Using QRM to improve delivery performance at Larsen Premium Precision Parts

A case study to investigate the usability of QRM

R.H. Knol (s1848941)

1-12-2012
Master Thesis

University of Groningen
Faculty of economics and business
Technology and Operations Management

Author: R.H. Knol
Student number: s1848941

Supervisors: dr. J. Riezebos
dr. G.D. (Erik) Soepenberg

Company supervisor F. te Hennepe

Company information: Larsen Premium Precision Parts
Ambachtsweg 36
3890 BC Zeewolde
The Netherlands
Management summary

Through globalization, competition is increasing resulting in companies that need to compete with others to obtain customer orders. Companies do this by obtaining competitive advantages that are hard to imitate (Hendry, 2010). Lately, this is done by means of faster delivery. Quick Response Manufacturing (QRM) is an approach that aims to reduce lead time in: make-to-stock (MTS), make-to-order (MTO) and engineer-to-order (ETO) companies (Suri, 1998). By doing this not only the market share will grow for a company, but it will also improve quality, reduce costs and eliminate non-value-added waste (Suri, 1998). There are, however, some ambiguities on how to use or apply QRM in certain ETO companies.

First, according to Suri, ETO companies are seen as companies that design and specify products before manufacturing them (Suri, 1998). However, this is quite a simplified view of existing ETO companies. Amaro et al. (1999) describe ETO companies as companies that manufacture customer specific products from the start. This, however, does not mean that designing, determining specifications and/or the purchasing of materials are always done internally. Sometimes the customer itself may supply the design, specifications and/or the materials. This results in ETO companies that are able to manufacture highly customized products, but with less internal responsibilities. This is different from MTO, because here customers cannot choose from a catalogue like in MTO companies. This has not been addressed by Suri and has led to an implementation problem. To reduce lead time, companies should try to find product families based on similar operations (Suri, 1998). Suri acknowledges that this is difficult to do in ETO companies and recommends a more quantitative approach in such cases. However, Suri also states that, if this quantitative approach does not lead to any results, companies should reconsider their product designs and product options (Suri, 1998). But what if companies only manufacture what the customer asks from them? The only influence they have on their product assortment is by declining customer orders. However, this might only be considered if a company has a large amount of back log.

Second, according to Hicks et al., companies can be classified based on their core competences. For example, the competitive advantage in a ‘vertically integrated’ company is their knowledge on products and processes, obtained through years of experience. Suri (1998) calls such people experts and acknowledges that it is difficult to utilize experts within QRM. This because multi training other personnel is hard to do, while knowledge is obtained through years of experience, and knowledge may be lost when an expert is dedicated to a cell/product family. Once dedicated to a cell, it cannot be used for other cells/product families. Nevertheless, Suri claims that companies usually have just a few experts (1998). This because in a QRM company an employee only needs to know that kind of information that is needed for that particular cell. This means that employees do not have to know as much as an expert does. The time of the few experts that remain can be time sliced just like is sometimes done with machines. But what do you do in case of a vertically integrated company where it takes multiple operators years of experience to deliver a certain quality on a machine?

Third, according to Suri, a lot of lead time is reduced by breaking through functional boundaries in the office: every time an order has to go from one person to the next, an order is waiting a lot of time between people or actions (Suri, 1998). Therefore, according to Suri, companies should obtain a flat organization to eliminate the time waste and should multi-train employees to do
multiple tasks. But what if a company is already quite flat and most employees in the office already do multiple tasks? How much time can be reduced and is it worth all the changes?

By means of a case study at Larsen Premium Precision Parts, I have researched to what extent QRM is a suitable solution to improve the delivery performance. Larsen has a flat hierarchical level, has more than one experts working on the shop floor, and is not responsible for the design nor the specifications. To examine the suitability of QRM, first has been researched if the tools provided by QRM are suitable to diagnose why Larsen is not able to achieve the desired delivery performance; and, second, to see if QRM provides an appropriate solution or if other approaches exist which are better.

Research showed that QRM is not focused on finding the root cause for late delivered orders, but on finding improvement projects for lead time reductions. A diagnostic tool, designed by New (1977), distributes the lateness of orders to find the root cause for late delivered orders. This tool revealed different problems than those provided by QRM. The distribution tool revealed a sequencing problem that leads to orders being delivered late. The QRM tools revealed two possible locations where lead time can be reduced: (1) in front of bench work and (2) between lathes and milling procedures.

Because the sequencing problem resulted in orders being delivered late to customers, a solution needed to be found. First, QRM has been examined and showed a possible solution in the form of a card based system called POLCA (Paired-cell of Overlapping Loops of Cards with Authorization). This card system uses push-and-pull mechanisms to control material flow between cells (Suri, 1998; Suri, 2010). This means that a cellular structure is needed before being able to implement POLCA.

A second solution was found in Work Load Control (WLC). This method requires less restructuring of the company and uses a pre-shop pool to limit the amount of work on the shop floor (Land & Gaalman, 2006a; Thurer et al, 2011; Stevenson et al., 2005; Ragatz and Mabert, 1984). This pre-shop pool regulates the waiting time and, therefore, stabilizes the shop floor, after which it regulates when is worked on what order. This is controlled at three levels, being: job entry, order release (from the pool to the manufacturing company) and dispatching rules (at the machine).

To better understand which method is more suitable, it should meet the requirements needed for Larsen. Important requirements is that the system deals with the sequencing problem, it can cope with more than one expert, and that it can handle high variety and highly customized products. But, most importantly, the system should minimize the average tardiness of delivery lateness and reduce overall lead time.

When reviewing both POLCA and WLC, they both come with advantages and disadvantages. POLCA will reduce lead time on a continuous basis, improve delivery reliability, and has the ability to be adapted to certain circumstances. However, POLCA does not give any clear solutions on how to implement it when a company is dealing with multiple experts, when it does not have product families, or when order routes are machine dependent. WLC, on the other hand, takes less reorganizing and has no problem with multiple experts or high variety products. However, it will only stabilize the shop floor, not continually improve performance or reduce lead times.

Both POLCA and WLC falls short and no system seems to be an ideal solution. WLC takes less physical reorganizing, while POLCA requires more research on how to be adapted to the situation at Larsen Premium Precision Parts. Nevertheless, POLCA, if adapted, seems to provide more results on the long term and it is recommended to explore these possibilities. For this, more research is needed
on the subject of POLCA in relation to having multiple experts in a company and having no clear product families based on common order routes.
Acknowledgement

For the content and support for carrying out this research, I received help from different people. I would like to thank Jan Riezebos for his guidance throughout my research, Frank te Hennepe for letting me carry out my research at his company Larsen Premium Precision Parts, Eric Soepenberg for willing to be my second supervisor, Godfried Kaanen for showing me around the plant of Bosch Scharnieren and Henri Kortman for showing me around at Variass.
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1 Introduction

Throughout history companies have continually searched for new ways to improve their businesses to gain better market positions. When demand started to increase during the industrial revolution, companies tried to find ways to enlarge their manufacturing scale. When supply started to exceed demand, companies started with cost cutting activities to compete with lower prices. When Japan started to increase quality while remaining to manufacture at low costs, companies tried to imitate their production processes. More recently, companies realize that they, again, are in need to find new ways to survive while globalization causes competition to increase. By developing competences that are hard to imitate, companies can gain competitive advantage (Hendry, 2010) and for some time now, competitive advantage is achieved by pursuing faster product delivery (Suri, 1998).

For companies that manufacture pure customised products, such as engineer-to-order companies, this is difficult to accomplish. Such companies have to deal with dynamic, uncertain and complex situations (Bertrand and Muntslag, 1993). Future demand is hard to predict, products depend on customer preferences and all products can follow different routes throughout the company with different processing times. These often result in long lead times, bottlenecks and difficulties in planning and scheduling problems (Bertrand and Muntslag, 1993), all making it difficult to meet due date promises or fast delivery.

For ETO companies to gain speed, QRM has come into existence and seems to be an appropriate solution. This because it concentrates on reducing throughput times within the entire company, external as well as internal (Suri, 1998). This results in higher quality, lower costs and quicker response (Suri, 2010). By means of, among other things, cellular manufacturing, multi-training employees and team ownership, flexibility is increased, product quality improved and employee motivation enhanced (Suri, 1998).

Suri has defined ETO companies as companies that design and specify products before manufacturing them. However, this is quite a simplified description of ETO companies. According to Bertrand and Muntslag (1993) ETO companies differ in product complexity, product specification, shop floor layout and complexity, and market characteristics and competitors. Amaro et al. (1999) and Hicks et al. (2001) have both been able to classify four ETO companies, although different from each other. This leads to some ambiguities on how to implement QRM in ETO companies and even questions if QRM is suitable in all ETO companies.

ETO companies, for example, do not necessarily have to be responsible for the design, specifications or purchasing of materials (Amaro et al., 1999). In such cases, this is supplied by the customer. Forming product families based on similar operations, like QRM advises ETO companies, might be difficult to accommodate to. Another example is that, according to Suri, there are not many experts in companies. However, some companies’ core competences is their knowledge on products and processes (Hicks et al., 2001). This may indicate that some ETO companies might have multiple experts. Last, implementing QRM successfully means reorganizing the whole company. But when a company is small and flat and is dealing with multiple experts and an unclear product families, does QRM provide enough results that it justifies all the changes?
In this chapter an overview has been given about the main subjects of this research. To investigate the suitability of QRM in an ETO company that deals with the above mentioned aspects, a case study will be conducted. The next chapter will elaborate on the subjects mentioned in the introduction more profoundly. This will result in a management and research question in chapter 3. Here will also be further explained the methodology used during this research and a company introduction. Chapter 4 will explain the results of the diagnose phase. Chapter 5 will show the results of the Design phase. Conclusions, recommendations and limitations will be given in chapter 6.
2 Literature research

Offering customized products is a strategic decision of companies to distinguish themselves from other companies. This choice comes from the increasing need of customers to obtain specific products (Hendry, 2010). However, there are different degrees of customization that can be aimed for (Amaro et al., 1999). ETO companies manufacture the purest form of customization but this often results in high complexity and problems on the shop floor. This chapter will clarify different kind of ETO companies and the problems they often experience. Hereafter, it will be explained what solution QRM provides to solve these problems. This will be followed by pointing out some irregularities between the problems ETO companies experience and the solution QRM claims to provide for ETO companies. This chapter will end with a research focus.

2.1 Custom made manufacturing

This sub-chapter will start by explaining what customisation actually is and what levels can be distinguished after which it will be explained how companies, that are engaged in processing custom made products, can be classified; especially ETO companies. This will be followed with their competitive advantages and improvement aspects.

2.1.1 Levels of customisation

According to Gosling (2009), companies can be categorized based on their supply chain structures. This has led to six structures to define the range of possible operations: engineer-to-order (ETO), buy-to-order (BTO), make-to-order (MTO), assemble-to-order (ATO), make-to-stock (MTS) and ship-to-stock (STS). The difference between these depends on the order-penetration-point (OPP). This is traditionally defined as: “the point in the manufacturing value chain for a product, where the product is linked to a specific customer order” (Olhager, 2003, p.2). It is also referred to as the customer-order-decoupling-point (CODP) as to highlight the involvement of the customer. For ETO companies this decoupling point is at the earliest point: at the design stage. For ATO companies this decoupling point is at the assembly stage. However, often a more simpler way to categorise companies is being used, being: MTS, ATO, MTO and ETO (Bertrand and Muntslag, 1993; Amaro et al., 1999). Of these, ATO, MTO and ETO companies fall under the category of customized manufacturing companies (Amaro, 1999).

Companies use customization as a strategic decision (Hendry, 2010). Only after receiving an order from the client, production is initiated (Amaro et al., 1999). There are different levels of customization that companies can pursue. Lampel and Mintzberg (1996) define five levels of customization, whereas Amaro et al. (1999) distinguishes four levels of customization. Because these last are sufficient for this research, these will be further described:

- **Pure customisation**: a product is made from scratch, making each product client- and situation specific. An example of pure customization is an architect designing a house for a client. This kind of customization is seen in ETO companies.

- **Tailored customisation**: a basic product is adjusted to the needs or specifications of a client. An example of tailored customisation is when a software company sells a software package that can be adjusted to suit the needs of the individual customer. This kind of customization is seen in MTO companies.
- **Customised standardization:** customisation is provided through modular design. Here, the customer can choose between several design options. For example, an IKEA wardrobe that can be made client specific by choosing between different items and putting them together. This kind of customization is seen in MTO and ATO companies.

- **Non-customization:** last is no customization. This, to complete the levels of customization.

### 2.1.2 Classifying ETO companies

ETO companies manufacture pure customised products, wherein the customer is involved from the design stage. This creates high variety in products which makes them able to deliver to a wide range of customers. However, ETO is still a broad term. According to Bertrand and Muntslag (1993), ETO companies differ in terms of:

- product complexity
- degree of customer product specific
- lay-out and complexity of the production process
- market characteristics and competitors

Hicks et al. (2001) and Amaro et al. (1999), were both able to classify ETO companies. Hicks et al. (2001) classifies ETO companies based on their core competencies, source of competitive advantage, degree of vertical integration, supplier relationships, environment and types of risk. This resulted in the following four types: (See full scheme appendix I)

- **Vertically integrated:** the core competences are design, manufacturing, assembly and project management. Here, the company’s competitive advantage is their knowledge on products and processes, and the integration of their internal processes.
- **Design and assembly:** the core competences are design, assembly and project management. Their competitive advantage is coordinating internal and external processes.
- **Design and contract:** the core competences are design, project management and logistics. Their competitive advantage is coordinating internal and external processes.
- **Project management:** the core competences are project management, engineering expertise and logistics. Their competitive advantage is engineering knowledge.

