situations, but it does offer a very good approximation. (Hopp & Spearman 2008, p. 238; Modig & Åhlström 2013, p. 34-37)

3.3 Work In Process

If a manufacturing process is running, it always has some WIP. As Little's law illustrated, WIP can be calculated by multiplying TH by CT. By turning that formula around we get CT which is WIP divided by TH. Thus, if manufacturing lead time is to be reduced, then either WIP needs be lowered, throughput increased or both. (Modig & Åhlström 2013, p. 31-47)

Lower WIP does leads to shorter manufacturing lead time. Thus, it also increases customer responsiveness. However, it does not come without problems. WIP is often used as a capacity buffer, meaning that if a machine breaks down in the beginning of a production system, then WIP between workstations ensures that the other workstations do not have to stop working. In other words, high WIP enables higher utilization in production systems that have high variability in workstation capacities.

In addition to machine breakdowns, variation in product quality causes variability in manufacturing systems in the form of scrap and rework. Thus, low WIP only works efficiently in production systems that have low variation in their workstations' capacities and quality. To illustrate this, many authors describe WIP and variability as a stream of water, where the water is WIP and the rocks are variation and problems of a manufacturing system. The rocks stay unnoticed as long as the water stays high enough, but when the water is lowered by reducing WIP then the problems become easily perceivable. (Hopp & Spearman 2008, p. 165)

3.4 Batch Size

One of the factors that greatly affect the production flow in a system is production batch size. To reach the shortest possible manufacturing lead time, a one-piece flow would be required. In many cases however, a one-piece flow is either not economically reasonable or for other reasons unfeasible. In such cases, the batch size should be reduced to the smallest possible. (Alukal & Manos 2006, p. 7, 59-70; Hopp & Spearman 2008, p. 318-327)

The reasons why large batch sizes negatively affect manufacturing lead time are mostly related to extra waiting time. If a product is manufactured in 1000 piece batches, then it often means that before the batch processing can be started in the next station, the previous station has to finish the whole batch. In other words, after the first product is processed it should be ready to be processed by the next workstation.

However, it has to wait for the remaining 999 pieces before it can be started by the next workstation. (Alukal & Manos 2006, p. 7, 59-70; Hopp & Spearman 2008, p. 318-327)

4 LEAN SIX SIGMA PROJECT EXECUTION

This chapter describes the execution of the improvement project. Most of the theory behind the actions has already been presented in the previous chapters so the rest of this work focuses on applying the theory in practice. The project was done using the Six Sigma DMAIC process with Lean tools incorporated into the different steps.

4.1 Define

Define is the first phase of the DMAIC improvement process of Six Sigma. This chapter answers to the following questions:

- What are the business problems that will be addressed?
- What are the goals?
- In terms of Y=f(x) what are the measurable business Y's?
- Who are the customers?
- Who are the key persons that form the core team for this project?

The project started with a kick-off meeting at Cembrit where the local managing director and head of both supply chain and research and development were present. Purpose of the kick-off meeting was to define the business problem at hand and establish a mutual understanding of the project's guidelines.

Most of Cembrit's products are made-to-stock (MTS) and for larger quantities, the products can be made-to-order (MTO). The target lead times promised to customers are one week for MTS and eight weeks for MTO products. These lead times are from order-received date to ready to be dispatched date.

Unfortunately, the target lead times are not always reachable. This is most often caused by product specific demand spikes that consume the safety stock. When this

happens, the stockout can sometimes result in lost sales. Even if no sales are lost, customers experience a longer delivery lead time for the specific products.

In addition to demand spikes, manufacturing problems can also create difficulties in keeping promised delivery dates. The manufacturing lead time fluctuates greatly and makes it harder to estimate when products are ready to be delivered. Furthermore, the manufacturing lead time performance is not systematically monitored.

Based on these problems, three main business goals were set for the project: a decrease of average net working capital, an increase of on-time delivery - % and an increase of sales through reduced delivery times and increased customer satisfaction. This means that the delivery capability cannot be increased through higher levels of MTS products, or else one of the goals, the decrease of average net working capital, will not be reached.

By combining the definition of the business problems and goals, two opportunity statements were also created: "Variance and lead time reductions for item manufacturing would increase Cembrit's delivery accuracy to external customers." and "Lead time reduction would decrease average net working capital.". Out of these statements at least two measurable business Y's can be identified: manufacturing lead time and average net working capital. In this work the focus will be on building the Y=f(x) function for the manufacturing lead time (Table 3).

Table 3. Y=f(x) function development - define step.

Phase	**Y=f(x) goal**	**Result**
Define	Identify and choose business Y's	Manufacturing lead time was chosen as the business Y.

One of the most important things in Six Sigma projects is that from the very beginning the projects are customer focused. This means that the customers for the processes' outputs need to be known. In this case the first customer is the end customer who will see the effects of manufacturing lead time reduction through faster and more reliable order lead times. Better delivery capability will then result in better customer satisfaction and possible increase in sales. The decrease of average net working capital on the other hand will not be noticed by the end customer (unless it lowers the product price noticeably), but by the shareholders. By freeing some of the capital invested in the manufacturing process, it can then be used on other investments.

After defining the problems and goals, the key persons for the project were identified. This was done by adapting the Six Sigma project team framework. The following key positions were identified:

- Executive Sponsor: Managing director
- Project Champion: Quality and supply chain manager
- Black Belt: Sampsa Tikkala
- Master Black Belt: Gregory H. Watson
- Financial Analyst: Finance representative
- Process Owners: Production Manager and Production Planners

As a result of the define phase, the business problem was identified and non-critical business issues were eliminated. This ensures that the scope of the project is manageable and that the project is focused efficiently. Most of the work in the define phase was done by the executive sponsor and project champion as they are most aware of the current business problems in the target company.

4.2 Measure

With the problem defined, the next step is to identify all the related processes and their current capabilities. This will be done by first mapping the overall process and its subprocesses. Next the performance measurement system needs to be evaluated to ensure data validity and accuracy. Then the focus will be on mapping the past performance of the overall and subprocesses. This chapter answers to the following questions:

- What are the related processes and their subprocesses?
- What are the X's in terms of Y=f(x)?
- How good is the measurement system used?
- Is the data used valid and accurate?
- What is the current performance of these processes?
- Does the data show any trend?

4.2.1 Process steps

The board manufacturing process steps are presented in figure 2. First of all the raw materials, including water, are mixed together to produce slurry mass. Mixing is done at three board machine dedicated mixers. The slurry mass is produced in batches and around three batches are done per board machine every hour.

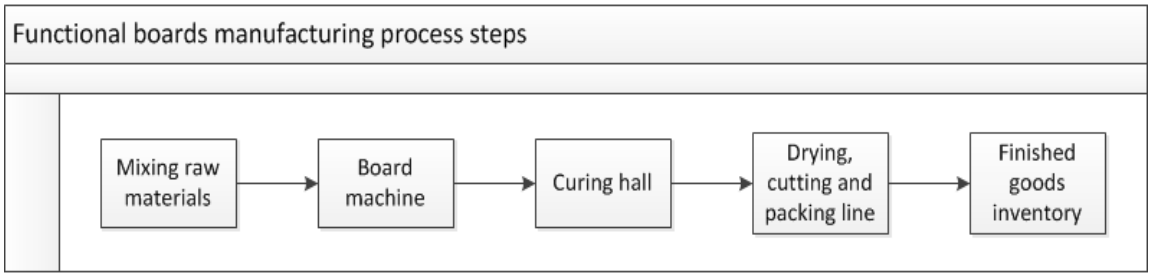

Figure 2. Board manufacturing flow chart.

After mixing, the slurry mass is pumped to the board machines. Total of three board machines are in use at the factory. The slurry mass is then pumped to a felt through which the excess water is removed by suction. Next the mass is pressed to a collection cylinder. After enough layers of mass are on the cylinder, it is cut and removed from the cylinder. Then wet cutting is done on the edges and the product gets its shape. Sheet diameters are adjusted between 3100 - 2500mm length, 1250 – 1192mm width and 3 - 12mm thickness. These wet sheets are then stacked and pressed in a hydraulic press. After the press and some time, the sheets are stacked on smaller pallets and moved to the curing hall by forklift.

At the curing hall the boards strengthen for 10 days. After the 10-day period, samples from the batch are tested for breaking strength, density and few other attributes. In normal circumstances, this testing takes maximum of two days to complete. After the testing is done and the batch is found to follow quality standards, it is ready to be dried, cut to delivery dimensions and packed. If the strength of the batch does not pass the quality testing, an additional 25 days is given for the batch to gather more strength. After this additional time the batch is tested again and it either gets permission to be dried and packed or is labeled as scrap.

From curing hall the boards go to one of the two drying, cutting and packing lines (referred to as drying lines from this point on). At this process step the boards are dried to delivery moisture, final cutting is done for the board edges and the boards are stacked and packed to the FGI.

Before the products can be considered ready in FGI, all the information that is needed for its dispatching has to be up to date. This means that a production planner registers the batch production complete to the company’s database. After this the batch is completely ready in the FGI.

The flow chart presented in figure 2 was constructed in collaboration with one of the production planners. All of these steps are subprocesses that affect the performance of the overall process. However, out of these subprocesses the first one which consists of raw materials mixing, was eliminated from the following analysis because it has very low utilization ensuring that it never acts as a bottleneck (unless there is a machine malfunction). The remaining process steps are the X's that drive the performance of the total manufacturing lead time (Table 4).

