Eindhoven University of Technology

MASTER

Improvement of rescheduling policies in a dynamic multi-echelon MTO/ATO environment at VDL ETG

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Improvement of rescheduling policies in a dynamic multi-echelon MTO/ATO environment at VDL ETG

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ABSTRACT

VDL ETG operates in an environment that faces many sources of uncertainty. This uncertainty exists both on the supply side (leadtime uncertainty and yield) and on the demand side (rescheduling). This complicates the goods flow control of these supply chains. The first part of this thesis provides an extensive problem analysis and a roadmap to a more controllable and efficient supply chain. The second part focuses on the rescheduling problem; discusses several methods to efficiently deal with rescheduling; and elaborates on static and dynamic methods. For both, heuristics are developed to find optimal parameter values and corresponding cost for any product. Furthermore, it describes a simulation (developed in this project) to compare the performance of the two methods for any predefined product.

MANAGEMENT SUMMARY

The supply chain environment of VDL ETG is characterized by various factors that complicate the efficient management of this chain. The nature of the product (module), combined with both supply and demand side uncertainties create this complexity (Figure 1).

Based upon interviews, we developed a cause-and-effect diagram and several projects that could improve VDL ETG's way of working. Using dependencies between these projects and the priorities of key stakeholders at VDL ETG, these projects have been planned within a roadmap to a more controllable and efficient supply chain.

Figure 1: Sources of supply chain complexity at VDL ETG (page 17 provides this figure in normal size)

We focus on one of these projects; the rescheduling project, aiming to improve the methods VDL ETG uses to deal with changes in delivery dates by customers. This problem is not typical for VDL ETG; the lengthening of supply chains due to globalization and the rise in product complexity due to innovation increases the urgency for companies to become more responsive to their environment. Rescheduling is one of the ways to deal with demand uncertainty.

It often occurs that customers reschedule an order; about a third of all customer orders is rescheduled. Although the magnitude of the shift often is a few days, it can be as large as several months (Figure 2). As module prices vary between several thousand up to a million euro, a shift of several weeks results in high inventory cost. On the other hand, advancements result in tardiness cost.

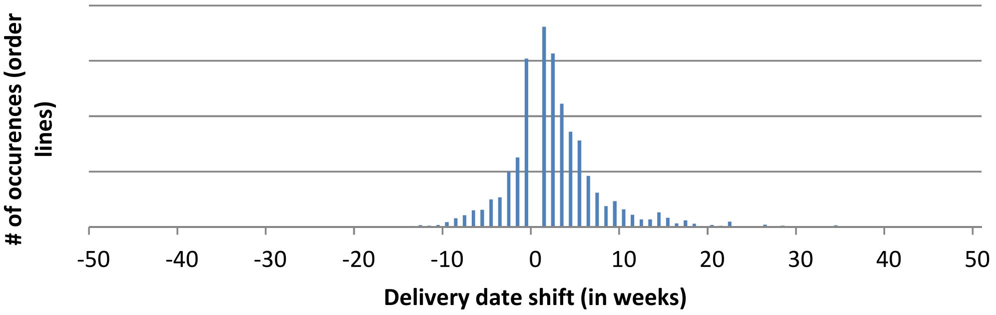


Figure 2: Magnitude of delivery day shifts in weeks (new delivery date minus old delivery date: positive numbers are delays, negative numbers are advancements)

To deal with the rescheduling, we distinguish two approaches. The first responds passively to rescheduling by making schedules that are robust against rescheduling messages (static scheduling). The second uses an active approach and decides for each arriving rescheduling message the best way to deal with it (dynamic rescheduling).

The static scheduling method uses historical information on leadtime and demand uncertainty and uses these as probability distribution to determine an optimal safety time buffer (T) to minimize the sum of holding and tardiness cost (Figure 3).

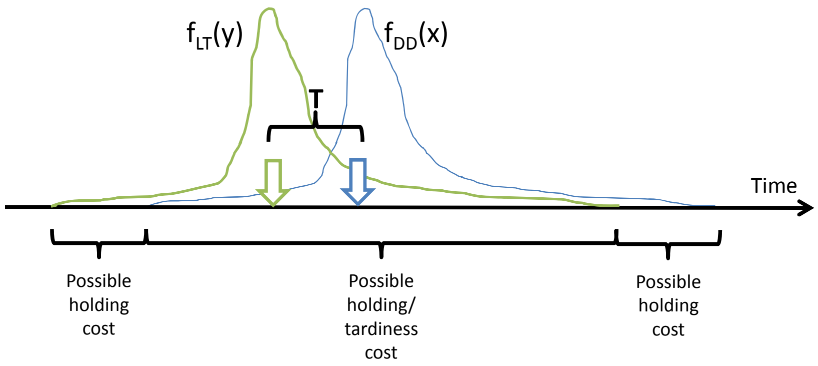


Figure 3: Safety time buffer T depending on the probability density functions of leadtime and delivery date uncertainty

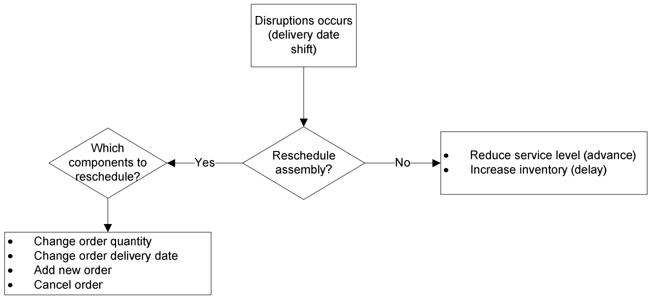


Figure 4: Dynamic rescheduling framework

In case of dynamic rescheduling, a decision is made every time a rescheduling message arrives. Figure 4 shows the decision framework used in evaluating this decision. The framework uses data on holding cost, rescheduling cost, and rescheduling occurrence. This framework resulted in an implementable procedure to support planners.