According to Amaro et al. (1999) ETO companies differ based on the responsibilities of the company. Although, ETO companies have a decoupling point at the design stage, the design, specifications and the purchasing of materials do not have to be done internally by the manufacturing company (Amaro et al., 1999). The client may supply these. In this case it may look like a MTO company. However, the difference between ETO and MTO companies is that in ETO companies a client cannot pick a product from a catalogue like in MTO companies.

Based on this classification, four different types of ETO companies are distinguished (Amaro,1999): (See full scheme appendix II)

- **ETO 1:** responsible for the design, specifications and purchasing of materials
- **ETO 2:** responsible for specifications and purchasing of materials
- **ETO 3:** responsible for only the purchasing of materials
- **ETO 4:** not responsible for any of the above activities
2.1.3 Production systems in ETO companies
ETO companies often experience certain problems like long lead times, bottlenecks/congestion and planning and scheduling problems. These lead to difficulties in meeting promised due dates. To understand the cause(s) for these, the production system in ETO companies will be first described below.

According to Bertrand and Muntslag (1993, p.2), in MTO and ETO companies, the customer “plays a central role in the production system and the production control system”. This because production activities are customer order driven. In Figure 1 is illustrates, the global flow of goods in ETO companies.

![Figure 1 - global flow of goods (Bertrand, 1993)](image)

Bertrand et al. (1993) describes ETO production processes as being dynamic, uncertain and complex.

Dynamic because mix and sales volumes fluctuate in ETO companies. These are also difficult to predict because production is customer order driven.

Uncertain because there is a gap between the knowledge that is required to perform a task and that what is known within the company. Bertrand et al. (1993) distinguishes three sources for uncertainty:

1. **uncertainty of product specifications**: at the beginning of a project, product specifications are still unclear. A project starts with design phases and includes the non-physical stage of the goods of flow. Here, uncertainties arise like decisions concerning capacity, lead time and price.

2. **mix and volume of future demand**: these are difficult to predict because orders are customer driven (Bertrand et al., 1993). Here, differences occur between the market a company is active in. When pursuing RBC businesses (repeat business customizers) it is ‘better’ predictable than in the VMC industry (versatile manufacturing customizers) (Hendry, 2010).

3. **production process uncertainty**: because of the uncertainty at the beginning of projects about product specifications, capacity related problems may arise at the production process.

Complex because of three factors:

1. **the goods flow**: the flow of goods do not only exist of a physical stage but also a non-physical stage. Especially in the non-physical stage, tasks are difficult to formalize and
therefore, difficult to control. This makes it hard to predict the progress of a product/project. There is also a limited amount of capacity available at companies, because of the unclarities in product specifications at the design stage, it is difficult to determine what the actual capacity will be. Also in the physical stages of production process complexity is seen. ETO companies use job shop manufacturing to fulfil orders. Because orders follow different routes throughout the company, with different processing times and possibly need to be assembled, internal processes are complex (Bertrand et al., 1993).

(2) multi project character: there is uncertainty in every project. Therefore, when dealing with multiple projects, uncertainty increases. This makes it hard to control. This creates bottlenecks on the shop floor (Bertrand et al., 1993).

(3) the assembly structure of products: when every product is customer specific, parts are often also unique. Assembly of unique products with unique parts is complex and often leads to long lead times (Bertrand et al., 1993).

The competitive advantage of ETO companies is focussed on order execution and lead time reductions (Suri, 1998; Gupta et al., 2004; Altendorf et al., 2011). In ETO companies, the two most often mentioned performance measures are the Service Level and/or Average Tardiness (Altendorf & Jodlbauer, 2011). The service level is defined by how quick a company can deliver products to the customer and the accurateness of their delivery, i.e. reliability (Hopp and Spearman, 2008). This is measured by the amount of orders that are being delivered on time. The average tardiness illustrates the amount of time a client has to wait if an order is late.

2.1.4 Problems in ETO companies

The dynamic, uncertain and complex situation often lead to certain problems, such as long lead times, bottlenecks/congestions and the planning and scheduling problems mentioned above. This chapter will elaborate on these problems.

Long lead times. ETO companies often cope with long lead times. According to Suri (1998), causes are not only traced to the manufacturing department, but also to the office. Every step or every activity an order has to go through often adds extra waiting time. For example, when an order is handed from one person to the next, an order is often waiting for the second person to start. At the office, it is not uncommon for an order to be handed over to more than two employees, leading to increased waiting times. Furthermore, because of uncertainties at the beginning of the process, mistakes occur that need to be fixed later on in the process (Bertrand et al., 1993). Mistakes like incomplete drawings, missing equipment, tools/moulds that need to be made/ordered, etc. Research showed that in a typical American company, 25% of total operating costs is spend on fixing problems (Suri, 1998). Not only on problems just mentioned, but also on rescheduling activities and conflicts. This because orders that need to be fixed are delayed and are competing to access common resources (Suri, 1998). Then there is the shop floor. There are four different kind of job shops: pure flow shop, general flow shop, general job shop and pure job shop (Stevenson, 2005).

- The pure flow shop: there is only one direction a product goes. This is mostly used in companies with RBC orders.
- The general flow shop: there is a main flow of which some products can go back occasionally. This is often seen in companies with high RBC and little VMC orders.
- The general job shop: there is a more general flow seen. Orders can often go back to a previous sub step. This is mostly seen in companies with high VMC and low RBC orders.
- The pure job shop: where no flow can be distinguished. This is seen in companies where only VMC orders are obtained.

It often happens that the higher level of customization, and the more VMC orders, the more complicated the shop floor becomes, and, often, the longer the lead times. This because orders follow different routes, undergo different processing and set up times causing high variety on the shop floor. To determine due dates, an extra safety margin is calculated in to buffer this variety. According to Suri (1998), this causes orders to start much earlier than necessary, causing more orders to be on the shop floor. This leads to longer lead times and a larger window to make mistakes, creating a situation that is difficult to plan and predict.

**Bottleneck.** Because product variety is high at custom made manufacturing companies, all orders can follow different routes throughout the company. This creates situations wherein multiple products are in line waiting to be processed. Other causes that create bottlenecks/congestion are: slow machine, long setup time, a slow operator, machine break down, etc.

**Planning and scheduling problems.** Because variety is high at custom made manufacturing companies, companies do not only deliver late, or on time, but also early. This is undesired because early deliveries take up capacity that could have been spend on late deliveries (New, 1977). Therefore, the aim of companies is to deliver as close to the due date as possible. This problem of early and late deliveries is also due to the job-shop-scheduling-problem (JSP). The JSP is an optimisation problem described as: “a number of jobs that need to be processed on a number of machines. The jobs visit each of the machines in a predefined sequence. The goal is to schedule the jobs on the machines, respecting the constraints that each machine can only process one job at a time and that pre-emption of the jobs is not allowed, while minimising one or more measures of performance” (Sels et al, 2012, p.2). All these uncertainties makes it difficult to predict when orders are finished, or not, in the long run. What is missing here that complicates it even more, is that processing times vary between orders, but also between operators (Jones, 2010). A more skilled operator may be finished faster than a less skilled operator. Furthermore, customers also may tend to disturb the planning process by changing the desired due date or cancel orders (Land & Gaalman, 2006a).

### 2.1.5 Determining the cause of unreliable delivery

ETO companies strive for reliable and fast delivery of their products to the customer. Late deliveries are unwanted but early delivery is also undesirable while it takes up capacity needed for orders that might now be delivered late. This means that in the ideal situation orders would be delivered as close to the due date as possible (New, 1977). According to New (1977), there are four possible reasons for orders to be delivered late: (1) shop floor overload, (2) pre-production delays, (3) sequencing problem and (4) insufficient lead-time allowance. By distributing the internal efficiency, the performance of the actual engineering process, and the external efficiency, meeting commitments placed on it extraneously, an indication is given about the cause for late delivered orders.
When all is under control the distributions looks as illustrated in Figure 2. Here, the orders are tightly spread around the due date. This means that capacity and orders are in balance, production is well under control and performance is good.

![Figure 2 - All under control internal/external (New, 1977)](image)

**Situation 1: shop floor overload.** Here, the internal efficiency is good, the external efficiency is bad. This is seen in situations where more orders are accepted than can be handled, but where most orders are kept outside the shop floor. Thus, the internal system is managed correctly but the order acceptance procedures are wrong. The distribution looks as illustrated in Figure 3.

![Figure 3 - Overload situation internal/external (New, 1977)](image)

**Situation 2: Pre-production delays.** Here, the internal efficiency is good, the external efficiency has a ‘lateness tail’. This is seen when problems occur with pre-production delays on some batches (like awaiting drawings, material, tooling, etc), while other batches continue through uninterrupted. The distribution looks as illustrated in Figure 4.

![Figure 4 - Pre-production delays internal/external (New, 1977)](image)

**Situation 3: sequencing problem.** Both distributions are widely spread around the mean. This indicates lack of control in the sequencing of jobs. If this is happening within a company, the scheduling system should be investigated, according to New. The distribution looks as illustrated in Fout! Verwijzingsbron niet gevonden..
Situation 4: Insufficient lead-time allowance. Both distributions are tight, but the means are late. Despite good control over inlet and scheduling, performance is poor. This indicates that planning and lead times used are insufficient. This could also be due to overload with no input control. However, then it would result in a more widely spread distribution. The distribution looks as illustrated in Figure 6.

2.2 Quick Response Manufacturing

QRM is an company improvement philosophy that improves company performance by focusing on lead time reductions, especially in custom made manufacturing companies (Suri, 1998). It has benefitted several companies already and has resulted in lead time reductions of 75% in new product introductions and 90% to fill orders of existing products (Suri, 1998). This chapter will start by explaining the four pillar of QRM to explain the basics. This will be followed by more technical details that are needed to achieve such results.

2.2.1 QRM, the four pillars

QRM is a company-wide approach that focuses on reducing lead time in companies, like MTS, MTO and ETO. It claims to be especially appropriate in the last two types of companies mentioned (Suri, 1998). Lead times are reduced both external as well as internal. External means that the time to deliver products to the customer is reduced. Internal means that the lead time of internal tasks and activities is reduced. Because lead time is a broad definition, QRM talks about the Manufacturing Critical-path Time (MCT) instead. The MCT is defined as follows: “the typical amount of calendar time from when a customer creates an order, through the critical path, until the first piece of that order is delivered” (Suri, 2010, p.10). In other words, the critical path is when an order is made from scratch and all activities need to be completed entirely. This includes the time it spends in the warehouse, but also the time it has to wait within the company (Suri, 1998). According to Suri, the founder of QRM, reducing MCT does not only lead to reduced lead times, but also increased product quality, reduced costs, and the elimination of non-value added waste (Suri, 1998).

QRM is based on four pillars: the power of time, restructuring the organization, system-dynamics and company-wide practice (Suri, 2010). These will first be described.
Power of time. The first pillar is focused on the power of time and the need to reduce time. In custom made manufacturing companies, products spend a lot of time on the shop floor, mostly waiting in front of machines. Therefore, eliminating waiting time often delivers high results. The solution of implementing QRM results in companies that are faster and more reliable, which leads to increased client satisfaction and more turnover (Suri, 2010).

Restructuring the organization. For companies to achieve the above mentioned results, they need to restructure the organization and start operating between 70 and 80 percent capacity on critical resources (Suri, 1998). When operating at this lower capacity level, reserve capacity is created that can be spend on unexpected orders. Restructuring the organization includes understanding the need to find new ways for developing products faster. Four structural changes are needed to accomplish this:

1. The shop floor needs to be changed from functional into cellular manufacturing. This means that machines and people are dedicated to a cell that, in their turn, is dedicated to a product family.
2. Ownership needs to be changed from top- down into team ownership.
3. Employees needs to be changed from specialized into multi- functional employees.
4. The key performance indicator needs to be changed from efficiency/utilization into MCT reduction.

System dynamics and company-wide practice. The structural changes need to take into account the system dynamics and company-wide practice. System dynamics implies that only forming QRM cells is not enough to reduce lead time, but that this needs to be supported with management decisions that are in line with lead time reduction. The last concept of QRM is company-wide practice, which means that it needs to be applied not only on the shop floor but throughout the whole company, including the office. These last two pillars are only possible if each component within the company is fully understood including their interactions. After understanding the company, structural changes can be made.

2.2.2 Starting with QRM

This paragraph will elaborate on what a company needs to do to start with QRM. This will be based on the QRM principles (see appendix III). It will first explain how to start (Suri, 1998) and includes some methods and tools that can be used. This will be followed with more profound information on the restructuring of the organization. Last will be described how the performance is measured in the new manufacturing layout.

Starting with QRM: Finding improvement opportunities

QRM advices to start with a QRM project of low-cost or no-cost and where most results can be gained. This because the biggest obstacle for implementing QRM is changing the mind-set of people from cost based thinking into lead time reduction thinking. Exploring possible projects can be done by means of MCT mapping and Process mapping.

- MCT mapping. The purpose of MCT mapping is to gain an overall view of the proportions between waiting time and touch times in a company and to come to possible improvement areas for lead time reductions (Suri, 2010). Often, the touch time (i.e. the time a product is
actually touched) accounts for about five percent compared to the waiting time. Therefore, the biggest results can often be gained to focus improvement projects on reducing waiting times instead of touch times.

- **Process mapping.** Process mapping is done by attaching ‘tagging sheets’ to orders. It aims to obtain data on where orders actually went in a company. This approach is suggested to use in the office and is focussed to understand all the activities done to an order before it goes to the manufacturing department. Results can be used to form office cells, or Q-roc’s as Suri has called them (Suri, 1998).

### Restructuring the organization

Often, a company is divided into office and manufacturing. The changes needed will be described per department.