Table 4. Y=f(x) function development - measure step.

Phase	Y=f(x) goal	Result
Define	Identify and choose business Y's	Manufacturing lead time was chosen as the business Y.
Measure	Identify X's	Lead time performance of board machines, curing hall, drying lines and registration to FGI were identified as X's that drive the performance of the Y.

4.2.2 Manufacturing Lead Time Measurement System and Its Accuracy

The data used for manufacturing lead time analysis comes from the company's database. The batch specific information includes the dates at which the batch is registered to different workstations. This means that the data concerning batch processing times is in the scale of days. In other words, if a small batch is started and finished at a subprocess level during the same day it will result in a zero day lead time for that batch at that process step. This will inevitably cause some misalignment when comparing the total manufacturing lead time to the sum of subprocesses' lead times.

Another issue that generates data inaccuracy is related to batch registration at the curing hall. Shift foremen are responsible for the batch registration to curing hall. Before the registration, the sheets need to be manually calculated to verify the exact number of items produced. This task is done a few times per week. Due to this, the

board machine lead time shows a slightly longer and curing hall slightly shorter lead times than what the actual times should be. However, these differences should not make a big difference in the analysis and they are therefore consciously ignored.

All in all, the data gathered is of good quality. The accuracy, which is in the scale of days, is enough because even the lead times at the subprocess level are relatively high. The data is also valid, with the few exceptions mentioned earlier.

4.2.3 Current Performance - Total Lead Time

As stated before, the manufacturing lead time has not been stable in the past. This variation can be seen in figure 3 where the lead times for individual batches are presented throughout the year 2013. Some of the longest lead times are the result of bad board quality as those batches that do not pass the quality testing have a minimum of 25 days of extra waiting in the curing hall. Never the less, variation in the lower lead times is also great resulting in very high lead time fluctuations. The average lead time during year 2013 was 23.6 days with median of 21 days.

Some special causes can be found from this dataset. For example during December 2013 the factory was shut down for a three week holiday, so the batches in curing hall at that time had to wait for an extended period of time before drying. This spike in the manufacturing lead time can be seen near the right border of figure 3.

If the lead times during December are ignored due to the special cause explained above, the data does exhibit a trend. After the summer, the variation has clearly decreased. The effects are most likely due to several improvement projects executed during the last half of 2013.

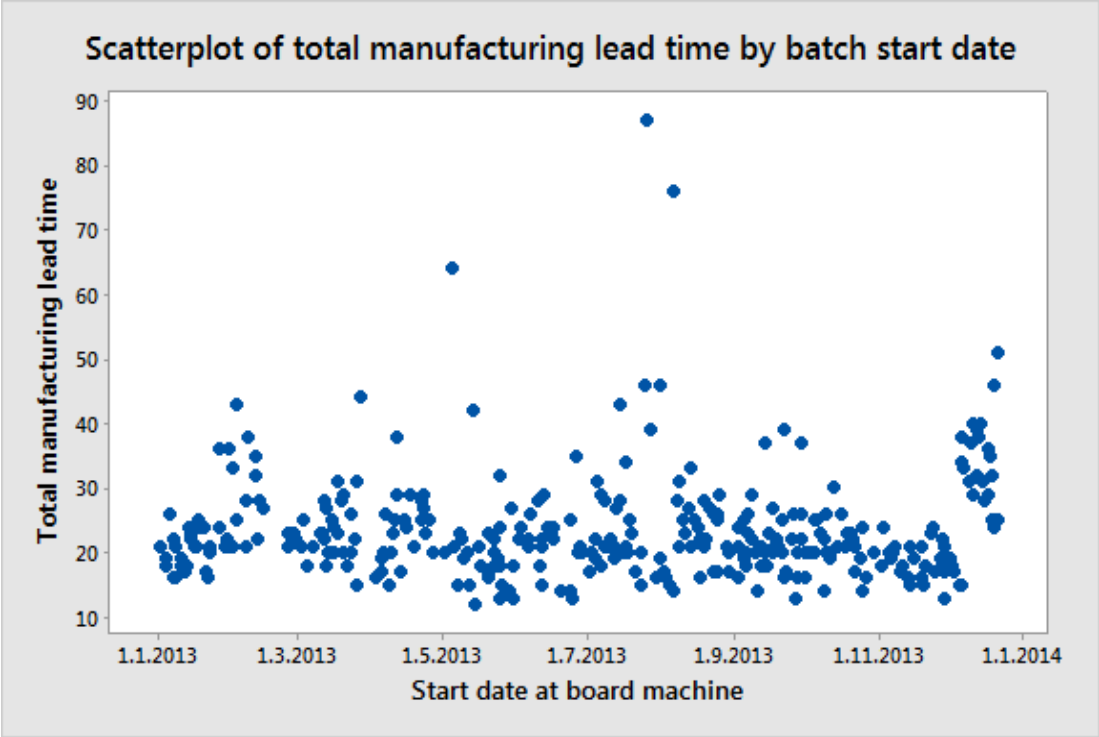

Figure 3. Total manufacturing lead time throughout the year 2013.

4.2.4 Board Machine Performance

As can be seen from figure 4 there are no conspicuous differences in batch manufacturing times at board machine throughout the year 2013. By this, it can be deduced that there are no clear special causes behind high manufacturing times. Instead, the manufacturing time varies rather randomly between high and low values due to common cause variation. Average lead time for board machine during the year 2013 was 2.3 days and the median 2 days.

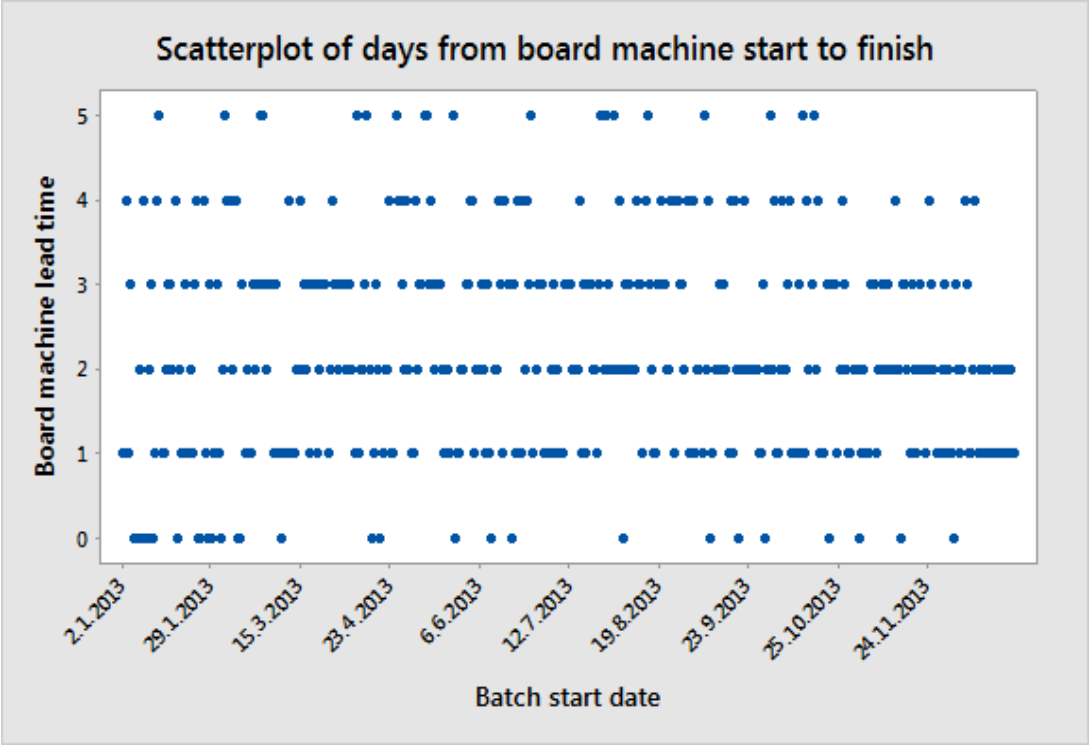

Figure 4. Batch manufacturing lead time at board machines throughout the year 2013.

4.2.5 Curing Hall Performance

In normal circumstances every batch gets the permission to be dried and packed at around 12 days of curing hall time. However, the actual cycle time performance differs greatly from this minimum of 12 days as can be seen in figure 5. During the year 2013 the average time a batch spent at curing hall was 16.1 days with median of 15 days.

The data shows a downward trend at the end of the year. This is however just an illusion created by the data used. Only those batches that were finished during the year 2013 were included, so those batches that were left for a longer period at the curing hall due to the Christmas holidays are not in this data set.