**Manufacturing department.** When the mind set of people has changed and possible improvement areas are found, the company needs to start with restructuring the organization into simple product-oriented cells. There are seven steps to successfully implement cells (Suri, 1998) (See appendix IV). These are focussed on:

- forming product families based on threats or opportunities or, for ETO companies, on common sets of operations, and
- making them self-contained by dedicating people, machines and equipment and tools to these cells

To control material movement between cells, a new material control system should be implemented. This system, called POLCA, is a system that operates by means of a High Level Material Requirements Planning system (HL/MRP), in a cellular environment and with flat bill-of-materials (BOMs) (Suri, 1998). The HL/MRP determines the release authorization of orders, where after POLCA-cards take over and are used to communicate and control material movement between cells. Within cells, other material control decisions can be made.

**Office.** Also in the office lead times should be reduced. This because office operations can account for “more than half the lead time” (Suri, 1998, p.308) and “more than 25 percent of costs” (Suri, 1998, p.34). Reducing lead times can be done by cutting through functional boundaries. By multi-training office personnel and by dedicating them to a product group or family, the times an order is going from one person to the next, is eliminated. This reduces the waiting time and therefore the lead time spend at the office.

### New performance measure

To improve company performance, a company should start by measuring lead time and setting this as a performance measure. Rewards should be given based on lead time reductions.

### 2.3 Research focus: ambiguities between problem and solution

Up until now is explained that there are different levels of delivering customised products and that ETO companies manufacture the purest form. Furthermore, literature has shown that ETO companies experience problems, like long lead times, bottlenecks, planning and scheduling problems, sequencing problems, pre-production delays and manufacturing overload, that lead to
problems in meeting promised due dates. Therefore, competitive advantage in such industries is obtained by pursuing: reliable delivery of customer specific products faster than competition. Based on this, it seems that QRM provides a good solution to ETO companies. This because it reduces lead time and improves quality, resulting in faster and more reliable delivery. However, when looking more profoundly into the given information, some ambiguities arise. This chapter will bring together the information on ETO companies and QRM to point out three ambiguities.

2.3.1 Company's responsibilities

According to Suri, ETO companies are seen as companies that design and specify products before manufacturing the products (Suri, 1998). However, this is quite a simplified definition of ETO companies. ETO companies differ based on their product complexity, degree of customer specificity, lay out and complexity of the production process and market characteristics and competitors. Furthermore, two classifications have been made, one based on the vertical integration of ETO companies (Hicks, 2001) and the second based on responsibility (Amaro et al., 1999). Suri, however, does not address this topic nor does he elaborate on this. This has lead to an implementation problem. As described, QRM operates based on cellular manufacturing dedicated to a product family. This cellular structure is based in MTO companies on threads and opportunities and in ETO companies on similar operations. This last can be obtained by a more quantitative approach. When this approach, however, does not deliver results, companies should reconsider their product designs and product options (Suri, 1998). Here, the question arises: what if companies cannot influence their product designs or product options because they are not responsible for the design nor the specifications? The only way such companies can influence their range of products is by declining orders. However, this might only be considered when a company does not have the capacity due to high amount of backlog or the capabilities to meet specifications.

2.3.2 Experts

When dedicating people, machines and tools and equipment to cells, they cannot be used for other product families. Therefore, when dealing with machines that are being used for multiple product families, QRM proposes time slicing to divide the available time between product families. This is also done with experts at the office, like a tooling expert. Suri defines an expert as someone who has obtained its current knowledge by years of experience (Suri, 1998). This makes it difficult to multi-train personnel to do the same job (Suri, 1998). According to Suri, time slicing used for machines can also be used for experts. He also states that “the tooling expert situation is an exception” (Suri, 1998, p.351). This because, according to Suri (1998, p.351), when working in cells based on product families “personnel need to be trained on a limited portion of that skill that are required by the worker to deal with orders for the specific FTMS1 served for this Q-ROC”. He does not mention the possibility of having experts in the manufacturing department or having multiple experts in a company. However, this might be the case in a vertical integrated company described by Hicks (1993), where knowledge on products and processes is their competitive advantage. This raises the following question: ‘how do you utilize multiple experts on the shop floor in a QRM environment?’.

2.3.3 Flat organization

According to Suri, QRM should be implemented throughout the entire company. This includes the office where sometimes more than half the lead time of an order is spend. By breaking through

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1 Focussed target market segment
functional boundaries the waiting time between personnel is eliminated resulting in reduced lead time. To obtain most results, the whole company needs to be restructured, tasks need to be rearranged, people need to be multi-trained and all should be dedicated to product-families all focused on lead time reductions. This will result, according to Suri (1998), in flat organizations. This raises the questions: ‘how much time can be reduced in a small and already flat organization?’ and ‘Is it worth all the changes?’.
3 Research methodology

This research will focus on how well QRM provides a solution to improve company performance in a small, flat and vertically integrated ETO company that does not design or set specifications internally. It will focus on the ambiguities mentioned in the previous chapter and tries to determine if QRM is the most appropriate solution to improve company performance, or if another solution(s) exists that fit more properly. This will be researched by means of a case study that will be conducted at the company Larsen Premium Precision Parts.

3.1 Problem statement and research question

The purpose of this research is defined as follows:

“The purpose is to gain a better understanding on how suitable QRM actually is in improving the performance of an ETO company such as Larsen Premium Precision Parts.”

The research question is stated as follows:

“How suitable is QRM to improve company performance (i.e. reliability and speed) in a vertically integrated company, such as Larson Premium Precision Parts, only responsible for the purchasing of materials?”

3.2 Sub questions in light of the DOV-model

Larsen Premium Precision Parts has a company performance problem and does not know what solution provides the best answer. When dealing with a problem situation, De Leeuw (2000) proposes to use the DOV-model (in Dutch: ‘diagnose’, ‘ontwerp’, ‘verander’). This model stands for diagnosing the situation (‘diagnose’), design or develop (‘ontwerp’) solution(s), and realise the change(s) (verander) that are needed. This model will be used to assess the applicability of QRM at Larsen Premium Precision Parts.

To be able to answer the research question the following sub-questions need to be answered first.

1. Do the tools, MCT mapping and process mapping, discover the cause for not meeting due date promises at the company Larsen Premium Precision Parts?
2. What criteria should the solution satisfy?
3. Does QRM provide a solution to solve the problems at Larsen Premium Precision Parts?
4. Are there alternative solutions that can/need to be considered?

Diagnosis. In the case of Larsen Premium Precision Parts the low company performance is a symptom observed by management. The diagnostic phase will start by examining if this is only a perceived problem or an actual existing problem. This will be followed by what is causing this. Here, the first research question will be answered: “Are the tools, MCT mapping and process mapping, capable to discover the cause for not meeting due date promises at the company Larsen Premium Precision Parts?” To find the root cause, some problems and causes were described in the literature research that are often experienced in ETO companies and that lead to low company performance. Based on this information, a conceptual model has been made as a guide line. However, because the possibility exists that there might be a reason that is yet unknown, an empty box has been placed in the model to keep all possibilities open.
**Design.** During this phase an appropriate solution will be designed. This includes determining criteria of what makes a solution ‘good’, but also exploring another possible solution(s). Here, research question two, three and four will be answered: “What criteria should the solution satisfy?”, “Does QRM provide a solution to solve the problems at Larsen Premium Precision Parts?” and “Are there alternative solutions that can/need to be considered?”. This will be researched by means of literature.

**Change.** During the change phase, actual changes should be made. However, this falls outside the scope of this research.

The results of this research will exist of:

1. recommendation(s) towards Larsen on how to improve their company performance, and
2. a review on the suitability of QRM in an ETO company that is not responsible for the design and specifications, has multiple experts and is small and flat.

<table>
<thead>
<tr>
<th>DOV-model</th>
<th>Sub question</th>
<th>By means of</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diagnose</td>
<td>Are the tools, provided by QRM, capable to discover the cause for not meeting due-date-promises at the company Larsen Premium Precision Parts?</td>
<td>Tagging and MCT</td>
</tr>
<tr>
<td>Design</td>
<td>What criteria should the solution satisfy?</td>
<td>Literature</td>
</tr>
<tr>
<td></td>
<td>Does QRM provide a solution to solve the problems at Larsen Premium Precision Parts?</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Are there alternative solutions that can/need to be considered?</td>
<td></td>
</tr>
<tr>
<td>Change</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
3.3 Research methods, validity and reliability

In this chapter the research methods, validity and reliability will be explained. It will start with a company introduction and the research area. Thereafter, it is explained how the nature of the problem (perceived, reality, goal problem) will be determined. This will be followed with the research methods, MCT- and process mapping, including their limitations.

3.3.1 Company introduction

To investigate what issues ETO companies may encounter with QRM, a company was searched for that fitted the criteria of not being responsible for the design nor the specifications, having multiple experts and being a small and flat organization, to perform the case study on. Such company was found in Zeewolde by the name of Larsen Premium Precision Parts, who currently is exploring the possibilities of using QRM to improve their company performance.

Larsen Premium Precision Parts is a company that manufactures custom made fine mechanical high quality products and is specialized in turning and milling procedures. See for more details Table 1. It has its origins in serial and small scale production of which a lot was repetitive. To monitor the performance of the company, the amount of orders not delivered on or before the due date is being measured. Within Larsen this is called ‘customer service’, however, in literature the term ‘service level’ is more often used and will be used during the rest of this research.

Table 1 - Larsen Premium Precision Parts

<table>
<thead>
<tr>
<th>Production process</th>
<th>Materials</th>
<th>Markets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turning</td>
<td>Stainless steel</td>
<td>Complex equipment building</td>
</tr>
<tr>
<td>Milling</td>
<td>Aluminium</td>
<td>Aerospace</td>
</tr>
<tr>
<td>(Assembly)</td>
<td>Plastic</td>
<td>Semiconductor industry</td>
</tr>
<tr>
<td>Ultrasonic clean</td>
<td>Exotic materials</td>
<td>Medical industry</td>
</tr>
<tr>
<td>Kit</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pack and label</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Symptoms

Over the year 2011 the service level at Larsen has fluctuated between 70 and 90 percent, with 80 percent on average. This means that (on average) 20 percent of their orders were not delivered on time. These percentages include (1) moved due dates and (2) contain all orders. These will be explained more in-depth.

(1) Moved due dates are due dates of orders that were not being delivered in time and, in agreement with the customer, moved. When the products are delivered on this new due date, the order is registered as on time delivery, even when the first due date was not met.

(2) All orders include serial and small scale products, and orders delivered from stock. The differences between these, regarding to the service level, is that small scale production more often do not meet due dates compared to serial production, and that orders delivered from stock are always delivered on time.

The service level does not provide a clear picture of the severity of the problems of small scale products at Larsen Premium Precision Parts. The presumption exists that the actual service level of small scale products is probably lower than the overall service level of the company. This because
most delivery problems that is experienced within Larsen relate to small scale products. However, the service level of small scale products is not measured by the company nor the average tardiness of orders.

3.3.2 Research area

Company performance, i.e. fast and reliable delivery of products, at Larsen includes researching the whole order fulfilment process, from order entry until delivery. Because Larsen is not responsible for the design and specifications, and because assembly does not happen often, the flow of goods is as depicted below.

![Flow of goods Larsen Premium Precision Parts](image)

**Figure 8 - Flow of goods Larsen Premium Precision Parts**

The order fulfilment process of Larsen Premium Precision Parts can be allocated to three departments within the company. These are: office, manufacturing department and shipping department. Their tasks and activities will be elaborated here and are shown in Figure 9.

**Office.** At the office the main activities include the acceptance or rejection of orders, determining due dates, preparing the order for manufacturing and releasing the orders to the shop floor.

- Order acceptance: almost all orders are accepted. Only when Larsen does not have the capabilities to manufacture the product, an order is rejected. However, this does not occur often.
- Due date determination: due dates are determined in negotiation with the customer and on the available machine capacity. The customer sets a desired due date. When this cannot be met, Larsen will come with an alternative due date, until both come to an agreement.
- Order preparation: this includes activities such as checking drawings for completeness and readability, material purchase, determining order route and processing times, ordering equipment and tools, etc.
- Order release: Larsen does not have decision rules when to release the order to the shop floor.

**Manufacturing.** At the manufacturing department, an order goes through the following activities: milling and/or turning, finishing activities (this includes assembly when necessary), cleaning activities and a quality check. When an operator starts with an order is determined by pre-calculated starting dates. This starting date is calculated by the due date minus the throughput time. The throughput
time is calculated by the cycle time of the order plus the setup time plus the pre-calculated waiting time.

- **Due date = in negotiation with the customer and available machine capacity**
- **Throughput time = cycle time + setup time + pre-calculated waiting time**
- **Starting date = due date – throughput time**

**Shipping department.** Here, orders are packed and shipped or, occasionally, placed in stock.

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3.3.3 Service level measurement

There are three different kinds of problems, according to De Leeuw (2000). First, the company may perceive a problem that actually does not exist (perceived problem). After diagnosing this, no further research is needed. Second, the company may have a problem, but that is due to unrealistic set goals (goal problem). Here, the company should reconsider or adjust their goals and targets. Third, the company may actually experience a problem (realistic problem). Goals are realistically set, but not achieved by the company. Here, more research is needed on why they cannot meet their targets and what needs to be changed within the company to alter this situation.

This research will start by determining the nature of the problem by measuring the service level and the average tardiness of orders. By means of MCT mapping, described later on, the due date will be compared to the date when orders are finished and ready to be shipped. This will indicate the severity of the problems.

3.3.4 Process- and MCT mapping described

If there is a realistic problem, process mapping and MCT mapping are provided by QRM to find improvement areas within the company. This paragraph will first describe these more profound.

**Process mapping**

Process mapping provides a way to understand the office processes better. It uses two techniques: interviewing office personnel and tagging orders. Interviewing is done to understand the flow of work. Tagging is done to reveal activities that are missed by the interviews. Together, they will provide opportunities for improvement at the office.

By attaching tracking documents to orders, more information becomes available, such as “Where did the order go?” and “How long did every step take?”. On the tagging sheets, information can be filled...
in on who did what activity and when did every person start and finish processing the order. The layout of the sheets depend on the situation of the company.

**MCT mapping**

MCT mapping is an approach to discover the main improvement area within a product family and gives an idea about the ratio between the time an order is waiting and the time an order is being processed, or touched. Often, the touch times are nothing compared to the waiting time. This means that most results can be gained by focusing on reducing waiting times instead of touch time. Knowing the ratio will provide a clear picture of how long orders are waiting compared to being touched.

MCT is defined as: “the typical amount of calendar time from when a customer creates an order, through the critical path, until the first piece of that order is delivered to the customer”. This will be explained here.

1. It measures in calendar time, instead of work time, because this is the time the customer has to wait
2. It measures the time to deliver the first piece of a batch, instead of the whole order, because order size may vary while the MCT of the first piece will stay consistent. This MCT can be used as a standard to compare the results of improvements to.
3. The critical path includes all activities needed to finish a product from scratch, including all waiting times and delays that are normally applicable at every stage within the company. It measures the critical path while it does not only quantify those activities that take the most time, but also the amount of losses.

When the touch times and waiting times are known, the area where most benefits can be obtained will become visible.

**Research limitation**

Because of time limitations, and because of the review above, the methods and tools have been adapted. These adaptations will be explained here.

**Research overview**

To diagnose the situation at Larsen, it is necessary to gain an understanding about the flow of goods throughout the company. Therefore, this research will start with interviews. Hereafter, because of time limitations and the limitations of the methods, Process and MCT mapping will be combined. Together, they will be able to provide information about the nature of the problem and the ratio between waiting times and touch times. In other words, all orders for which production is needed will be followed by means of tagging documents, throughout all departments. Orders that can be filled from stock are not interesting for this research and will not be followed.

<table>
<thead>
<tr>
<th>Method</th>
<th>Aim</th>
<th>Department(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCT</td>
<td>To determine the nature of the problem of small scale products</td>
<td>All</td>
</tr>
<tr>
<td>Interviews</td>
<td>To get an overview of the flow of goods through the company</td>
<td>All</td>
</tr>
<tr>
<td>MCT</td>
<td>To obtain the ratio between waiting times and touch times</td>
<td>All</td>
</tr>
<tr>
<td>Tagging</td>
<td>To understand the flow of goods</td>
<td>All</td>
</tr>
</tbody>
</table>
**Interviews**

The interviews will be semi-structured and in private. This because it is important to gain qualitative information on how orders flow through the company (exploratory) (Saunders, Lewis, & Thornhill, 2011). During the interviews the questions were adapted, changed, added or removed in order to obtain the most complete picture of the happenings at Larsen. The questions were open and sometimes complex. By using interviews the respondents were able to ask questions and to explain their answers. However, there are some concerns with this method according to Saunders et al. (2011).

According to Saunders, Lewis and Thornhill there may arise problems with the reliability of the interviews, while no standardized interview will be used. This means that different interviews may obtain different results. However, it needs to be clear that these interviews are a snapshot and that answers might depend on the time a question is asked. For this research it is necessary to be aware of this, but that it is not of influence on the diagnosis. This because not all people experience the same problems within the company and because these problems change continually. Meaning that today’s problems may be solved tomorrow.

The second problem Saunders et al. mentions is that bias may arise in the way the questions will be asked (interviewer bias) or in the answers that are given (respondent bias). Different questions will be asked to different people in different situations. Some interviews will be held in the office while others will be held in the factory, for some there is more time available than for others, and some will be able to give full attention, while other interviews were conducted during their work. The answers of the respondents may also be slightly biased, meaning that information might be held back or is altered on purpose. To deal with the interviewer bias, a thorough preparation will be been done before conducting the interviews. This consist of information gathering about the company and their products, but also in-depth information gathering about job-shop manufacturing, make-to-order companies and how to conduct interviews. In these topics problems may arise that often come with these company characteristics. To deal with the respondents bias, multiple respondents will be asked that have different positions within the company to obtain different perspectives of the problems. The respondents are chosen based on their position within the company to gain different perspectives about the problems and a follow up of the interviews might be done when information is not fully understood.

The third problem with this kind of interviews mentioned by Saunders et all. is the validity. In semi-structured interviews the results depends on the ability of the interviewer to interpret the answers; meaning that another researcher may obtain different conclusions from the same interviews. This will be dealt with through a thorough research before conducting the interviews.

**3.3.5 MCT and process mapping**

MCT and Process mapping will be combined as explained in previous chapter. The purpose is to understand the flow of goods and obtain the ratio between waiting time and touch time. However, because this is in the diagnostic phase, it will also be investigated what the root cause is for missing due-date-promises to see if QRM is the right approach to solve the problems or that an alternative may exist.
Flow of goods. This will be measured by attaching sheets to orders, not only in the office, but through the whole company. All orders that enter the company, starting from August until at least two months have passed, and triggers production will be followed. On this sheet, everyone who receives this order can fill in:
- the time and date when they started and finished processing the order
- what activity they performed
- write down comments when disruption(s) occurred and what was caused by.

**Figure 10 - Tagging sheet used at Larsen Premium Precision Parts**

**Ratio between waiting and touch time.** By means of the tagging sheets, the ratio can be calculated based on the starting and finishing dates/times.

**Root cause.** A link will be made between tagged orders and delivery dates. By comparing the information found during this research and comparing this to the information on due-date-promises and actual delivery, the root cause(s) may be found.

The MCT time is divided into touch times and waiting times for the departments: office, manufacturing and shipment. **Touch times** are when an order is actually being touched; the **waiting times** stands for the time it is not. The purpose of measuring MCT’s, and by dividing them into touch times and waiting times, is to gain an overview of what happens to an order and to locate where most results can be gained.

**Rules and concerns**
There are, however, some rules and concerns. The rules will be explained first, followed with the concerns. The three rules for MCT mapping are:

1. **All activities need to be carried out from scratch.** For this research it is important to obtain a clear picture of what happens to orders and why some are delivered late. Therefore, orders are followed from the moment they enter the company until they are delivered. However, no emphasis will be placed on that it needs to be made from scratch or that it needs to follow the critical path.

2. **The MCT should include all waiting times: normally applicable waiting times, but also other delays the orders go through.** During this research the moment someone starts with the order until (s)he is finished with this order is being measured. This means that the throughput time at a station is measured, which includes some waiting time. This might cloud the difference between touch times and waiting times, but it was necessary to obtain the cooperation from operators to make it as easy as possible. However, to deal with this,
operators will be asked to write down when disruptions occur during the time they are handling the products.

3. **The time a (partial) product is waiting in (intermediate) stock need to be included in the MCT.**
   For this research this was not a problem, because there is no intermediate stock at Larsen Premium Precision Parts.

**Concerns.** To ensure that all personnel would fill in the forms a short presentation has been given to inform them. During this presentation the emphasis was laid on the purpose of this research: what needed to be measured, why this was important, what would be done with the information, what the forms looked like, what needed to be filled in and why they should participate in this research. Extra emphasis was laid on the fact that the whole order fulfilment process would be examined and not some individual worker, and that the information would be held anonymously.
4 Diagnose phase

This chapter will start by elaborating on the nature of the problem. Hereafter, will be investigated if the tools provided by QRM are capable to find the root cause suggested by De Leeuw. Presented first will be the results of the QRM tools. Hereafter, will be shown if (some of) these results are the root cause. Research will show that a clear diagnosis could not be made based on the QRM tools used. The last chapter will add distribution tool of New (1977).

4.1 Service level

Orders, that were followed, were delivered before or after the due date, not on the due date itself. 11 orders were delivered early, six late. This is represented in Table 2. Based on the orders that were followed, the service level\(^2\) would be around 65 percent. Results also show that on average, an order is 10 days early, or four days late. However, the deviation is quit high between orders that are delivered early, varying between one to 23 days. This is represented in Table 3. Based on these orders, the average delay would be around four days. From this can be concluded that Larsen experiences a real problem.

Table 2 - Service level information

<table>
<thead>
<tr>
<th>General info on early/late delivery (number of orders)</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="chart1.png" alt="Bar chart showing number of orders" /></td>
</tr>
<tr>
<td>- early delivered</td>
</tr>
<tr>
<td>- on time</td>
</tr>
<tr>
<td>- late</td>
</tr>
<tr>
<td>- not yet</td>
</tr>
<tr>
<td>- internal order</td>
</tr>
</tbody>
</table>

Table 3 - Average delay

<table>
<thead>
<tr>
<th>General info on early/late delivery (number of days)</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="chart2.png" alt="Scatter plot showing days vs. order number" /></td>
</tr>
<tr>
<td>- early delivered</td>
</tr>
<tr>
<td>- late delivered</td>
</tr>
</tbody>
</table>

\(^2\) Service level = amount of orders being delivered on or before the due date.
4.2 QRM: finding improvement areas

4.2.1 Interview results

The purpose of the interviews was to explore the causes for not meeting the due dates, but also to find explanations why due dates are not met, according to the employees, and where lead time can be reduced. Seven participants were interviewed of which one production leader, one production planner, one office manager, one floor manager, two operators of the lathes department and one operator of the milling department. In Appendix V, the results are included.

The overall results showed that most employees mention the same causes. These have to do with the planned and actual processing- and set up times which take longer than is planned for during the order preparation phase, according to the respondents. However, there is disagreement why this happens. Reasons were mentioned like lack of skills of the operators, but also that processing times were wrongly estimated/determined and order preparation was insufficient causing extra work for operators. The last leads to situations where operators are not able to start processing after receiving the order, because of reasons like incomplete drawings, absence of equipment/materials etc. When processing- and setup times take longer than planned for, waiting time increases for upstream orders causing blockages in front of machines.

Other problems often mentioned during the interviews are machine breakdown and equipment wearing off, quality failures that causes rework, no one to take over work when operator is absent and checking products in and out of the system. These all influence the lead times and will be explained hereafter.

According to the employees, machines break down and equipment wears off causing longer throughput times. The first does not happen often, but, when it happens, it may take a while before it is fixed. This because the manufacturer of the machine that broke down, needs to send a maintenance man. When equipment wears off, new ones need to be ordered or made. This takes up extra time. A reason mentioned by operators is that there is no clear maintenance program to maintain the machines and equipment.

Quality failures do happen more often than machine breakdown and are therefore more interesting for this research. Quality failures are handled in three steps. First, the client is called to ask if they would accept the products as it is. If they do not, possibilities of reworking the products are investigated. If this is not possible, the whole products need to be made again. So, depending on the customers’ desires, quality failures may cause disruptions in the production process, leading to increased waiting times, longer throughput times, etc.

Another factor that disrupts the production process is when an operator is absent. Taking over machines is not easy to do and orders are often waiting for the operator to get back. However, this sometimes can lead up to days, or more, causing orders to pile up. One person mentioned that this might also have to do with a lack of trust between operators. Afraid to “mess someone’s machine up”.

Lastly, checking products in and out of the system is done to measure how long an operator worked on a certain order. Keeping track of this should lead to more correct estimations for when a repeat order is asked for and a better prediction can be made of the due date. However, checking products in and out of the system, according to the operators, is difficult to do when operators work with more than one machine. Because of this, some operators choose to not do this at all. Also, when an operator can not start on a product because of insufficient order preparation, this might lead to wrong estimations as well. This causes situations that make it difficult to estimate processing times but this is not a direct reason that causes orders to be delivered late or have long throughput times.

Other once or twice mentioned reasons can be found in the table below.

- Producing more products than needed and having no local performance measures. This ensures increased fluctuations in processing times. Operators do not get rules imposed on them and therefore cannot be penalized. This has created, according to the employees, less commitment to achieve targets and less motivation.
- Not enough time to operate more than one machine. This is related to planning and capacity issues. Switching between machine is not possible when a machine breaks down often or when one machine has a lot of small orders. Than more time is spend on one machine taking time away from the other machine.
- Operators work with given start dates. However, these sometimes lay in the past and cannot be finished despite the hard work of the operator. This leads to less commitment from operators and less motivation.
- Outsourced products not delivered back in time. Some procedures are outsourced for reasons such as not having enough capacity at Larsen or because Larsen cannot do it themselves. However, sometimes orders are not delivered back in time by the supplier causing Larsen to be unable to finish up on time and send the products to the customer before or on the due date.
- Changing due dates by clients. Some clients tend to change due dates themselves. If the client is important, the production process will be disrupted to meet the wish of the customer.
- Missing information about due dates. Operators do not have information on when products need to be delivered. Some operators are able to decide on which order to work first to deliver the products on time based on their experience. However, because this information is not given, they cannot interact in the process.
Table:

<table>
<thead>
<tr>
<th>Symptoms</th>
<th>Root cause</th>
<th>Mentioned</th>
</tr>
</thead>
<tbody>
<tr>
<td>More processing and setup time than planned for</td>
<td>Operator skills/planning/order reparation</td>
<td>II</td>
</tr>
<tr>
<td>No checking products in and out of the system</td>
<td>Motivation</td>
<td>III</td>
</tr>
<tr>
<td>Absence of the right materials, incomplete drawings</td>
<td>Order preparation</td>
<td>IIII</td>
</tr>
<tr>
<td>Machine breakdown</td>
<td>Maintenance</td>
<td>IIII</td>
</tr>
<tr>
<td>By absence of an operator there is no one to takeover</td>
<td>Operator skills</td>
<td>III</td>
</tr>
<tr>
<td>Quality failures</td>
<td>Quality policy</td>
<td>III</td>
</tr>
<tr>
<td>Wearing out machine parts</td>
<td>Maintenance</td>
<td>II</td>
</tr>
<tr>
<td>Producing more products than needed</td>
<td>Operations management</td>
<td>II</td>
</tr>
<tr>
<td>Not enough time to operate more than 1 machine</td>
<td>Planning</td>
<td>II</td>
</tr>
<tr>
<td>Starting dates in the past</td>
<td>Planning</td>
<td>II</td>
</tr>
<tr>
<td>Too many hierarchical layers</td>
<td>Company structure</td>
<td>I</td>
</tr>
<tr>
<td>Lack of trust to take machines over</td>
<td>Team commitment</td>
<td>I</td>
</tr>
<tr>
<td>Outsourced products not back in time</td>
<td>Supplier management</td>
<td>I</td>
</tr>
<tr>
<td>Changing due dates by clients</td>
<td>Client relations</td>
<td>I</td>
</tr>
<tr>
<td>Missing information about due dates</td>
<td>Communication</td>
<td>I</td>
</tr>
<tr>
<td>No local performance measurements</td>
<td>Operations management</td>
<td>I</td>
</tr>
</tbody>
</table>

4.2.2 Tagging and MCT results

The results of Process and MCT mapping should indicate where lead time reduction projects should be initiated to obtain most results, and the ratio between waiting time and processing time. Because multiple orders have been researched, it will be investigated if there may be differences between the following:

- New and repeat orders (this was indicated during the interviews)
- Number of production steps (this was indicated by literature)

MCT and ratio

It takes about 31 work days (about six calendar weeks) to fulfill an order. Of this time, an order is being touched for 104.5 work hours and waiting for 143.6 work hours. This means that the ratio between touch times and waiting time is close to 1:1.4. This means that about 42% of total time an order is being touched at Larsen Premium Precision Parts.