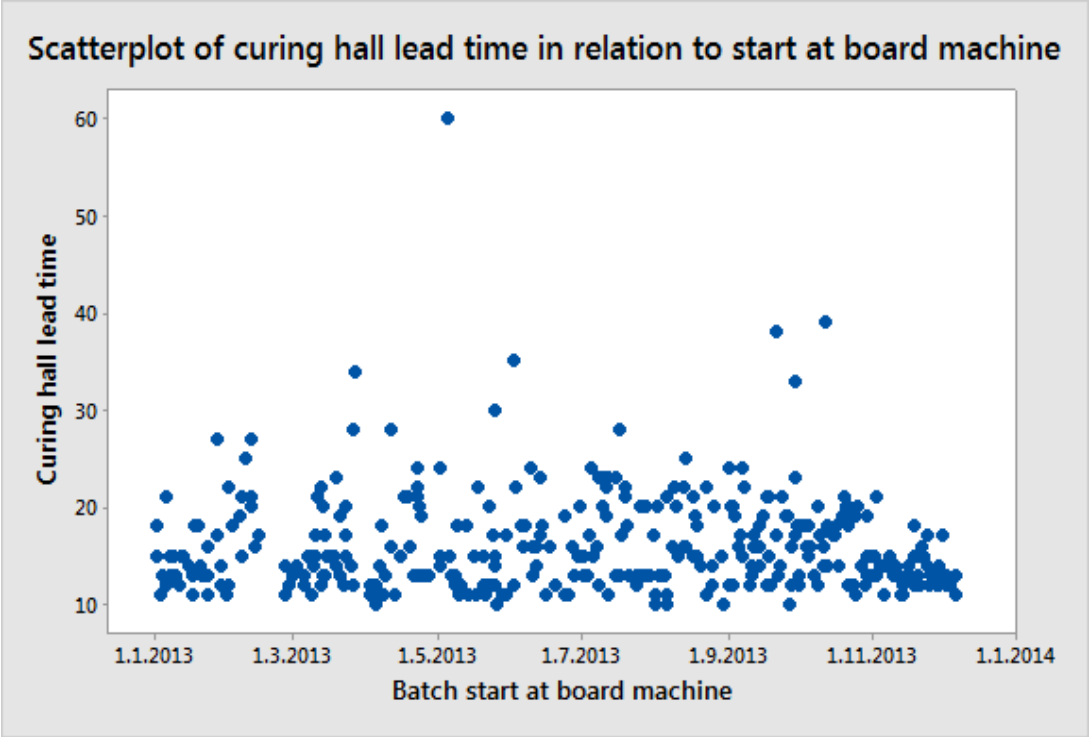

Figure 5. Curing hall lead time throughout the year 2013.

4.2.6 Drying, Cutting and Packing Performance

After the curing hall, every batch is dried, cut and packed before it reaches the FGI. For this process the data used is from a different source. Reason for this is that the last data registration for each batch is done by the production planners. There is a delay for that (which is examined in the next chapter), so for better data accuracy of the drying line performance, a manually maintained data source was used.

As can be seen in figure 6, the lead time at this process steps varied greatly throughout the year 2013. This data gives us an average lead time of 1.57 days and median of 1 day.

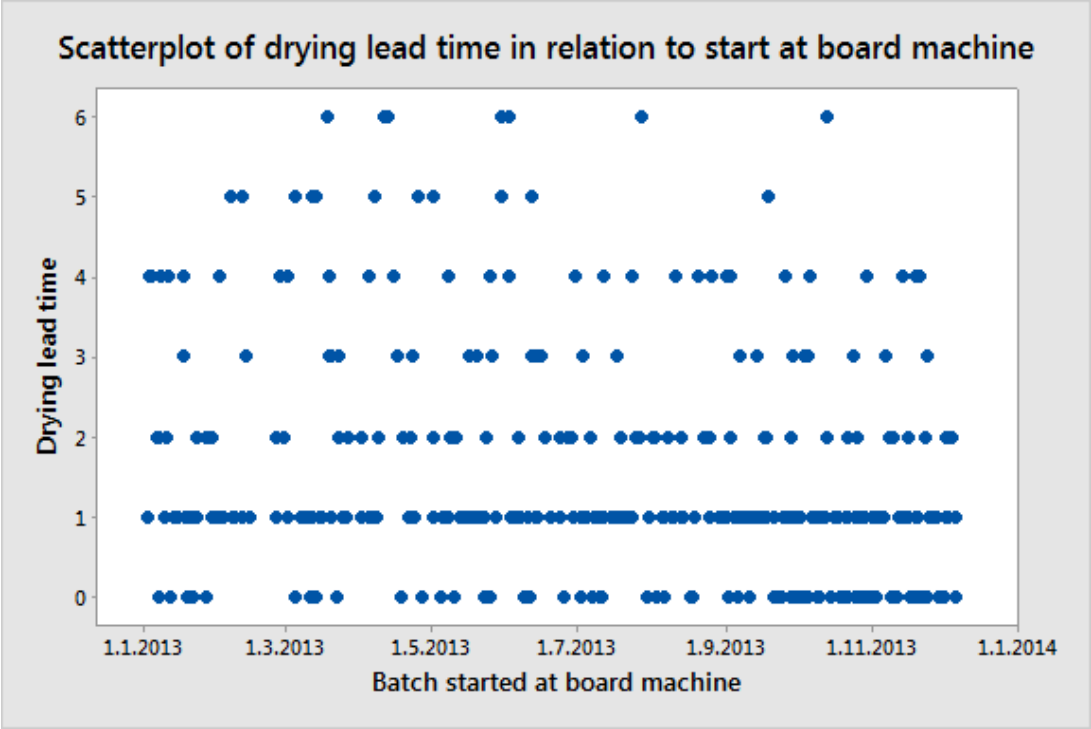

Figure 6. Drying line lead time throughout the year 2013.

4.2.7 Batch Registration Performance

Last thing that needs to be done before a batch is ready at the FGI is to close the work order for the specific batch by registering the batch ready in the company's database. Even though the batch is physically ready it cannot be shipped before the information in the database is up to date. The production planners currently do this work order closure and batch registration. The delay from physically getting the batch ready to the point when the batch is registered ready in the database had an average of 2 days and median of 1 day during the year 2013.

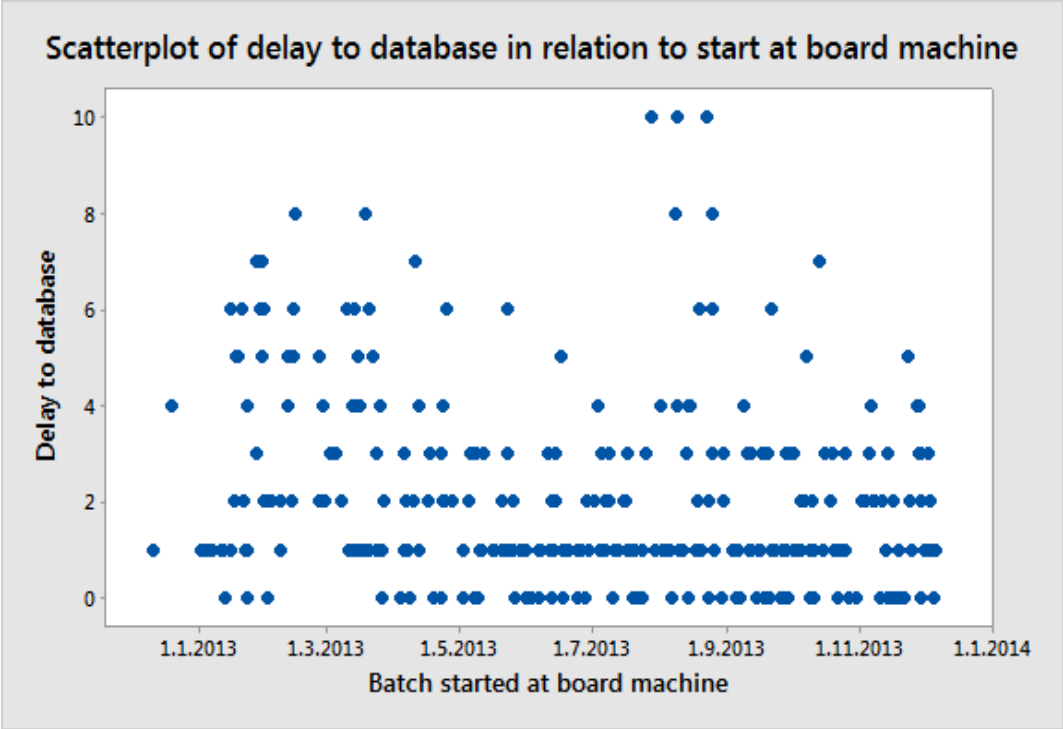

Figure 7. Batch registration delay throughout the year 2013.

4.2.8 Measurement Error

Average lead time for the whole manufacturing process averages at 23.6 days during the year 2013. By summing up the averages of all the subprocesses' lead times we get a 22 days average as shown in table 5. The difference between 23,6 days and 22 days is explained by the round off errors of the individual subprocesses. Reason for this round off is in the data recording system which only keeps track of the dates and not the times for these events. This results in an optimistic estimate of every subprocess performance. For more realistic values, the 1.6 day difference was divided and added to the subprocesses in relation to their proportion of the total time (Table 5).

Table 5. Measurement error of the manufacturing lead time measurement system.

	Board machine	Curing hall	Drying, cutting and packing line	Delay to database	Total time
Original estimate	2.3	16.1	1.6	2	22
Round-off error	0.17	1.17	0.11	0.15	
Final estimate	2.47	17.27	1.71	2.15	23.6

4.3 Analyze

As a result of the measure phase, the current performance of the manufacturing process and its subprocesses are now known. Next step is to take this performance data and find out both the gap between current and optimal performance as well as reasons behind the performance gap. For this analysis, linear regression analysis, theories presented earlier and interviews with key personnel were used. This chapter answers to the following questions:

- What are the potential root causes behind lead time variation?
- How much of the variation do these factors explain?
- What are the missing factors that explain the remaining variation?
- What is the best possible lead time with this system design?
- In terms of Y=f(x) what is the gap between current and optimal performance?

4.3.1 Potential Root Causes

Lean methodologies are heavily focused on lead time reduction. Therefore many of the potential root causes described in this chapter were found by looking at the manufacturing process from a perspective based on lean principles. The focus in this

chapter is on root causes that can be controlled with a reasonable effort. Root causes that require more effort to be controlled, significant investments or further analysis, are discussed later.

One of the factors affecting manufacturing lead times is the batch size used. Lowest possible lead time would in most cases be reached with a batch size of one item. However, in many cases the batch size of one is either unreachable or just not desirable from a financial view point. Never the less, the larger batch sizes are, the longer the manufacturing lead times per batch will be. Therefore the first potential root cause is the use of large batch sizes.

The measure phase of the project revealed another relatively obvious root cause. The last process step concerning batch manufacturing was identified to be the registration of the batch to the FGI. Execution of this procedure does not take more than a few minutes, but the delay at which this was done was found to be on average over 2 days. This work procedure incorporates so much non value adding time in relation to the nonexistent value added to the customer that this potential root cause can be named a certain root cause without any further analysis.

Interview with the production manager revealed other issues that affect especially the curing hall and drying lines. First of all, in order to keep the drying, cutting and packing lines running at highest possible utilization, some buffer stock was knowingly always kept at curing hall. By doing so the drying, cutting and packing lines never lacked products to process. Even though some variation occurs at board machine output and some batches may not reach the quality requirements, the end of the process never lacked items to process. By doing this the end of the manufacturing process may have been (cost) optimized, but the overall performance was suffering. This is a good example of a situation where partial optimization decreases the overall

performance of a system. From this we get the third potential root cause which is the queue build up at curing hall.

By allowing a queue to build up at the curing hall, it made it possible for the second factor to emerge. Without a queue there would be no question about which batch to process next. Due to the queue, some batches got prioritized over others at the middle of the manufacturing process. This was done to cope with the poor lead time performance and to ensure that urgent batches got in time to the customer. Such optimization however increased the average queuing time even further as some non-urgent batches were left unattended for longer periods of time. Fourth potential root cause is therefore the non-standardized queuing prioritization from curing hall to drying line.

4.3.2 Batch size effects on manufacturing lead time

First potential root cause that will be taken into closer examination is the effect of large batch sizes. The effects are studied at two process steps, which are the board machine and drying line. Reason for this is that the other two steps that are the curing hall and registration to database are not so heavily affected by batch sizes.

To find out how much the variation in batch sizes affect the lead times, a linear regression analysis was done to both the board machine and the drying line. Linear regression analysis for batch sizes' effect on board machine manufacturing time can be seen in figure 8. It shows that the batch size explains around 50% (R-squared value 49.1%) of the differences between the lead times. When taking into account that there are many other factors also affecting the lead times, such a high R-squared value can be considered to be very significant.

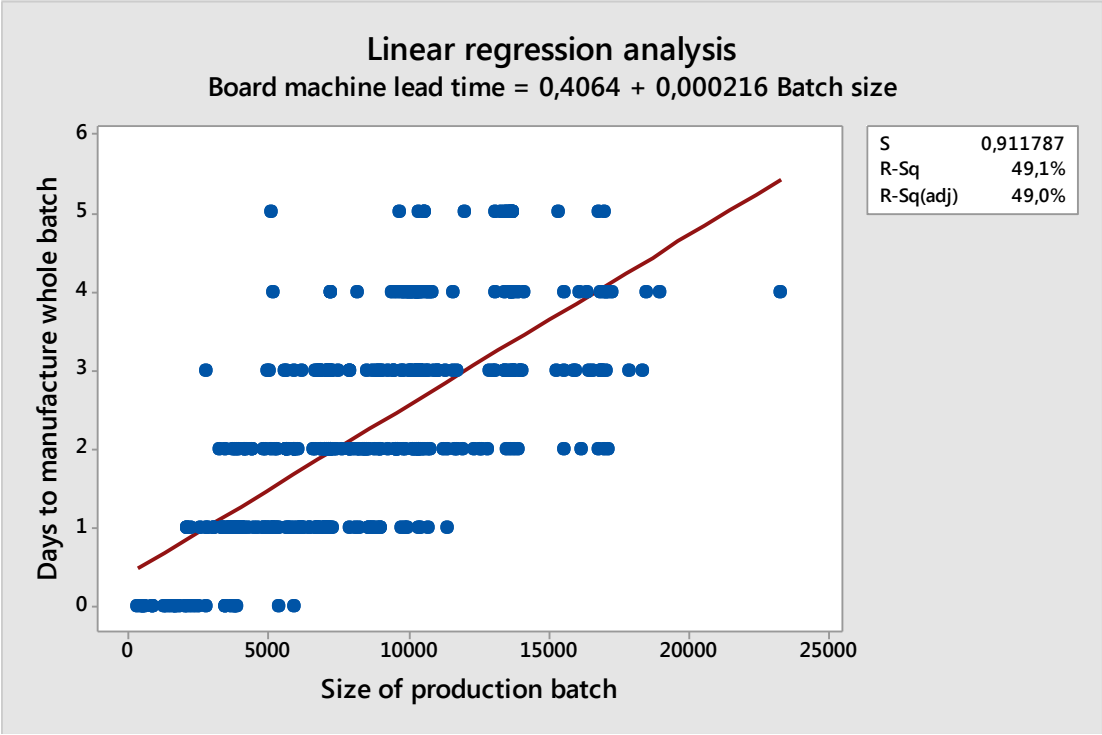

Figure 8. Linear regression analysis of batch manufacturing lead time at board machine in relation to batch size.

The same analysis was also done for the drying line and the results can be seen in figure 9. The amount of variation explained is lower at R-squared value 17.7%. Reasons behind the lower R-squared value were found to be related to non-standardized work procedures.

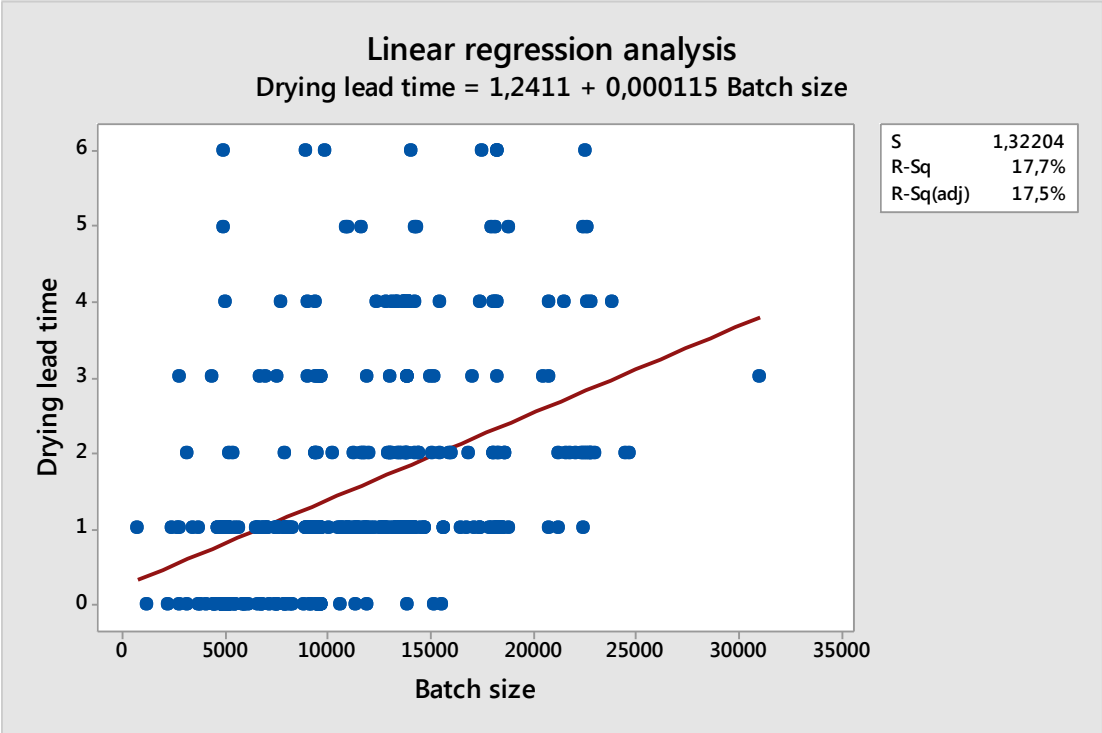

Figure 9. Linear regression analysis of batch manufacturing lead time at drying line in relation to batch size.

The lower R-squared value at drying line is partially the result of work habits. Interviews revealed that when the drying of a batch gets started, it does not always mean that the batch will be dried completely. If part of the batch is in a difficult location in the curing hall, then those might be delayed for later processing by work personnel. One reason for this is that the queue buildup at curing hall has filled the hall so full that some pallets can be in very laborious places behind other pallets.

To sum it up, the batch size does play a major role when looking at the manufacturing lead times. The effects were studied for board machine and drying line phases. Batch size will probably affect the curing hall time as well, but that effect is concealed by other factors that affect the time spent in the curing hall much more heavily. The time it takes to register a batch ready to database on the other hand is not dependent on

batch size. At board machine the batch size explained up to 49.1% of the variation experienced and at the drying line the same number was 17.7%.

4.3.3 Queue build up at curing hall

The curing hall lead time performance plays a major role in the overall manufacturing performance as it forms over 73% of the total manufacturing lead time. This said, the queue that has build up at the curing hall affects the performance greatly. All of the time a batch has to wait in the queue is purely non value added time. In addition to manufacturing lead time, the queue increases WIP also and therefore it increases the average net working capital.