Results give the following representation of the average throughput time of orders at the company.

<table>
<thead>
<tr>
<th>Office</th>
<th>Manufacturing department</th>
<th>Preparing for Shipment</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 work days</td>
<td>21 work days</td>
<td>2 work days</td>
</tr>
</tbody>
</table>

Total throughput time = 31 work days

Results show that the ratio between total touch time and waiting time is quite big. This means that at Larsen Premium Precision Parts the waiting times are not necessarily their most important source for
lead time reductions. However, results also show the most waiting time is spend at the manufacturing department.

**Difference in MCT between new- and repeat orders**

According to the interviews a possible difference between repeat and new orders might exist. Results show that the MCT for repeat orders is smaller than new orders. But the ratio of new orders is bigger than for repeat order. This last indicates that new orders are waiting a lot longer than repeat orders. The illustration below represents the waiting times and touch times of new and repeat orders.

<table>
<thead>
<tr>
<th></th>
<th>MCT (work days)</th>
<th>Ratio</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Repeat</td>
<td>29</td>
<td>1:1,1</td>
<td>48%</td>
</tr>
<tr>
<td>New</td>
<td>34</td>
<td>1:1,6</td>
<td>38%</td>
</tr>
</tbody>
</table>

The comparison between new and repeat order, based on waiting time and touch time is depicted below. This may be (partially) explained by the interviews where was told that new orders need to be programmed while repeat orders do not.

**MCT of different productions steps**

Because of the variety between orders that are followed, the number of production steps also varies. Here is depicted the MCT of orders with different amount of production activities. Results show that the number of activities varies between four and nine. On average the MCT of orders with four steps is about 27 work days. On average the MCT of orders with nine steps is about 38 work days. However, the MCT fluctuates highly when the amount of production steps increases. This indicates
that some orders that go through many steps (nine) can be finished very quick. The MCT's are depicted below.

**Throughput time - production steps**

*Flow during touch time*

Because the ratios between the waiting time and touch time are quite large, for new and repeat orders, the flow of goods during touch time at the manufacturing and shipping department has been investigated. First, the planned and actual touch time has been compared to see if they deviate. Hereafter, the causes: bottleneck/congestion, disruption or batching of orders, has been researched.

**Planned and actual touch times**

Results show that touch time at the manufacturing and shipping department always exceeds the planned processing times. However, the amount of excess varied a lot between 40 min being the smallest excess, and 4672 min (77.9 work hours) being the largest excess. This is depicted below.

Here as well, has been researched if differences occurred between new and repeat orders. Results show that repeat orders, on average, have less excess than new orders, -883.9 min (14.73h) and -2087 min (34.78h) respectively. However, there were less new orders that could be used to compare to than repeat orders.
Cause and effect relations

The differences in planned and measured times has been investigated to understand what it was caused by. To understand why touch times exceeded the planned, the following causes have been investigated:

- whether time excess was due to a machine being a bottleneck (indicated by literature)
- whether time excess was due to operators experiencing disruptions (indicated by interview results)
- whether time excess was due to batching (indicated by interview results)

Machine/ activity being a bottleneck. Results show that all machines exceeded the planned time minimal once, and that it cannot clearly be traced back to one machine or activity.

Some machines exceeded often in small quantities (one or two work hours) (Ultrasonic cleaning, quality check, sawing and distribution). These were not very interesting for this research because QRM focuses on those spots where most results can be gained.

Other machines exceeded once or twice in very large quantities (between 11 and 77 work hours) (Mazak Nexus 100-I, Mazak Nexus 100-II, DMU 80T1 and VTC-200 C-4). These were explained by change of order route, mold had to be made and/or drillparts were not ordered.

The machines that regularly exceeded the planned time, with between four and seven work hours, were most interesting for this research. This happened at benchwork and rotofinish. Of these, the rotofinish is an unmanned machine, whereas benchwork consist of most manual work. This may indicate that for both machines more work is planned than can be handled.

One machine, the Mazak Nexus 100-III, exceeded the planned time three times in quite large quantities (28, 23 and 12 work hours). One time was explained by molds that still had to be made.

Disruptions mentioned by operators. Results show that disruptions occur. These were caused by:

- drill parts that were not ordered (mentioned once at VTC-200 C-4)
- molds that had to be made (mentioned once at VTC-200 C-4 and at Mazak Nexus 100-III)
- an order that had to follow a different route than was pre-determined during order preparation (mentioned once at Nexus-100)
These are all related to order preparation activities and caused exceedingly longer touch times than was planned for. Because of uncertainty and complexity of the shop floor, and the variety between products, these are often seen in ETO companies, like described in the literature research.

**Batching.** Results showed that batching of orders was done at the Mazak Nexus 100-III and at the Mazak Nexus 100-I. On both it did not lead to exceeding the planned time.

**Mapping of waiting time**
When orders are waiting, the flow of goods have been disrupted and were already explained above. This part will start by locating the waiting times in the order-fulfillment process. Hereafter, causes are investigated to see if long waiting times is caused by:
- number of activities
- number of main procedures
- backlog

*Waiting times in the order-fulfillment process*
The order process has been explained earlier. Here, the average waiting times between activities have been calculated and made visual in Figure 11.

Results show that most waiting time can be traced to the first half of the order-fulfillment process. After arriving at the finishing department, orders often leave the company very quick. With the exception of bench work, where orders are waiting on average 33 work hours. This confirms the results found in chapter 4.2.2 that indicated that bench work might be a bottleneck.

Before work preparation and before and between, milling and turning procedures, most waiting time is spotted.

To supplement the picture of waiting times, the figure depicted below will zoom in on the average waiting times between job preparation and quality check.
Results show that long and short waiting times are spread throughout the company. Only after the Mazak Nexus 100-I, constant average long waiting times are measured. This might be due to batching of orders found in chapter 4.2.2. Batching of orders causes many orders to be released at the same time.

In front of the DMU 80T1 also constant average long waiting times are measured. Because from paragraph 4.2.2 can be concluded that here no problems exist between planned and actual touch times, it can be concluded that a lot of orders arrive at this station causing congestion.

**Cause and effect relations**

In paragraph 4.2.2 it has been investigated if disruptions occurred, how often and where. Some of these can explain long waiting times in front of machines. However, waiting times can also arise when a lot of orders come together at a station creating congestion. This means that the planned work-load exceeds capacity for a machine or station. In this paragraph, will be researched what the average backlog was and if this causes long waiting times. This will be investigated for the machines that had high waiting times, i.e. DMU 80T1, Mazak Nexus 100-I, Mazak Nexus 100-III, Schaublin 125, FJV 20, Mazak FJV 200.
Results show that two orders had long waiting times which might have been caused by high backlog (nothing was mentioned of disruptions). One order had little waiting time while there was a high amount of back log. This order might have been given preference. Overall, high backlog is measured indicating that more work is planned than it can handle.

Results show that at the mazak nexus 100-I a continues backlog exists of on average about 8 hours. High waiting times are measured when high backlog occurred.

Results show that on overall high backlog is measured. Waiting times vary often. This might indicate that more work is planned that it can handle.
Results show that there is no high backlog measured, though waiting times vary frequently.

Results show that longer waiting times are caused by higher amounts of backlog.

Results show that even though high backlog was measured, waiting times were less than one hour. It indicates that these were given preference.
4.2.3 Conclusion QRM method

The purpose was to measure the MCT, calculating the ratio between waiting time and touch times, discovering flow disruptions during touch times and locating waiting times within the company. All, to discover where most lead time reduction can be gained.

**MCT and ratio**

The MCT for an order at Larsen is 31 work days (6.2 calendar weeks). A small distinction can be seen between new and repeat orders. New orders take 34 work days (6.8 calendar weeks), repeat orders 29 work days (5.8 calendar weeks).

The ratio between touch time and waiting time of all orders is 1:1.4. For new orders this is 1:1.6 and for repeat orders this is 1:1.1. This means that the difference between waiting time and touch time is not as big as mentioned by Suri. For all orders, 42% of the MCT is spend on processing. For new orders, this is about 38% and for repeat orders this is around 48%. This indicates that waiting time is not necessarily a bigger problem than processing times, at Larsen.

**Flow of goods during touch time**

Here, first has been investigated if actual touch times were different from what was planned for and, if so, by what it was caused. Results showed that all machines exceeded the planned times. When large excesses were measured, this was often due to insufficient order preparation, for example when an order had to follow a different route or molds had to be made. There were also a lot of machines/activities which often exceeded in small quantities. Because here no big results can be gained, which was the aim of this method, this has not been further researched. This is also caused by uncertainty, the gap between the needed knowledge and what is available within the company. However, at benchwork and the rotofinish the planned time was often exceeded by middle high quantities. These may be bottlenecks.

**Mapping waiting time**

Most waiting time is located during the first half of the order fulfillment process. Especially high waiting times are measured in front of work preparation, in front of milling and lathe machines and between milling and lathe machines. The machines with the highest waiting times in front are: DMU 80T1, Mazak Nexus 100-I, Mazak Nexus 100-III, Schaublin 125, FJV 20, Mazak FJV 200. These have been researched to see if long waiting times were caused by backlog.

Results showed that some machines experiences high backlog while they do not often exceed the planned touch times. This is the case for DMU 80T1 and Mazak FJV 200. This indicates that there may be more work planned for than the machines can handle. However, at the Mazak FJV 200 it does not necessarily lead to longer waiting times. Here, orders did not have to wait long despite the high backlog.

The Mazak Nexus 100-III experiences also a high amount of backlog, however here, the planned time was exceeded a few times. A clear reason was not found. Results also showed that for some machines, long waiting times were caused by high backlog. This was seen at: Mazak Nexus 100-I and FJV 20. At the Schaublin 125, no high backlog was measured. Though, the waiting times were high and varied a lot.
4.3 Reviewing delivery performance
This sub-chapter will provide some general information on what orders are delivered late or not. This will be followed with researching some cause and effect relations. Hereafter, the lateness of orders is described to enhance the tools provided by QRM to find the root cause for late delivered orders. Last sub-chapter will conclude the information from this chapter.

4.3.1 General information
Here is investigated what kind of orders are delivered late, to what customers, the difference between new and repeat orders, and number of activities.

Customer
The following presents the delivery performance per customer. Results show that no clear preference is given to a certain customer. However, it is noticeable that customer B more often receives his orders late rather than early. Far more often than other orders.

![Customer dependent graph]

**New and repeat orders**
The following presents the difference of performance delivery between new and repeat orders. Results show that new orders are more often delivered late than repeat orders. The orders delivered early are approximately equal between new and repeat orders.

![New and repeat orders graph]
Number of activities
The following presents the delivery performance based on the number of activities orders had to go through. Results show that more activities do not result in late delivered orders. On the contrary, orders with only four activities all were delivered late, while of nine activities only one of five were delivered late. This might indicate that orders with more production steps would be given preference or more safety time.

4.3.2 Cause and effect relations
During previous research three problems emerged. First, long waiting times were measured between turning and milling procedures (these will be referred to as main procedures). Second, a bottleneck was spotted, being benchwork. Third, sometimes disruptions occurred causing touch time to exceed the planned time. These disruptions were related to order preparation activities.

Of all these problems, it did not show if these were causing more orders being delivered late. Here, the following will be investigated:

One or two main procedures
Benchwork
Insufficient order preparation

One or two main procedures
Long waiting times were measured between the turning and milling department. Here has been examined if this waiting time caused orders to be delivered late. Results show that there is no indication that orders going through two main procedures were more often delivered late.
Benchwork

In front of benchwork, high waiting times were measured and it indicated that more work was planned for than they could handle. To see if this leads to more orders being delivered late, the finishing activities have been further researched. Results are as follows:


\[\text{Main procedures} \quad \begin{array}{c|c|c}
\text{number of orders} & \text{one main procedure} & \text{two main procedures} \\
\hline
default & 6 & 4 \\
early & 2 & 2 \\
\end{array}\]

Results\(^3\) show that all orders going through rotofinish were delivered on time. One out of three orders going through benchwork was delivered late. This might indicate that some orders may be delayed because of benchwork. However, of all late delivered orders (six), only two that went through benchwork were delivered late. Also, more orders are delivered early rather than late.