4.3.4 Hidden factors affecting the lead time

Previously presented root causes form only a portion of the total variation experienced in the manufacturing lead time. Other factors were also identified based on manufacturing theories and interviews with the key personnel. Those factors are presented in this chapter and they are either things that only distort the data or are difficult to improve and would require a dedicated improvement project to address them.

As mentioned earlier, the data used for analyzing the performance of the different manufacturing phases, is in the scale of days. The variation in batch start time and end time inside those days causes data inaccuracies. Even though the data shows zero lead time for some batches at some phases, it is not physically possible to process a batch instantaneously. For example, a batch can be started at drying line at 1 am and finished at 11 pm during the same day resulting in a zero lead time even though it took 22 hours to complete. On the other hand if a batch is started at 11 pm on Wednesday and finished at 1 am on the following Friday, the data shows lead time of 2 days even though it only took 26 hours. This distortion only affects analyzes done

on the manufacturing lead times. It does not affect the daily operations at the company, so it can be left as it is.

Partially due to the large batch sizes, some batches experience longer lead times due to work holidays or other scheduled stops. A batch can be started before a holiday and ended after it, resulting in a longer manufacturing lead time. This could be solved by setting up a different kind of work procedure for machine rundowns. However, the effect this issue has on the manufacturing lead time is not so significant that the matter should be strongly pursued.

As previously mentioned, every batch is tested after the curing hall phase. If the batch does not reach the quality requirements, it is given two weeks extra time to strengthen in the curing hall. If the batch does not reach the quality requirements even after that, then the batch is labeled as scrap, or sold as second quality. Any batch that is sentenced for the two weeks extra curing time increases the average lead time as well as the lead time variation. Quality of the product is the result of two set of factors. First is the recipe that is used to make the product. Changes to the recipe will affect the qualities of the products. Second is the manufacturing conditions and settings that are used for the manufacturing process. These also have a great impact on the quality of the products. Both of these are important for reducing the bad quality products resulting in shorter lead times and reduced costs. These issues require separate projects to address them as they are out of this project's scope.

As in almost every manufacturing process, machine breakdowns have a large impact on lead time performance. This is true at Cembrit also. Machine breakdowns increase both the average lead time as well as the variation seen in the lead times. This is an important issue that needs to be continuously monitored and improved. Focus should be on reducing both the mean time to failure and the mean time to repair. However,

the scope of such improvement is well outside the boundaries of this project and should be approached separately.

4.3.5 Improvement opportunity

Effects of batch size reduction, queue removal and database registration automation were then estimated to find out the best possible manufacturing lead time that is reachable without major investments or changes to the current process. First of all due to the nature of this manufacturing process, the ideal batch size of one piece is not reachable. Never the less, even if the batch sizes were to be reduced so that under normal circumstances it would never take more than 24 hours to produce, the effects would be significant on the manufacturing lead time. This would mean that the time required at both board machine and drying line would drop to around 1 day.

Secondly by eliminating the queue from curing hall the overall process can be improved further. The curing should only take 10 days plus two days for the test results. This means that in optimal conditions the curing should only last 12 days per batch. Immediate drying after the test results will probably not be reachable always and some variation will always occur at some point of the overall process so for a not too optimistic estimate, we will add a 0 to 2 day margin to the target lead time estimate at this step. With this, the calculatory estimate for curing hall target lead time is set to 12 to 14 days.

In addition, the way a batch is registered ready to the company's database should be changed. This is a clear waste where the product is physically ready, but cannot be shipped because the information regarding the batch is not up to date. Easiest way this can be done is to authorize the personnel at drying line to make the registration to the database. This will ensure that the products are ready for delivery as soon as they are physically ready. By doing this, the 2.15 days average delay that it took to register the batch ready during the year 2013 can be eliminated completely.

Table 6. Improvement opportunity.

	Board machine (X)	**Curing hall (X)**	**Drying, cutting and packing (X)**	**Delay to database (X)**	**Total lead time (Y)**
Final estimate of past performance (days)	2.47	17.27	1.71	2.15	**23.6**
Estimate of performance after improvements (days)	1	12-14	1	0	**14-16**
Improvement (days)	1.47	3.27-5.27	0.71	2.15	**7.6-9.6**
Improvement-%	60 %	19 - 31 %	42 %	100 %	**32 - 41 %**

When looking at the combination of all these improvements, we get a major improvement opportunity as can be seen in table 6. The total manufacturing lead time can be reduced by 7.6 to 9.6 days, in other words by 32% to 41% without any major investments. In building materials industry where customers are very concerned about their schedules, over one week reduction to production lead time can be considered as a remarkable improvement. This improvement opportunity is also added to the Y=f(x) progression seen in table 7.

Table 7. Y=f(x) function development - analyze step.

Phase	Y=f(x) goal	Result
Define	Identify and choose business Y's	Manufacturing lead time was chosen as the business Y.
Measure	Identify X's	Lead time performance of board machines, curing hall, drying lines and registration to FGI were identified as X's that drive the performance of the Y.
Analyze	Estimate improvement opportunity for Y and each X	Total improvement opportunity for the Y was estimated to be 32 - 41 %.

4.4 Improve

As a result of the previous phase, the root causes behind the poor performance are known. In addition, the improvement opportunity for each X and the Y is known. Based on the previous phases, this chapter presents a set of solutions to address the root causes. The solutions are then explored deeper, explaining how those address the root causes and what are the adverse effects these solutions bring to the process. This chapter answers to the following questions:

- What are the recommended solutions?
- How do these solutions address the root causes?
- Do these solutions cause any adverse effects?

4.4.1 Recommended solutions

In this chapter the recommended solutions are presented and more detailed explanations to how the solutions address the root causes are given. The solutions are based on the findings described in the previous chapters. These solutions are also listed in Table 8.

Table 8. Y=f(x) function development - improve step.

Phase	Y=f(x) goal	Result
Define	Identify and choose business Y's	Manufacturing lead time was chosen as the business Y.
Measure	Identify X's	Lead time performance of board machines, curing hall, drying lines and registration to FGI were identified as X's that drive the performance of the Y.
Analyze	Estimate improvement opportunity for Y and each X	Total improvement opportunity for the Y was estimated to be 32 - 41 %.
Improve	Define changes required to X's to reach optimal Y	Optimal performance of Y requires smaller batch sizes, queue removal from curing hall and bottleneck shift to board machines, FIFO queuing to drying and changes to batch registration to database.

4.4.1.1 Smaller batch sizes

When trying to reach shorter lead times, the reduction of batch sizes is an important factor. This does not mean that a single unit batch size is a necessity, but that smaller sizes should be pursued. Optimal batch size is established by evaluating the pros and cons for different sizes.

In order to capture the calculatory benefits to lead time presented in the previous chapters, the batch sizes should be reduced at least as much as to ensure that the production of a single batch does not take more than 24 hours at board machine. However, because the production system gives several advantages for producing long runs of the same products continuously, several batches of the same product should be allowed to be manufactured in succession.

In addition to shorter manufacturing lead time, there is also another significant benefit from smaller batch sizes. Because the quality testing and possible rejection is done on a batch by batch basis, smaller batches mean that fewer number of products are delayed in case the tests indicate bad quality products. Possible quality problems often occur in a relatively short time period. Thus, if a batch of 30 000 boards is manufactured and 5 000 of those are of bad quality, the whole batch will be stopped and sentenced to 25 days of extra curing and follow-up testing. If that batch of 30 000 would have been split into four batches the size of 7 500 boards, the delay would only have been for one or two of those batches, meaning that 15 000 – 22 500 boards or in other words 50-75% of the total production amount would have passed the testing, on contrast to 0% with a batch size of 30 000.

The number of samples taken from each batch for quality testing, is given by standard EN12467 and related sampling standards. Smaller batch sizes will increase the total number of samples required. This will add both positive and negative effects, the latter of which will be discussed later. The positive effect is that the quality data regarding the products is more comprehensive throughout the production of each batch. This will make the quality data more accurate in describing the actual quality of the batch.

To sum it up, smaller batch sizes reduce the average manufacturing lead time, ensure a much steadier flow of products to FGI and reduce the risk of late deliveries due to quality problems. It also makes the quality data more comprehensive throughout each batch.

Meeting with the production planners and their director was held to determine the batch sizes that would be used in the future. After discussing about the positive and negative effects, a decision was made to set the batch sizes to 5 000 and 7 500 boards. This means that for example if 20 000 boards of a specific product are needed, then

consecutive batches of 7 500, 7 500 and 5 000 will be manufactured. First of all this means that the first set of 7 500 boards are ready to be delivered much faster than the 20 000 batch. Secondly, even the last 5 000 batch will be ready to be delivered faster than the 20 000 would be. Last but not least, if any quality problems occur, it will most likely mean that only one of those smaller batches is delayed in contrast with the whole 20 000 boards delayed.

4.4.1.2 Bottleneck location and excess queue

In order to reduce manufacturing lead time Little's Law suggests that there are only few options: increase process throughput, reduce WIP or do both. Largest amount of WIP in the manufacturing process in question resides in the curing hall waiting for drying. This means that in order to reduce the manufacturing lead time, the excess queue should be cleared from curing hall. If the level of items in curing hall is kept low, the overall WIP will be reduced significantly. By the definition of Little's Law, the average lead time is bound to decline if the excess queue in curing hall is eliminated at the same time as the throughput stays at least the same and no WIP increase occurs anywhere else in the process.

The logical reason for the queue in the curing hall is that the throughput of board machines has been higher than the throughput of drying lines for quite some time. Thus, the only way to reduce the queue in curing hall is to increase the throughput of drying lines to a higher level than of the board machines. Furthermore, if the capacity of drying lines is kept on a higher level than of the board machines after the queue is eliminated, it will ensure that such queue cannot emerge again under normal circumstances as the bottleneck of the overall process is shifted from drying lines to board machines. This type of excess capacity that would be in use at the drying lines does increase the overall labor costs at that process step, but at the same time it will make sure that the manufacturing lead time stays as short as possible.

4.4.1.3 First in first out queuing

In order to ensure low variation and lowest possible mean of manufacturing lead time even with the queue in the curing hall, the drying order of batches should be base on first-in-first-out (FIFO). First of all this will make the production planning simpler as there will be only one criterion for the drying order. Secondly, FIFO will ensure that no batch will needlessly have to wait for excess periods of time for its turn to be processed further. Thirdly and partially as the result of the two prior benefits, this will reduce the variation of production lead times. Lesser variation makes the production plan more accurate and therefore the information of delivery capability for specific orders will be known earlier, resulting in better customer service level.

4.4.1.4 Batch registration to database

Last step of the manufacturing process is the batch registration as ready to FGI. The procedure does not take much time, but as long as it is not done right after the physical production of a batch is complete, it will add non value added time to the lead time. Therefore the batch registration should be done by the work personnel right after the batch reaches FGI. This procedure should be made as simple as possible by modifying the database interface at the workstations.

4.4.2 Negative effects

All the changes recommended do not come without some unwanted effects or costs. These disadvantages need to be identified, estimated and minimized before the implementation decision and the actual implementation occurs. Some of these costs or extra work can be implementation related one time hindrances and others might add work or costs to the process permanently.

4.4.2.1 Smaller batch sizes

Smaller batch sizes also mean more batches for a given time unit. This means that if there is any work that needs to be done fixed number of times for each batch, then the amount of work done increases. When looking at the manufacturing process at Cembrit, there are few of these work procedures that need to be done for each batch. First of all, production planners schedule the production batch per batch. The more batches are planned into the system, the more work is needed to change the schedule. However, the scale of this extra work is insignificant.

Second negative effect from smaller batch sizes is related to the quality testing. The number of boards to be tested per batch is set by the quality standard the factory is following. Smaller batch sizes will result in a small increase to the number of boards tested per given time unit. The test that is done to the boards is destructive so the tested boards go to scrap. In addition, the testing procedure requires manual work, which will also increase by the sample amount. These costs and extra work should be manageable.

Thirdly, the smaller batch sizes will mean that there are more batches in the manufacturing process at the same time. Higher number of batches increases the chance for mix ups when moving the pallets from place to place. This effect should be small in scale and diminish after the initial bafflement.

Different work phases require data entries to the company database. Higher number of batches will result in higher number of entries done at the workstations. This extra work is not major in scale and should be manageable.

4.4.2.2 First in first out queuing

Most of the extra work related to the FIFO queuing at curing hall is related to logistics. The hall is relatively small and it needs to be restructured for the batches to be accessible in the correct order. This should be done so that no pallets require to be moved back and forth just to access other pallets. Otherwise the FIFO principle will result in extra work for forklift drivers and increased the probability for item damage due to excess transfers. Restructuring the curing hall will require extra work, but when done correctly, it should result in a more logical structure and give easier access to those pallets that are going to be processed next.

4.4.2.3 Bottleneck location and excess queue

Most significant improvement to the manufacturing lead time comes from the elimination of the excess queue of products that reside in the curing hall. The queue will not vanish unless the throughput of drying lines is increased higher than the throughput of board machines. However, this means that unless the speed of the drying lines is somehow increased, extra shifts are required. Costs incorporated in this improvement are the labor costs for the extra shifts required for queue liquidation.

In order to keep the queue from emerging again in the future, the process bottleneck needs to be moved. For some time it has been the drying lines, but as explained before, by making the drying lines the bottleneck of the process the excess queue was able to arise. However, if the bottleneck is changed from drying lines to board machine, such queue should not be able to form. This means that the drying lines' capacity needs to be increased to a little bit higher level than the board machines'. Costs from this are related to the extra capacity at drying lines. If the drying lines have a higher capacity than board machines, then there will also be some idle time for the drying lines. This is a strategic decision that ensures minimal manufacturing lead

time and variation of it on the cost of higher labor costs at drying lines, unless the speed of the drying lines is somehow increased.

4.4.2.4 Batch registration to database

Changing the batch registration to FGI procedure requires some adjustments to data entry system. These changes can be done by the service provider. This of course means that there are some costs related to the implementation phase, but after these changes are done, the system should run without any additional costs. Marginal increase to drying line personnel work is possible.

4.5 Control

As a result of the previous steps, the recommended solutions are now known as well as the positive and negative effects these solutions bring to the system. During the last step of the DMAIC process, the implementation responsibilities are given to the key personnel. In addition, measurement systems for the monitoring of these implementations are recommended. Later on the Y=f(x) function is finalized and other potential projects listed. This chapter answers to the following questions:

- Have the improvements been approved?
- How will the process be monitored to ensure effectiveness of solution?
- Who are responsible for these measurements?
- What is the final form of the Y=f(x) function?
- What other potential projects were identified during this project?

4.5.1 Implementation approval

Important part of getting improvements approved is to convince the responsible persons of the implementation's superiority over the current practice. For this purpose it is important to clearly present the historical performance, compare it to the

performance estimated after the improvement and present the benefits and negative effects of the implementation.

Responsible persons for the implementation of smaller batch sizes and FIFO at curing hall are the production planners and their director. Other related persons are the production manager and process development manager who are responsible for many of the affected areas in the factory. This group of people has the authority to drive the change and the knowledge to ensure that the change is possible to execute from a practical point of view. A meeting was held to discuss about the effects of these changes. The findings presented in the previous chapters were shown and discussed further. A mutual understanding was achieved about the overall effects of such change. With a consensus, the implementation of smaller batch sizes and the use of FIFO principle was approved and set in motion.

As previously stated, the queue removal from curing hall requires that the capacity of drying lines is increased to a higher level than the capacity of the board machines. As the solution for this problem is to add extra shifts to the drying lines and therefore increase labor costs at those workstations, the nature of this bottleneck shift is a more strategic decision. For such decision the persons with authority to approve the change are the managing director and production manager. The findings presented in the previous chapters were presented to them. After discussing about the pros and cons of this change, the decision was made to shift the bottleneck to the board machines. This decision together with the smaller batch sizes and FIFO will enable the physical part of the manufacturing lead time to reach its improvement potential that was presented in the analyze phase of this project.

The last improvement, which is the batch registration to database, is more focused on information flow rather than physical production. This case was presented in the same meeting as the smaller batch sizes and FIFO principle. The approved idea was that the

registration should be integrated into the database interface currently in use at the drying line workstations. Thus, it should not increase the workload at the workstations noticeably, but speed up the batch registration to FGI by more than two days.

4.5.2 Process monitoring and responsibility areas

Even though the implementation of the proposed changes has been approved, it does not mean that the implementation is dead certain. For this purpose, it is of vital importance to name the persons responsible for each implementation, agree on a schedule of the implementation and set up a monitoring system that indicates the successfulness of the implementations.

Out of the four improvements, three are almost purely implementable by the production planners, thus on the responsibility of their director. Those three are the smaller batch sizes, FIFO at curing hall and batch registration to database. These improvements do not require a sophisticated measurement system as they are easily observable. Production planners set up all the batch sizes and schedule drying order of batches. This means that the implementations are easily manageable as there are only few persons who control these process steps. Implementation of batch registration at workstations was also assigned as a responsibility for the production planners. All these three improvements should be implementable in a short time period and no separate monitoring is needed.

The fourth improvement is the elimination of queue build up at curing hall and the shift of bottleneck from drying lines to board machines. Out of the improvements, this will offer the most significant improvement to the manufacturing lead time. Therefore it is important that this implementation is closely monitored. Another reason for monitoring of this implementation is that it is not as plain and simple to perceive as the other three improvements.

Several aspects need to be considered when setting up a monitoring system for the queue removal and bottleneck shift. In this manufacturing system the production speed depends highly on the product family and final dimensions of the product. Therefore the queue build up at curing hall cannot be accurately monitored on the basis of pieces. A better unit of production amount that illustrates the production speed throughout the range of products and dimensions more equally is cubic meters of products produced. This measurement could be followed on a weekly basis by comparing the cubic meters produced at board machines and the throughput cubic meters of the drying lines. As long as more cubic meters of products go through the drying lines than are produced at the board machines, the excess queue will diminish. Because the capacity increase at drying lines requires extra shifts, the implementation is on the responsibility area of the production manager.

Even though it is important to follow the implementation of all these improvements individually, the overall performance should also be monitored. Reduction of manufacturing lead time and net working capital were some of the goals set for this project at the very beginning. The improvements recommended will reduce the manufacturing lead time by reducing the WIP in the process. This WIP reduction has another benefit also as it reduces the average net working capital. These changes could be monitored by following how the WIP and overall manufacturing lead time shape up after the implementation. The outputs of these measurements give a good indicator of the manufacturing system's overall performance. However, these types of measurements only indicate the past performance of a process.