**Insufficient order preparation**

Two orders experienced longer touch times because of insufficient order preparation. Here, molds had to be made, drillparts were not ordered and/or wrong cycle time was calculated, causing differences between what was planned and what was actually performed. These two orders were both delivered nine days early.

\(^3\) Ultrasonic cleaning has not been added to this table while all orders go through here.
4.3.3 Lead time distribution
Up until now, no root cause has been found to explain the low delivery performance of Larsen Premium Precision Parts. Therefore, the distribution of lateness will be used to better understand the situation.

When reviewing the lateness of orders at Larsen Premium Precision Parts, it is noticeable that the delivery of orders is very wide. This indicates that it looks most like situation 5: ‘sequencing problem’ (see paragraph 2.1.5). This is supported by earlier found information that internally orders are waiting very long to be processed sometimes, while other times orders are waiting very short, despite the backlog at a machine (paragraph 4.2.3).

4.3.4 Conclusion delivery performance
The purpose was to understand what kind of orders were delivered late and to test if the problems found at 4.1 and 4.2 would cause orders being delivered late.

Of the general information, results showed that most orders were delivered early (by 10 days on average), and only a few were delivered late (by four days on average). It was noticeable that the deviation of early deliveries was high, meaning that orders were delivered early varied between one and 23 days. Results also showed that between customers, it seems that, of all orders delivered late, most were for client B. Between new and repeat orders, a small difference is seen. New orders are slightly more often delivered late. However, this is about two orders more than repeat orders. When comparing orders to each other, based on the number of activities, most orders were delivered late with four production steps, and delivered early within nine productions steps.

At paragraphs 4.1 and 4.2 problems that arose consisted of long waiting times between main activities, bench work being a bottleneck and insufficient order preparation.

Results show that all problems, long waiting time, bottleneck and insufficient order preparation, all did not cause more orders being delivered late. No difference is seen in delivery performance between orders that went through one or two main procedures. At bench work was detected that some orders were delivered late, but these were only two out of six. Also, more orders were delivered early than late. Of the orders that experienced insufficient order preparation were delivered nine days early.

Because no root cause has been found in paragraph 4.1 and 4.2, in paragraph 4.3 the distribution of lateness of orders has been used. Here, results showed that Larsen Premium Precision Parts experiences a wide distribution of delivery of orders. This indicates that problems with sequencing orders causes orders being not delivered on the due date and that scheduling should be further investigated.

4.4 Conclusion diagnosis phase
QRM is an approach that improves delivery performance by reducing lead time, especially in custom made manufacturing companies. This is done by discovering the most important improvement areas. However, according to De Leeuw, when you are dealing with a problem situation, you first need to discover what the root cause is, to understand how to address the problem. Only when the root cause is known, it can be concluded if QRM is a good solution. Therefore, the first research question
was: “Are the tools, MCT mapping and process mapping, capable to discover the cause for not meeting due date promises at the company Larsen Premium Precision Parts?”.

Results show that, while MCT mapping and process mapping do provide a lot of insight in the manufacturing process, it only discovers possible improvement areas are not the root cause for the low delivery performance.

From the QRM methods, it has become clear that it takes Larsen Premium Precision Parts about 31 work days to manufacture an order. The ratio between touch time and waiting time is 1:1.4. This means that 42 percent of the MCT an order is being processed. This is quite different from what QRM states, which is around 5 percent. Furthermore, QRM tools showed that the following improvement areas are:

- Insufficient order preparation, like missing equipment, causes disruptions. This leads to longer touch times.
- Results indicated that bench work and rotofinish appears to be bottlenecks and that, for the machine DMU 80T1, more work is planned than can be handled. This increases waiting time.
- Lastly, longest waiting times are measured between turning and milling procedures.

When reviewing the delivery reliability, it has been investigated if these improvement areas are the cause for missing due date promises. However, despite that these causes results in longer MCT’s, it does not lead to orders being delivered late. Therefore, they are not the root cause for their low delivery performance.

Finding the root cause was eventually done by use of the distribution of lateness tool. Results showed that the situation at Larsen looked most like situation 5 ‘sequencing problem’, because the delivery span was very wide. Some orders were delivered early by 23 days, other late by five days.
5 Design phase
During the diagnostic phase some problems emerged that led to longer MCT’s. However, research pointed out that these were not the root cause of low delivery performance at Larsen Premium Precision Parts. Results showed that Larsen has problems in the way they sequence their orders, causing a wide distribution span. In this chapter, research question two, three and four will be investigated: “What criteria should the solution satisfy?”, “Does QRM provide a solution to solve the problems at Larsen Premium Precision Parts?” and “Are there alternative solutions that can/need to be considered?”. In this chapter, some solutions will be given on how to deal with this problems. First will be started with describing an overview about the possible solution to sequencing problems and how a company can choose between them. This will be followed with a list of requirements that a solution should satisfy for Larsen Premium Precision Parts. Two sequencing methods arise and will be more elaborated on. Thereafter, a conclusion and recommendation will be written.

5.1 Possible solution sequencing problem: overview
More solutions exist that deal with the sequencing problem. Stevenson et al. (2005) developed a decision matrix to decide what system fits best. Suri (2010) approaches it in another way: by focusing on what is needed within the system, i.e. push, pull or hybrid. These will be further explained.

5.1.1 Decision matrix
Stevenson et al. (2005) wrote an article wherein they investigated Production, Planning and Control (PPC) systems in MTO companies and created a matrix to help decision making between these systems. PPC systems are tools to meet current customer demand and the expectations in the future. Functions of these systems include: planning material requirement, planning demand management, capacity planning, but most importantly, the scheduling and sequencing of jobs.

These systems contribute to this by minimizing the work-in-process (WIP) level and the shop floor throughput times and lead times. Furthermore, it lowers stockholding costs, improves responsiveness to changes in demand, and most importantly, improves delivery due date adherence.

They investigated the following systems: Kanban, Manufacturing Resource Planning (MRPII) and Theory of Constraint (TOC), and the following techniques: WLC, CONstant Work In Process (CONWIP) and POLCA.

According to Stevenson et al. (2005) the most appropriate system for a custom made manufacturing company is determined by the company industry and the shop floor configurations. They distinguish the VMC and RBC industry, and the general flow shop and the general job shop. A matrix is created to help decide which system is most appropriate in what companies. They also took into account the size of companies and the kind of customization, when reviewing the systems and techniques. They developed the following Table 4. Thereafter, these systems will be further explained.
Table 4 - Decision matrix (Stevenson, 2005)

<table>
<thead>
<tr>
<th></th>
<th>MTO (RBC)</th>
<th>MTO (VMC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>General flow shop</td>
<td>WLC</td>
<td>Not applicable</td>
</tr>
<tr>
<td></td>
<td>CONWIP</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ERP</td>
<td></td>
</tr>
<tr>
<td></td>
<td>POLCA</td>
<td></td>
</tr>
<tr>
<td></td>
<td>TOC</td>
<td></td>
</tr>
<tr>
<td>General job shop</td>
<td>WLC</td>
<td>WLC</td>
</tr>
<tr>
<td></td>
<td>ERP</td>
<td>ERP</td>
</tr>
<tr>
<td></td>
<td>TOC</td>
<td>TOC</td>
</tr>
</tbody>
</table>

Larsen is a company that receives VMC as well as RBC customizers. Their shop floor should therefore be general job shop instead of flow shop. However, at Larsen a general flow is seen, which makes about all systems possible solutions for Larsen, including WLC, CONWIP, ERP, POLCA and TOC.

WLC uses a pre-shop pool of orders to reduce shop floor congestion (Stevenson et al., 2005). This means that when orders are waiting to be released, unexpected changes can be accommodated to without great impact on the production process. Because of these aspects, the shop floor becomes stabilized and independent of variations in the incoming order stream. Queuing times become more predictable and release decisions may lead to lead time reductions. However, this method is more focussed on stabilizing the shop floor by regulating the flow of orders to the shop floor instead of continually reducing lead times.

CONWIP is a card based system that regulates the flow of work by controlling the WIP level. The cards are ‘job number specific’ which makes it an appropriate system for high variety environments; however, the work load of each card needs to be approximately similar. When high fluctuation exists, this may become a problem. Furthermore, inventory levels inside the system are not controlled individually causing high inventories to appear in front of slow machines or when machine breakdowns occur (Stevenson et al. 2005). Alternatives exist that deal with these problems, like for example CONLOAD (Stevenson et al. 2005).

ERP (enterprise resource planning) originates from MRP, but contains new software capabilities that increases the functionality. It include software modules, each responsible for a business function. However, failure rate is high (Stevenson et al. 2005).

POLCA is a card system that emphasises the reduction of lead times, cutting production costs, increasing due date adherence, and cutting scrap and rework. It is applicable in highly engineering production, small batches and high variety, and uses MRP for higher production planning. However, according to Stevenson et al. (2005) POLCA is more focussed on RBC customizer in the MTO industry instead of VMC customizer, and is better implemented in the flow shop than the job shop configuration (Stevenson et al. 2005); although, Riezebos (2010) states that the flow between cells is
controlled by POLCA, not within cells. A suitable cellular structure need to be designed that might differ from the current structure and that takes hold of the ‘inter-cellular traffic’ between cells.

TOC is a bottleneck-oriented concept. It runs the production process according to the needs of the bottleneck and can be implemented in job shop as well as flow shop, and for VMC and RBC customizers. However, Larsen experiences a moving bottleneck and, in situations with high customized products, MRP tends to perform better than TOC (Stevenson et al. 2005).

In the matrix, the systems have been researched in quite a pure form, while, often, systems can be adapted to different situations. POLCA for example, works with cards that combine two cells, called two-coloured cards. However, for a specific company, the cards were cut into two to enhance flexibility between multiple cells (Powell et al., 2012). Here, single-coloured cards were combined to show where products has to go. So, to enhance flexibility between multiple cells, POLCA had to be adapted to the situation. Furthermore, in this research, all systems and techniques are reviewed individually, while the writers acknowledges that most are not mutually exclusive and that combining systems and techniques may enhance results.

5.1.2 Push, pull or hybrid
According to Suri, systems are better distinguished by dividing them into push and pull, or a combination between them (hybrid system). Depending on what is needed within the company, a system is chosen.

Push systems
Push systems are driven by the due date for a shipment. It uses planned lead times and determines starting dates for when materials need to be released to the next work centre. Here, the push aspect is that orders are worked on based on a given schedule, without considering other work stations. However, it creates situations wherein orders are worked on that thereafter go to a work station that is overloaded, while another station might be idle (Suri, 1998). Furthermore, lead times are determined per order, fixed, and independent from facility load, batch size policy, production mix and order release activity (Karmarkar, 1991). However, previous research showed that lead times are functions of these factors and that they depend on shop activity. To accommodate errors in lead time, lead times are often calculated based on the worst case scenario, which results in very early starting dates and may lead to early completion (Karmarkar, 1991).

Other problems with these systems are that information handling is often expensive. Hardware and software are needed and data entry, data generation, instruction generation, communication and maintenance costs time and money (Karmarkar, 1991). Also, failure to understand order release may lead to wrong release dates, causing orders to be delivered late, and wrong in-process inventories and finished parts inventories (Karmarkar, 1991). Furthermore, because of centralized decision making and lack of responsibility, workers tend to be less motivated to improve manufacturing performance like reducing lead times (Karmarkar, 1991). Therefore, push systems often do not live up to what is desired in an ETO company very well.

An example of a push system is MRP. MRP is based on scheduling orders that have a known BOM, a known product routing and the possibility to forecast future demand. However, when implemented
in a changeable environment and variation in design and production, it may lead to high WIP levels and long lead times.

Pull systems
Pull systems are driven by the removal of inventory from finished goods (Suri, 1998). When at a work station inventory becomes below a certain level, it sends a signal to a preceding station that more products are needed. This means that actual demand triggers production and that no more than a preset number of products are in line. Furthermore, it is easy to control, because of the visibility and the simplicity, and it motivates continuous quality and reliability improvements while it highlights sources of disruptions (Suri, 1998). However, a big disadvantage of pull is that “pull starts with sale of a product already in stock and then works its way upstream through replenishment of inventories” (Suri, 1998, p.233). When implemented in ETO companies, this would only be possible for RBC businesses since VMC businesses cannot be predicted or made in advance.

An example of a pull system is Kanban. Here, containers or cards are used to signal further up the line that replenishment is needed. The disadvantage of Kanban is, however, that small amount of inventory is needed between work stations. This causes extra waiting times for orders and when variety in orders is high, a lot of containers or cards are needed. Also, when such a card system is used in a Just-In-Time environment, Total Productive Maintenance and other quality improvement systems are needed, or else continuous disruptions causes problems for the delivery of products (Suri, 1998).
Hybrid systems
Both push and pull systems are not very suitable in ETO companies with RBC and VMC customizers. However, beside push and pull, there also exists combinations between them, called hybrid systems. These systems combine push and pull components. When, for example, there is no variability in demand or in lead times, pull systems can be used. When demand is variable but known, push systems can be used. This means that variability and predictability of demand determines for a great deal if a push or a pull system is most applicable (Karmarkar, 1991). Examples of hybrid systems are CONWIP (including m-CONWIP) and POLCA (Stevenson et al., 2005). Both use cards to limit the workload on the shop floor. However, the difference between POLCA and (m-) CONWIP is that (m-) CONWIP balances the shop floor and initial production when an order is finished. The control loop covers all workstations, wherein m-CONWIP is capable to control every possible routing (See Figure 16). POLCA balances the shop floor but prioritizes orders as well. Production is initiated by a customer order and control loops cover two workstations (see Figure 17). When an order visits two or more stations, overlapping loops ensure that capacity is regulated (Germs et al., 2012).