There is also a way to predict the future performance of manufacturing lead time in a short time frame. By the definition of Little's Law, the manufacturing lead time is calculable by dividing WIP with the process throughput, which in this case is the output of the drying lines. This type of measurement would give a good estimate of the manufacturing lead time for the following weeks. As a result, the future

manufacturing lead times are approximately known and more accurate estimate of delivery ability can be given to customers. In addition, as WIP is an important part of the average net working capital, this measurement will indicate whether the process is improving or getting worse in this area also.

4.5.3 Finalizing the Y=f(x) function

Building up the Y=f(x) function was one of the tools used in this project. It helps to keep track of the different phases of the project and present them in a summarized way. The final version of the Y=f(x) progression can be seen in table 9.

Table 9. Y=f(x) function development - control step.

Phase	Y=f(x) goal	Result
Define	Identify and choose business Y's	Manufacturing lead time was chosen as the business Y.
Measure	Identify X's	Lead time performance of board machines, curing hall, drying lines and registration to FGI were identified as X's that drive the performance of the Y.
Analyze	Estimate improvement opportunity for Y and each X	Total improvement opportunity for the Y was estimated to be 32 - 41 %.
Improve	Define changes required to X's to reach optimal Y	Optimal performance of Y requires smaller batch sizes, queue removal from curing hall and bottleneck shift to board machines, FIFO queuing to drying and changes to batch registration to database.
Control	Manage X's and monitor Y	Implementation responsibilities for X's improvements were given to key personnel. Recommendations were given to monitor the curing hall WIP level and overall manufacturing lead time traditionally or by using principles of Little's Law to predict future performance.

4.5.4 Other potential projects

During the project several improvement opportunities were identified and the ones that appeared to give the best benefits within the time limitations of this project were chosen. After this project the other improvement opportunities should also be addressed. These include optimization of product recipes, optimization of board machine operating parameters, optimization of drying line operating parameters, setting up raw materials control, setting up the measurement system that ensures efficient tracking of production on different organizational levels and developing a measurement that provides reliable information about product's quality right after the board machine phase. There lies a great improvement potential in each of these issues and going through all of them systematically would increase the process overall capability significantly.

5 OVERALL PROJECT BENEFITS

Goals for this project were to decrease the average net working capital, increase on-time delivery percentage and increase sales through reduced delivery times and increased customer satisfaction. These goals were then approached by focusing on reducing the manufacturing lead time as well as its variance. The overall benefits that the suggested improvements offer are however wider than just the original goals. When assessing the successfulness of a project, it is important to understand the total scope of the benefits. For this purpose, the different aspects of the benefits offered by the improvements are presented in this chapter.

5.1 Benefits from Lower Manufacturing Lead Time

The main focus in this project was to improve the chosen business Y which was the manufacturing lead time. As a result, a set of improvements were recommended that would reduce the average manufacturing lead time by a total of 7.6 to 9.6 days. This reduction gives several benefits for the target company and those benefits will now be explained more deeply.

The reason why companies keep buffer stocks of finished products, is to answer to customer demand fluctuations. In addition to buffer stocks, there are only two ways to buffer against demand spikes. One is to give a long delivery lead time to the customer, thus buffering with time. The second is to have excess capacity for the demand spikes, thus buffering with capacity. If the demand would always be known far to the future and no uncertainties would occur in the manufacturing process, then there would be no need to keep stock of finished goods. This however does not happen in the real world. Cembrit's strategy is to have the most common products manufactured with MTS principle. When the target stock levels are defined, an important factor of the calculations is the manufacturing lead time, as it tells how fast

the company can react to demand spikes. This means that lower manufacturing lead time enables lower FGI levels for a given customer service level. Thus, when the manufacturing lead time reduction is realized, the company can lower its FGI levels by an estimated (by the company's financial rep) 800 000 €. Because the FGI is a part of the average net working capital, this reduction will affect it directly, as long as the FGI levels are redefined after the manufacturing lead time reduction has been realized.

There is also another dependence between lower manufacturing lead time and lower average net working capital. When looking at the Little's Law, it is clear that if the throughput of a production system stays constant and the manufacturing lead time is lowered, then the WIP will also get lower. Thus, in the long run a lower average manufacturing lead time will result in lower WIP, which is a part of net working capital. This reduction was calculated to settle down to around 100 000 – 125 000 €. When combining the WIP reduction with the FGI level reduction, the total reduction of net working capital is estimated to be 900 000 – 925 000 €.

In addition to direct financial benefits, the reduction of manufacturing lead time offers also benefits to customer lead times. As mentioned earlier the faster manufacturing lead time enables lower FGI levels for the MTS products. Some products are however made to order. For these MTO products, the manufacturing lead time reduction affects directly to the customer lead time. Over seven day reduction to the manufacturing lead time of MTO products can be a deal breaker when it comes to construction projects with tight schedules. These kinds of improvements are hard to estimate exactly in numbers, but it is clear that they offer major benefits that should not be overlooked.

5.2 Benefits from a Return on Investment Point of View

ROI (return on investment) is often presented from a finance point of view. However, this viewpoint does not offer a very in depth understanding of the manufacturing aspects that contribute to the overall performance. Hopp and Spearman present (Figure 10) some of the different aspects that are eventually perceived as ROI. This viewpoint is very useful in understanding the effects different changes bring to the whole system. Out of these different components, the ones that will be most heavily influenced by the improvements presented in this work are highlighted in green color.

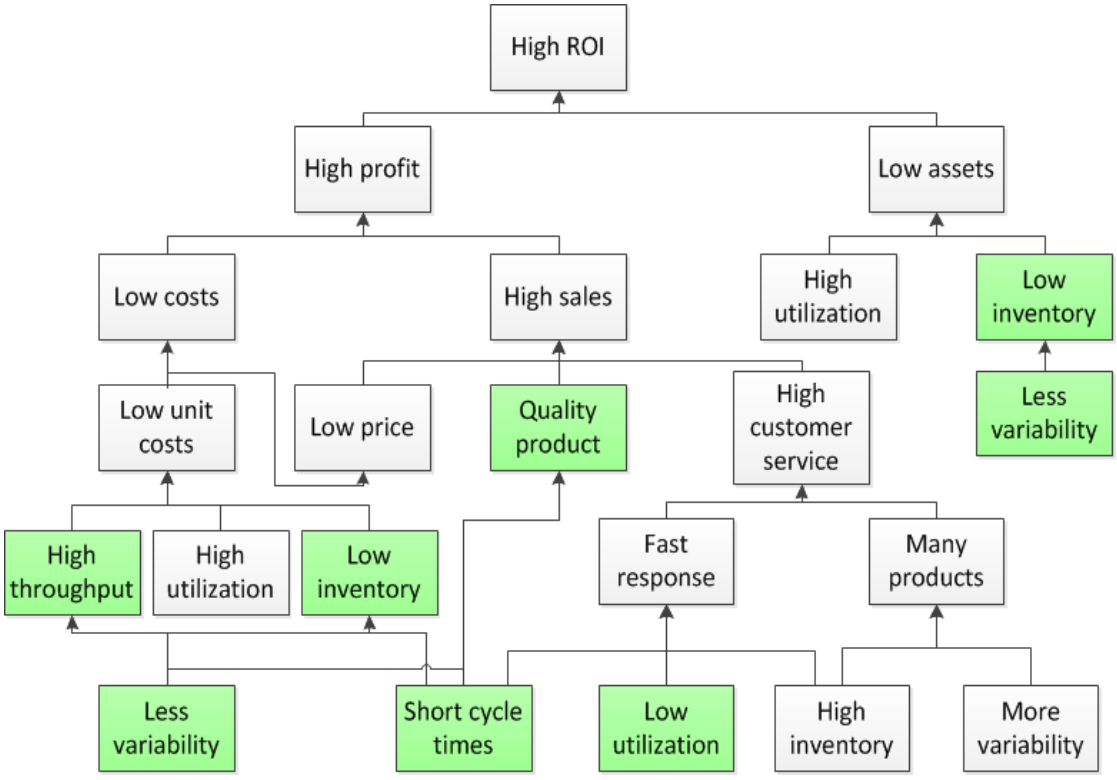

Figure 10. Return on investment hierarchy in a manufacturing company. (adapting Hopp & Spearman 2008, p. 207)

As can be seen in figure 10, shorter manufacturing lead time together with lower utilization at the process bottleneck (drying lines) contribute to faster response time and higher customer service. Higher customer service leads to increase of sales in the

long run. In addition, shorter manufacturing lead time allows lower inventory levels. Lower inventory levels then lead to lower costs and higher profits. Another benefit of lower inventory levels is that it also lowers assets. Thus, the overall benefits these improvements offer are much wider than the benefits that are easily calculable after the implementation.

6 CONCLUSIONS

The goal of this research was to improve the target company's manufacturing lead time. This was to be done using the Lean Six Sigma improvement process DMAIC, in order to illustrate the use of this methodology and related tools. In addition, the system evaluation and solution formulation were to be done based on data analyzes of the process data. Thus, illustrating how to base the decision making on actual data rather than intuition and guesswork.

The project succeeded in its goals. The production batch sizes were quickly reduced to 5 000 and 7 500 pieces in order to reduce the lead times at board machine and drying line. The curing hall queue built-up was eliminated and the batch scheduling was transformed to follow FIFO principle. By the end of this research, the average manufacturing lead time had dropped from 23.6 days to around 15 days meaning a total of over eight days and 36% improvement. This was reached even though the batch registration to database was still under development, so further improvement will occur in the near future. Such overall improvement is major in the field of construction materials manufacturing where majority of customers are working on tight schedules.