5.2 Requirements
The sequencing problem deals with how orders are being processed to ensure that all orders are being finished as soon as possible (French, 1982). When dealing with a few jobs and a few machines, this is not very difficult to determine. But when dealing with n-number of jobs and m-number of machines, finding the most optimized solution for each order becomes more difficult to find (French, 1982).

There are different solutions to solve this problem. What solution fits best with a company depends on certain aspects. First, it depends on the kind of industry a company is active, i.e. RBC or VMC industry, and second, on the shop configuration, i.e. flow shop or job shop. (Stevenson, 2005; Suri, 1998).
To understand what system is most appropriate for companies such as Larsen Premium Precision Parts, it needs to be clear what requirements it needs to conform to. This means that the solution needs to be applicable in an ETO company with a high level of customization, with RBC and VMC customizers and multiple experts. It searches for a system that deals with the sequencing problems in order to reduce the make span of the lateness distribution. However, it should also take into account that in the long term the purpose is to reduce lead time to enhance their competitive advantage. This leads to the following criteria:

1. Ability to cope with repeat and non-repeat production (VMC and RBC)
2. Ability to cope with highly customized products (ETO)
3. Ability to cope with multiple experts
4. Ability to provide planning and control when shop floor routings are variable, i.e. general job shop.
5. Ability to sequence orders to minimize the distribution span close to zero
6. Ability to continually reduce lead time to enhance competitive advantage in the future

5.3 Design choice

When considering the decision matrix the WLC method appears to be the best solution. It is applicable in all situations and not many changes are needed. However, when considering between a push, pull or hybrid system, the hybrid system seems to fit the requirements best. This puts forward CONWIP and POLCA systems as possible solutions, as well, of which POLCA seems more appropriate for Larsen. In this chapter WLC and POLCA will be further elaborated on to gain more in-depth information.

5.3.1 QRM solution: POLCA

QRM has been created to reduce lead times and increase reliability in MTO companies. This is done by restructuring the organization into cellular manufacturing to increase flexibility and decrease lead time. To regulate and control orders in the production process, a card system has specially been designed, called POLCA.

As mentioned in chapter 2.2, POLCA communicates and controls material movement between cells, which is done by cards. These cards are assigned to pairs of cells; these are called loops. Figure 18 shows a loop between cell Z and A. To this loop a Z/A-card has been dedicated, which means that an order that needs to go from cell Z to cell A will be dedicated to this loop. Cell Z however, can only start with the order when it has a Z/A-card. This card needs to be available at cell A, which is when there is enough capacity at cell A. When cell Z has a Z/A-card, it can start with the order and transports it to cell A when finished. Cell A, however, can only start with the order when the next cell (for example cell B1) gives authorization by giving an A/B1-card to cell A. They will only do this when they have enough capacity and will authorize cell A to start by giving them an A/B1-card. When this card has been received cell A can start with the order.
By means of this POLCA system, a situation is created wherein operators only work on orders for which capacity is available downstream. Therefore, this system does not only determine when to work on what order, but also tries to make sure that the work is more balanced on the floor. However, this card system is very strict and a cell may only start with a product when the following conditions are complied to:
- the materials must be available
- the authorization date has to be earlier or of today
- a POLCA card needs to be available

This means that operators need to be disciplined in their work. When one of the rules is not complied to the system may become unbalanced. For example, when a cell becomes idle, they might ask a cell upstream for work. When this is given to them without a card being available or without the authorization date being earlier or of today, favouritism decides when to work on a job instead of cards. This will degrade the system (Suri, 2010).

Also, operators need to be motivated to obey these rules. This is, for example, done by decentralization and by giving power to operators over their own cells. These operators need to be dedicated to cells to achieve the best results.

**PROPOS**
Bosch Scharnieren is the first company in Holland that has implemented POLCA and QRM. When implementing POLCA, they actually went a step further and designed a software system based on POLCA. This system, called PROPOS, is a digital POLCA system for manufacturing companies. It plans and monitors orders in order to shorten delivery times, increase reliability and lowers manufacturing costs\(^4\). A plant visit (2012) has delivered the information below.

PROPOS uses information from a MRP system to online authorize the release of orders. By means of controlled access to the manufacturing department and by guiding orders throughout the company while keeping track of unusual events, such as high waiting times, congestion is prevented.

\(^4\) [http://www.propos-software.nl/PROPOS_in_detail.html](http://www.propos-software.nl/PROPOS_in_detail.html)
Authorization and providing operators information of the orders is done by screens. These screens provide information, such as what order has the highest priority or when an order risks to be delivered late. Operators are then able to take appropriate precautions to prevent this from happening.

Because operators can see what workload will arrive shortly, it raises awareness and responsibility among operators. Openness in information tends to create involvement with operators and motivates them, and stimulates communication between office and the manufacturing department.

For implementing PROPOS, ERP is normally used, but, when it is not available within the company, there are other possibilities. It is not necessary to have it within the company. The system will be delivered according to customer desire and requirements. This means that it will be tailor-made. Furthermore, the system is based on POLCA, which is part of QRM. However, it is not necessary for companies to have already started with QRM or lead time reduction; though, it will make it easier to implement QRM by means of this system. Lastly, because of this system the need for a planner is also not necessary. These tasks can then be taken over by the system.

**Applicability of POLCA at Larsen Premium Precision Parts**

POLCA is a system that determines when to work on what job (job sequencing) and makes sure the practices are more aligned and balanced. However, to implement POLCA, Larsen should turn their company into cells first. These cells need to be dedicated to product families/groups. However, as mentioned before, it is not easy to divide the products at Larsen because of their pure customized products. Furthermore, order routes are firstly determined by machines, then by operators. When a machine is dedicated to a cell, problems may arise for orders to be fulfilled. Also, Larsen does not have an HL/MRP yet, which is needed for POLCA for higher level planning and material coordination. These are fundamental practices that need to be applied before being able to start with POLCA.

There are, however, some possible solution found in literature that might be applicable at Larsen. For example, cells based on a more functionalistic approach can be made instead of product families, like in the report of Westerbeek and Knol (2011). Also, cards cut in two, like done at Variass, may give the needed flexibility. Furthermore, for implementing PROPOS no HL/MRP system is needed and no cells have to be created to achieve the desired results; it will even make it easier for taking the next steps to start with QRM.

**5.3.2 Work Load Control**

WLC is a PPC method to control workloads on the shop floor by creating a pre-shop pool wherein orders are waiting to be released to the shop floor (Land & Gaalman, 2006a). This is regulated by combining three levels of control decisions: job entry, job release and priority dispatch (Thurer et al, 2011), all dedicated to limiting the amount of orders within the shop floor and therefore the queue lengths. Controlling the queue length results in more predictable lead times and due dates. Also, pooling jobs before entering the shop floor provides management to delay final production decisions, reduces waste due to cancelled orders, facilitates late ordering of raw materials and takes away the need for expediting rush orders (Land & Gaalman, 2006a). However, job entry control is important, as well, for it will keep the pre-shop pool under control. By having no job entry control, the pre-shop pool can explode, which leads to decreased accurateness of due dates.
Levels of control decisions

There are three levels of control decisions: job entry, order release and dispatching rules. However, of these three, the most important are the job entry and order release. When these are set accurately, the dispatching decisions will not be of high influence on the performance of the company. Because every company can set their own rules, this approach is applicable in almost every company, but especially in job shop environment when variety is high (Stevenson et al., 2005).

Customer enquiry and job entry stage. Customer enquiry and job entry stage has mostly been researched by Lancaster University and is therefore called the LUMS approach. The LUMS approach is the interaction between the customer and the company and determines the price and due date of an order. Hereby, information about the order and the shop floor is taken into account. This is better than those who do not, according to Ragatz and Mabert (1984).

Order release. After due date and price setting, the order is accepted (or not) by the client and prepared, after which it waits in a pre-shop pool to be released to the shop floor. By keeping the orders in a pre-shop pool, fluctuations in demand can be absorbed. The decision when to release an order depends on the sequencing decision and the selection decision.
- The first decision prioritises the orders in which to release, while
- the second decision determines if the order is to be released, or not, at a specific moment (Land & Gaalman, 2006).

The release methods can be divided into infinite loading and finite loading. Finite loading places restrictions on the quantity of work, infinite assumes infinite capacity.

Infinite methods can be further categorized as uncontrolled and controlled release decisions. Uncontrolled includes immediate/periodic releases of jobs to the shop floor. Controlled decisions include backward-infinite-loading and modified-infinite-loading. These aim at reducing the dispersion of lateness (Land, 2004). The first by using job characteristics to determine the release date; the second includes estimates of loads (Land, 2004).

The finite loading methods can be further categorized in load limiting, and load limiting and balancing methods. Load limiting reduces the maximum number of jobs on the shop floor; load limiting and balancing includes forward-finite-loading and classical WLC release methods. These balance the load across stations and over time (Shimoyashiro, 1984). This to improve the throughput of orders (Land, 2004). See Table 5 for a summary.

Table 5 - release methods categorised with some typical examples (Land, 2004)

<table>
<thead>
<tr>
<th>Infinite loading</th>
<th>Finite loading</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncontrolled: (no particular influence) Immediate/periodic</td>
<td>Load limiting: (reducing WIP)</td>
</tr>
<tr>
<td></td>
<td>Reduces max nr of jobs on floor</td>
</tr>
<tr>
<td>Controlled: (Reducing lateness dispersion)</td>
<td>Load limiting and balancing: (reducing WIP and</td>
</tr>
<tr>
<td>Backward infinite loading</td>
<td>controlling throughput)</td>
</tr>
<tr>
<td>Modified infinite loading</td>
<td>Forward finite loading</td>
</tr>
<tr>
<td></td>
<td>Classical WLC release methods</td>
</tr>
</tbody>
</table>
Dispatching rules

The final control decision is the dispatching rules which determine the processing sequence of orders that are waiting in front of the machine. However, when combined with the release decision, the impact of the dispatching rule is less significant. Therefore, more simple dispatching rules, like first-in-system-first-served or first-at-work-centre-first-served, can be used. The dispatching rules can be either focussed on conserving the flow, improving throughput or to reduce lateness dispersion.

To enhance the flow within the company, the first-come-first-serve method is applicable. The order wherein orders arrive is the order wherein they will be processed. Here, job release decisions determine the sequence of orders.

Improving the throughput can be done by making use of the processing characteristics or by reacting to workload imbalances. The following methods make use of the processing characteristics: shortest-processing-time, least-operations-remaining and least-work-remaining. The shortest-processing-time method results in lowest job average throughput time. The least-operations-remaining and the least-work-remaining methods sequence orders by giving priority to orders than can be done quickly. To react to workload imbalances, work-in-next-queue method can be used. Here, priority is given to the order for which less waiting time downstream is measured. This last method, however, is difficult to implement because continuous information is needed on other station.

To reduce lateness dispersion earliest-due-date, operation-due-date, slack-per-remaining-operation or critical-ratio can be used. The first gives priority to the order with the earliest due date. The second gives priority to the order with the earliest operation due date. The third gives priority to the least slack per remaining operation. This means that the lead time minus the processing time (called slack), is divided by the number of operations. The order with the least slack per operation will be processed first. The last, critical ratio, is measured by dividing the time left until due date with the processing time left. The order with a ratio less than one will become late and will be processed first.

Applicability of WLC at Larsen

For Larsen Premium Precision Parts the release decision should be focused on reducing lateness dispersion. This can be achieved by the controlled infinite loading methods. This can be supplemented by dispatching rules like earliest-due-date, operation-due-date, slack-per-remaining-operation and critical ratio which are all focused on reducing lateness dispersion, as well. However, when using WLC, the total lead time might be shortened at first, but it is more focussed on stabilizing the shop floor than on continually reducing lead times. Furthermore, sufficient feedback from shop floor is needed, as well as someone with authority to manage the shop floor (floor manager or foremen), and calculations and methods need to be performed to determine the right methods (Henrich et al., 2004). The biggest advantage of WLC is, that it increases predictability and enhances due date prediction. Also, restructuring is less radical than POLCA. It does, however, need support from operators to turn it into a success. But most importantly, WLC is focused on stabilizing the shop floor and not to continually reduce this. This means that at first some lead time reductions may appear but that this will not be on a continuous basis and might not deliver the results expected by customers.
5.4 Conclusion design phase

From the diagnose phase it became clear that sequencing of orders resulted in a wide distribution span. In this chapter solutions have been researched, tested along the requirements and further elaborated on. All to answer sub-questions: “What criteria should the solution satisfy?”, “Does QRM provide a solution to solve the problems at Larsen Premium Precision Parts?” and “Are there alternative solutions that can/need to be considered?”. 

Results show that for Larsen Premium Precision Parts it is important that a system is implemented that deals with their sequencing problem to reduce their distribution make span; to improve their delivery reliability. Furthermore, it should be able to deal with multiple experts, RBC and VMC orders and be future oriented. The systems that fit these criteria best are POLCA and WLC. However, both fall short in some way or another, meaning that there is no ready solution.

POLCA is future-oriented meaning that it will provide competitive advantage in the future. Also, it is a hybrid system, meaning that it uses the best of push and pull mechanisms. However, POLCA is part of QRM and to turn it into a success, the whole company needs to be restructured. Furthermore, POLCA is based on cellular manufacturing based on product families. At Larsen this does not exist because of the high level of customization and the mix between RBC and VMC orders. Also, QRM does not provide a solution on how to handle multiple experts in such a company. However, POLCA does have the ability that it can be adapted to certain situations.