After the project, one of the challenges for the target company will be to sustain the gains and improve even further. The threat of performance degradation is always present. A good example of this came when one of the two drying lines was under renovation, the queue in the curing hall started to build-up again resulting in lead time performance deterioration. It is important that such situations are recognized quickly and actions taken without delay.

Even though the project as a whole was a success, some parts of the project could have been executed a bit better. Firstly, some of the improvement implementations

took much longer than expected and partly due to that the benefit realization took much longer than expected. Secondly, the new batch sizes were set to 5000 and 7500 pieces. These sizes were decided after evaluating the pros and cons on a rough level with key personnel. A more in depth analysis would have most certainly resulted in different kind of batch size. This was however considered more tedious to execute than the benefits gained from it. In addition, the quality sampling rules set by the EN12467 and related standards limited the possibilities at some level.

One of the challenges of LSS is that the appropriate tools for each step of each project need to be selected. The total number of tools is great, but many of those work on only specific kind of projects and problems. This means that the LSS specialized individuals (GBs, BBs and MBBs) need some intuition and experience for selecting the right tools and no more, for the tasks at hand. If the tool selection is not on a sound basis then either excess time is used for usage of too many tools, or the tools that are needed for finding the optimal solution are not used. Thus, whether the LSS projects of an company wields significant bottom line results or not is quite heavily related to the quality of the LSS training and the capabilities of the trained personnel.

Even though many processes in a manufacturing environment can be calculated or simulated, it is often rather time consuming. In order to make good decisions in a suitable time frame, the persons making the decisions need some kind of knowledge regarding the subject or related cases. This type of knowledge is often mainly experience based. However, lean tools and methodologies are good examples of this type of knowledge. There is for example no need to simulate and calculate the optimal batch size in a manufacturing environment where one piece batch size is reachable without additional costs or other disadvantages, the one piece batch size will lead to the fastest manufacturing lead time in such environment. By gaining such knowledge, the decision making process of almost any type of improvement project can be quickened. This applies to the Six Sigma DMAIC process also. Even though

the main idea of Six Sigma is to base the decisions on actual data and prove that the improvements will work by for example executing experiments, some of the problems faced in these projects do not need such a heavy process to solve them.

What Six Sigma and Lean Six Sigma exactly are, is something that many authors describe differently. It seems that a great many articles describe Six Sigma only as a variation reduction program. Even though the origins of Six Sigma and the term itself are focused on variation, the Six Sigma methodology has developed much further from the 80's. For example, the DMAIC process was introduced in its current form much later than the Six Sigma concept itself. Studies on different usages of the DMAIC can easily be found and it truly seems that it works well in almost any kind of improvement project. Furthermore, it seems that combining Lean and Six Sigma into Lean Six Sigma has widened the scope of problems that can be solved using the DMAIC process. All in all, it seems that the Six Sigma methodology has developed from its original scope of variation reduction in manufacturing to a much more comprehensive LSS methodology that can effectively be used to improve processes throughout different industries.

The project described in this work is one of those projects that benefited from the use of Lean tools inside the DMAIC structure. Lean offered some of the basic principles behind optimal production flow. These principles guided the direction of the project in many of its phases. At the same time the tools of Six Sigma enabled the scientific analysis of the data and accurate estimations of process improvement potential. In addition, the DMAIC process gave a clear framework through which the project was easy to systematically execute. Based on the experiences from this manufacturing lead time improvement project, it can be said that the Six Sigma improvement process DMAIC can benefit considerably from the incorporation of Lean tools to its different phases. The DMAIC process itself worked well in this type of project, guiding the project through the different phases and ensuring that no shortcuts were

taken. For example, the second phase “Measure” includes the evaluation of the measurement system accuracy, which is easily to forgotten. If such an important step would be skipped, then the project team cannot be certain of the actual performance of the system and the conclusions would be based on possibly false data.

7 SUMMARY

The goal of this research was to improve the target company's manufacturing lead time. In addition, the goal was to demonstrate how this type of project can be executed using the Lean Six Sigma methodology. To better understand the Lean Six Sigma concept, both Lean and Six Sigma methodologies were studied.

The project described in this work is one of those projects that benefited greatly from the use of Lean Six Sigma. Lean offered some of the basic principles behind optimal production flow where as Six Sigma enabled the scientific analysis of the data and accurate estimations of process improvement potential. These together with the structure of DMAIC ensured that the project stayed on track and that no shortcuts were taken.

Six Sigma projects are systematically executed processes that have the goal of reducing unwanted variation in processes to ensure better quality for processes and products. The methodology itself started in Motorola in the late 1980's and it has been developed ever since. Six Sigma projects have a basic team structure. In the project described in this work, the researcher acted in the role of black belt. Black belt does most of the data analyzes and acts as the project manager and leader. In addition to a basic team structure, Six Sigma also has a basic predefined process for project execution. This process consists of five steps that are Define, Measure, Analyze, Improve and Control (DMAIC).

Lean on the other hand focuses more on waste removal and work streamlining. The ultimate goal of lean is zero waste in all processes. The different types of wastes are divided into eight categories to better perceive possible improvement areas. Like Six Sigma, Lean methodology also recognizes the effects of variation in processes. Some

level of variation is always present in processes and it leads to three types of buffers, which are inventory, time and capacity.

The project was executed according the Six Sigma improvement process DMAIC with lean tools incorporated into the different steps. This combination of lean and Six Sigma is commonly referred as Lean Six Sigma.

In the define phase, a business problem was chosen for this project. The business problem was identified to be inadequate on-time delivery percentage. Initial discussions about the manufacturing system revealed that the manufacturing lead time fluctuates greatly. In addition, the manufacturing lead time is not systematically monitored. Based on these problems, three main business goals were set for the project: a decrease of average net working capital, an increase of on-time delivery percentage and an increase of sales through reduced delivery times and increased customer satisfaction. From these business goals, two opportunity statements were created: "Variance and lead time reductions for item manufacturing would increase Cembrit's delivery accuracy to external customers." and "Lead time reduction would decrease average net working capital.". Out of these, at least two measurable business Y's can be identified: manufacturing lead time and average net working capital. Out of these, the manufacturing lead time was chosen as the main focus of this project.

Second step was the measure phase. At this point the related processes were identified and studied. The performances of both the overall system as well as the individual processes were estimated based on the process data. In addition, the data was studied to evaluate its accuracy and possible measurement errors. As the result of this step the related processes were identified and the overall performance of the manufacturing system's lead time during the year 2013 was estimated to be 23.6 days.

Third step was the analyze phase. During this step, the performance data was studied further to find out both the gap between current and optimal performance as well as the root causes behind the poor performance. The main potential root causes were identified to be large batch sizes, a queue built-up in the manufacturing process and a data registration delay at the end of the manufacturing process. The improvement opportunity for the total manufacturing lead time was estimated to be 7.6 – 9.6 days, in other words 32 – 42 %.

In the improve phase, the recommended solutions were developed. These solutions were as follows: smaller batch sizes, queue removal by bottleneck shift, FIFO order for batch processing and changes to batch data registration procedures. The negative effects these solutions bring were also evaluated and the overall negative effects were estimated to be insignificant.

With the solutions developed, it was time for the last step, control. The purpose of this step is to ensure that the improvements are implemented and the performance monitored so that the performance does not degrade over time. During this step, the improvements were approved by the key personnel in the company and responsibilities for the implementation were given. In addition, a monitoring system was recommended so that the performance is visible for the related personnel.

The project succeeded in its goals. The production batch sizes were quickly reduced to 5 000 and 7 500 pieces in order to reduce the lead times at board machine and drying line. The curing hall queue built-up was eliminated and the batch scheduling was transformed to follow FIFO principle. By the end of this research, the average manufacturing lead time had dropped from 23.6 days to around 15 days meaning a total of over eight days and 36% improvement. This was reached even though the batch registration to database was still under development, so further improvement will occur in the near future. Such overall improvement is major in the field of

construction materials manufacturing where majority of customers are working on tight schedules. Faster lead time enables a much better customer responsiveness and it can also be used to offer faster delivery times for customers.

The lead time improvement also brings other benefits for the company. Faster lead time means lower WIP, thus it also means a lower average net working capital. The reduction of average net working capital was estimated to be 100 000 – 125 000 € from lower WIP alone. In addition, when the manufacturing lead time stabilizes to the improved level, the safety stock levels can also be re-evaluated. If the calculation model for the company's MTS levels stays unchanged then the improved lead time would mean an estimated 800 000 € reduction to the stock levels. This gives a total of 900 000 – 925 000€ reduction to the average net working capital in addition to the other benefits the faster lead time offers.

During the project, some challenges regarding Lean Six Sigma were identified. One of these challenges is that the appropriate tools for each step of each project need to be selected. The total number of tools is great, but many of those work on only specific kind of projects and problems. This means that the LSS specialized individuals (GBs, BBs and MBBs) need some intuition and experience for selecting the right tools and no more, for the tasks at hand. If the tool selection is not on a sound basis then either excess time is used for usage of too many tools, or the tools that are needed for finding the optimal solution are not used. Thus, whether the LSS projects of an company wield significant bottom line results or not is quite heavily related to the quality of the LSS training and the capabilities of the trained personnel.

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