WLC does not need much restructuring, can handle multiple experts, RBC and VMC orders, and high product customization. However, this system will only increase predictability of due dates. It stabilizes the shop floor, but it does not continually reduce lead times nor will it improve existing processes within the company, including the office.

Recommendation to Larsen would be to investigate the possibilities of adapting POLCA to their situation. Here, answers need to be found for dealing with the multiple experts problem and forming cells without having product families. This will deliver in the long term more results. However, in the short term, some WLC decisions might be considered as well. The company does not use release decisions or dispatching rules. Here, the release decisions should focus on reducing the lateness dispersion, like Backward infinite loading and Modified infinite loading. These can be supplemented by dispatching rules like, earliest-due-date, operation-due-date, slack-per-remaining-operation or critical ratio.
6 Conclusions and recommendations

QRM is a company improvement method that focuses on reducing lead time to improve company performance. It claims to be especially applicable in custom made manufacturing companies as well as make-to-order as engineer-to-order. However, the definition that is used to define ETO companies, is rather simplistic and some ambiguities were found in literature. This has led to the following research question:

“How suitable is QRM to improve company performance (i.e. reliability and speed) in a vertically integrated company, such as Larson Premium Precision Parts, only responsible for the purchasing of materials?”

Results showed that just starting with QRM might not result in dealing with the root cause of low delivery performance. QRM provides tools to search for improvement opportunities, but, in the case of Larsen Premium Precision Parts, it would not immediately solve their biggest problem. Companies might consider to additionally use the distribution of lateness tool (New, 1977) to obtain more profound insight in what is causing their low performance in order to decide what improvement method is best to be used. At Larsen Premium Precision Parts, their problems were caused by a sequencing problem.

To solve this sequencing problem, QRM does provide a solution for the long term; POLCA. However, this is only possible if some adaptations are made. POLCA does not provide answers on how to deal with multiple experts or having no clear product families to form cells. However, cases are known where adaptations resulted in a success. Future research might focus on how to apply QRM and POLCA in different ETO companies.

Besides POLCA, another solution may be considered, being WLC. WLC is a method that uses a pre-shop pool to limit the load on the shop floor. Three decision levels are used: customer enquiry and job entry stage, order release, and dispatching rules. Especially the order release rule is important. However, WLC only stabilizes the shop floor; it will not provide competitive advantage by continually reducing lead time.

To answer the main question, the current status of knowledge on QRM is not sufficient to implement in a ETO company such as Larsen Premium Precision Parts. Although, QRM has some important positive aspects, like future oriented, there are some problems with implementing QRM and POLCA. Further research is needed on the possibilities of adapting QRM to the needs of Larsen Premium Precision Parts.

6.1 Research limitations

This research had some limitations. These will be described below.

First of all, time limitations. Based on this, some decisions were made that might not be in the interest of this research. For example, the tools provided by QRM, process mapping and MCT mapping, were combined.
Secondly, because of time limitations and the absence of other possible methods, a lot of orders were followed during this research, but only a few received orders were useful for this research. Most tagging sheets were not filled in completely and some were not received in time to be included. This may have influenced the results as well.

Thirdly, the orders were followed during the summer period, July till September. Here, less orders were received, people went on holiday, etc. This may have affected the outcome of this research.

And finally, some results, on which the eventual conclusion and recommendations are based, depended on subjective interpretation of the information that was received during, for example, interviews. This may have led to conclusions that are not in line with how another researcher would have done. This may have influenced the outcome of this research.
Reference list

### List of abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ETO</td>
<td>engineer to order</td>
</tr>
<tr>
<td>FTMS</td>
<td>focussed target market segment</td>
</tr>
<tr>
<td>HL/MRP</td>
<td>high level/ material requirements planning</td>
</tr>
<tr>
<td>JSP</td>
<td>Job shop scheduling problem</td>
</tr>
<tr>
<td>MCT</td>
<td>manufacturing critical-path time</td>
</tr>
<tr>
<td>MRPII</td>
<td>material requirement planning II</td>
</tr>
<tr>
<td>MTO</td>
<td>make to order</td>
</tr>
<tr>
<td>MTS</td>
<td>make to stock</td>
</tr>
<tr>
<td>OPP</td>
<td>order penetration point</td>
</tr>
<tr>
<td>POLCA</td>
<td>Paired-cell Overlapping Loops of Cards with Authorization</td>
</tr>
<tr>
<td>PPC</td>
<td>production planning and control</td>
</tr>
<tr>
<td>QRM</td>
<td>quick response manufacturing</td>
</tr>
<tr>
<td>RBC</td>
<td>repeat business customizer</td>
</tr>
<tr>
<td>STS</td>
<td>ship to stock</td>
</tr>
<tr>
<td>TOC</td>
<td>theory of constraints</td>
</tr>
<tr>
<td>VMC</td>
<td>versatile manufacturing customizers</td>
</tr>
<tr>
<td>WIP</td>
<td>work in process</td>
</tr>
<tr>
<td>WLC</td>
<td>work load control</td>
</tr>
</tbody>
</table>
## Appendix I – Classification scheme (Hicks et al., 2001)

<table>
<thead>
<tr>
<th></th>
<th>Type I</th>
<th>Type II</th>
<th>Type III(i)</th>
<th>Type III(ii)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Definition</strong></td>
<td>Vertically integrated</td>
<td>Design and assembly</td>
<td>Design and contract</td>
<td>Project management</td>
</tr>
<tr>
<td><strong>Core competencies</strong></td>
<td>Design, manufacturing, assembly, project management</td>
<td>Design, assembly, project management</td>
<td>Design, project management, logistics</td>
<td>Project management, engineering expertise, logistics</td>
</tr>
<tr>
<td><strong>Competitive advantage</strong></td>
<td>Product and process knowledge; integration of internal processes</td>
<td>Systems integration; co-ordination of internal and external processes</td>
<td>Systems integration; co-ordination of internal and external processes</td>
<td>Reputation; engineering knowledge</td>
</tr>
<tr>
<td><strong>Vertical integration</strong></td>
<td>High</td>
<td>Medium</td>
<td>Low</td>
<td>Very low</td>
</tr>
<tr>
<td><strong>Supplier relationships</strong></td>
<td>Adversarial</td>
<td>Partnership</td>
<td>Partnership</td>
<td>Contractual</td>
</tr>
<tr>
<td><strong>Environment</strong></td>
<td>Stable</td>
<td>Uncertain</td>
<td>Dynamic</td>
<td>Dynamic</td>
</tr>
<tr>
<td><strong>Type of risks</strong></td>
<td>Capacity utilisation, return on capital, under-recovery of overheads</td>
<td>Lack of manufacturing may undermine design capability. Sharing core knowledge with suppliers makes them potential competitors</td>
<td>Overall contractual risk, capability and performance of suppliers</td>
<td>Loss of reputation</td>
</tr>
</tbody>
</table>
Appendix II – classification scheme (Amaro et al., 1999)

<table>
<thead>
<tr>
<th>The classification categories</th>
<th>ETO</th>
<th>ETO</th>
<th>ETO</th>
<th>MTO</th>
<th>MTO</th>
<th>MTO</th>
<th>MTO</th>
<th>ATO</th>
<th>ATO</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>1</td>
</tr>
</tbody>
</table>

- **Degree of customisation**
  - Pure ✓ ✓ ✓ ✓ ✓
  - Tailored ✓ ✓ ✓ ✓ ✓
  - Standardised ✓ ✓ ✓ ✓ ✓
  - None ✓ ✓ ✓ ✓ ✓

- **Company responsibility for:**
  - Design ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓
  - Specification ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓
  - Purchasing ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓

- **Activities after receipt of order:**
  - Delivery ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓
  - Assembly ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓
  - Processing ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓
  - Purchasing ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓
  - Routing ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓
  - Specification ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓
  - Design ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓

Appendix III – QRM principles

- **QRM principle 1:** Find whole new ways of completing a job, with the focus on lead time minimization
- **QRM principle 2:** Plan to operate at 80% or even 70% on critical resources
- **QRM principle 3:** Measure the reduction of lead times and make this the main performance measure
- **QRM principle 4:** Stick to measuring and rewarding reduction of lead times
- **QRM principle 5:** Use MRP to plan and coordinate materials. Restructure the manufacturing organization into simpler product-oriented cells. Complement this with new material control method that combines the best of push and pull strategies.
- **QRM principle 6:** Motivate suppliers to implement QRM, resulting in small lots at lower costs, better quality and short lead times.
- **QRM principle 7:** Educate customers about your QRM program, and negotiate a schedule of moving to smaller lot sizes at reasonable prices.
- **QRM principle 8:** Cut through functional boundaries by forming a quick response office cell, which is a “closed loop”, collocated, multi-functional, cross trained team responsible for a family of products. Empower it to make necessary decisions.
- **QRM principle 9:** The reason for embarking on the QRM journey is that it leads to a truly lean and mean company with a more secure future.
- **QRM principle 10:** The biggest obstacle to QRM is not technology, but ‘mind set’. Combat this through training. Next, engage in low-cost or no-cost reductions. Leave big-ticket technological solutions for a later stage.
Appendix IV – 7 steps for successfully implement cells

Step 1: Begin with a market opportunity or threat
Step 2: Find a product family that will make a splash
Step 3: Stepwise quantitative approach to find candidate families
Step 4: Choose a self contained family
Step 5: Create the physical cell
Step 6: Education on manufacturing system dynamics
Step 7: Call for volunteers

Appendix V – interview results

The results are given per interview to make clear if and what the differences are per person and how they experience the problems. However, to keep their identity and answers confidential (as far as possible) the interviews are randomly sequenced.

Respondent 1
Causes for not meeting due dates:
- Preparation is not done properly. It would improve quality and flow if operators can start immediately after receiving an order and not have to fix the mistakes made at the office.
- Wearing out machine parts
- Absence of the right materials
- Machine breakdown

Respondent 2
Causes for not meeting due dates:
- operators that do not cooperate with the rest in the company. This is based on operators that do not check products in and out of the system which causes inaccurate information at the office.
- operators that do not want more responsibility or want to be educated to increase their skills. By absence of an operator there is no one to takeover when necessary and some complex products take more time than necessary.
- Finally, operators produce more than needed using more time than made available. This is partially caused by the long set up times which make operators decide to manufacture more than needed.

Respondent 3
Causes for not meeting due dates:
- Order preparation is not done properly: incomplete or missing equipment and incomplete or wrong drawings. Takes time to correct which could have been spend on processing orders.
- Too many layers for such small company. It takes too much time if you need to get something done.
- Absence of knowledge in the office about manufacturing. Planning and preparation are not done properly and they are not trying to gain this knowledge.
- Increase of smaller order quantities makes it sometimes impossible to operate two or more machines
- Lack of knowledge of operators to programme within planned time
- Lack of trust between operators to takeover by absence of operators
- Machine breakdown

Respondent 4
Causes for not meeting due dates:

- Increase of new orders due to the increase of new clients
- Lack of skills of the operators. Some operators take more time to set up a machine or to programme the order than needed.
- Operators are not eager to learn and improve their skills or to share their knowledge. This makes it difficult to train and cross train operators. When an operator is absent his work can sometimes not be taken over by another operator.
- Operators producing more than needed. Due to the increase of different orders there is no time left to manufacture more than needed. This leads to long setup times of small order quantities.
- Operators do not check in and out their products. This is needed to compare the actual processing time with the planned time after which it could be adjusted. Operators do not take part in this which makes it difficult to do it better the next time.
- Machine breakdown.
- Quality failures. Orders are inspected on quality after the products are finished. Often products are rejected of which some need to be adjusted causing delay for that order but also for other orders.
- Outsourced products are nor delivered back on time. Some supplier of for example surface treatments do not deliver on time which causes disruptions.
- In the office it sometimes happens that clients call to move the delivery date forward. This interrupts the process.

Respondent 5
Causes for not meeting due dates:

- Preparation is inaccurate. Equipment is not present.
- Inaccurate planning. Orders with starting dates in the past and orders that are alike but are not bundled together. This last means that the machines needs to be set up more often while it could be done once while processing multiple orders. Not enough time planned in to manufacture the products and no information is given when products need to be delivered to the clients.
- No measurement are done at machine. If this is done properly it would make it more clear what the problems are and people can be held responsible for their actions. It would also lead to better predictions of processing times and due date calculations.
Respondent 6
Causes for not meeting due dates:
- The detail planner is not up to the task given to him and also not interested in that function
- Programming is done at the machines. Difference in skills between operators causes for longer programming time than pre-calculated. This should be done by one or two programmers before being released to the shop floor.
- Lack of cross-trained operators. Operators cannot take over when an operator is absent.
- Lack of communication and cooperation between order preparation and manufacturing.
- Mistakes in order preparation. Equipment not present, drawings incomplete and no after control to see if materials have arrived
- Processing time often exceed prospects.
- Operators who do not check products not in and out of the system. This makes it difficult to track differences in planned and actual processing times.
- Automated equipment not working, machine breakdown, wearing out of machine parts and clamping tools not finished
- Plan de champagne plans orders with starting dates in the past. This because it calculates back from the wanted delivery date.

Respondent 7
Causes for not meeting due dates:
- Order preparation is not done thoroughly. Missing information, unclear drawings,
- Planning not done thoroughly. Order are not bundled and they do not try to see order patterns. Some orders can almost be predicted. Due to long set up times it would save time if they would anticipate on repeat orders.
- Not holding stock at all. Some clients want their product faster than currently can be manufactured. If products are more often ordered throughout the year why not keep stock.
- Checking products in and out of the system
- Lack of knowledge in the office about lathes and milling machines.
- Lower order qualities makes it difficult to operate more than one machine.
- Lack of knowledge operators. Most are not able to take over other machines by absence of operator
- Quality defects are detected too late in the process. If detected earlier it takes less time to fix the problem.
- Machine breakdown.