A comparison for a specific module shows the following results (Figure 5) for the two different scheduling methods and 22 identical runs. The stochasticity on rescheduling occurrence has a high impact on the cost, which makes a good comparison harder.

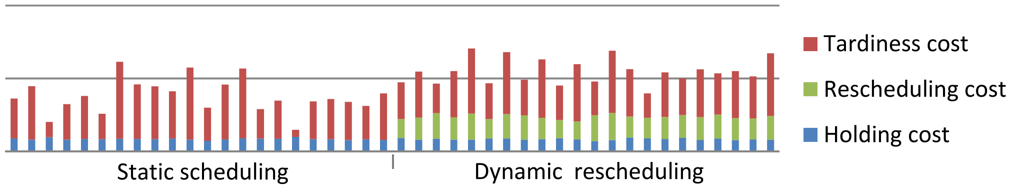


Figure 5: Comparison of static scheduling and dynamic rescheduling

Figure 5 shows that static scheduling is clearly cheaper than dynamic rescheduling. Sensitivity analysis (using a simple product structure) shows the impact of differences on the environment to the cost of the static and dynamic method. Lower rescheduling occurrence; higher product complexity; lower product prices; lower tardiness cost; higher rescheduling cost; lower holding cost rate; lower leadtime uncertainty; and smaller rescheduling shift magnitude are in favor of a static scheduling method. The last effect (magnitude of rescheduling shift magnitude) is shown in Figure 6 and Figure 7 below. Section 7.6 provides the complete sensitivity analysis.

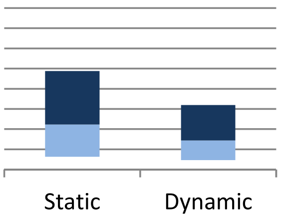


Figure 6: Small rescheduling magnitude. The figure shows the 5% and 95% quantiles of the cost of both methods.

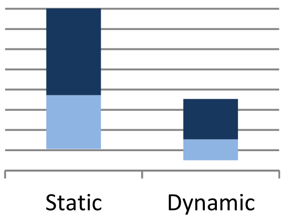


Figure 7: Big rescheduling magnitude. The figure shows the 5% and 95% quantiles of the cost of both methods.

PREFACE

This is my thesis project. The travel report of a five-month adventure. The start of an improvement project at VDL ETG. The completion of my study period. An extension to rescheduling knowledge. An attempt to reduce cost. A tool to help those who aim to manage most complex supply chains in a globalizing and innovating world.

Starting at VDL ETG shortly after a four-months experience at asset management; the contrast could almost not have been bigger: from a position at a suited up investment team in a Zuidas' tower to a role in a pounding and grinding manufacturing company in the Eindhoven area. Suddenly a "linker" was not an inflation-linked government bond anymore, but the left version of a wafer handling module. I enjoyed both projects; I liked to work at VDL ETG especially because the added value of both my solution and my research are more visible.

I am very grateful to Zümbül Atan, my supervisor at the TU/e. It was no surprise that she won the TU/e education award; she is a committed and accessible teacher who explains complex matters very clear. Furthermore, I thank Ton de Kok for his feedback and enthusiasm, as well as for the environment he shaped to perform the series of theses projects at VDL ETG of which this project is the first.

I also want to express my gratitude to John and Jeroen, supervising me at VDL ETG. John's strong focus on practice helped me to stay focused on delivering useable results and to make sure my abstraction remained connected to the workplace. The insights and feedback Jeroen provided, contributed to the integrality of the roadmap and to a broader application of my findings. Next to these, I am thankful to my other colleagues at VDL ETG, for introducing me to the complexity that they face in managing their supply chains; for providing me with needed information; and for the pleasant days I have worked there. I had the chance to work with a colleague student at VDL ETG who will start his thesis in February. Jaap, it has been very valuable to be able to reflect my ideas with you and I liked our collaboration on the development of the roadmap. I would not have been able to develop my ideas this fast without you.

In the completion of this project, I could count on Bas for a textual review. After several revisions, a fresh, critical view is very welcome. Thank you for your feedback.

During my study period in Eindhoven, and to a smaller extent in Leiden, Tilburg and Amsterdam, I had the opportunity to work at a diverse set of challenging problems with incredible people; at the University and Department Council, Industria, SSL Leiden, Honors Program, Hajraa, UniPartners, in courses and during internships. This project does not only mark the end of this period, but also embodies a lot of the skills and knowledge I have obtained during these years.

Finally, I want to thank my family, Marja, Michiel, Anne & Roos, for the support they provided during my study, not only at the moments of sharing enthusiasm and happiness, but especially at the moments where those were far away.

Tom Kamps
Eindhoven, January 2015

CONTENTS

1 INTRODUCTION

Manufacturing companies in high-tech environments face a complex task in the management of their supply chain. Short product life cycles; yield and quality issues; complex product structures; unreliable suppliers; and strong fluctuating customer demand are only a few of the dimensions that make these chains hard to manage.

The growth in both the volume and the complexity of high-tech products combined with the globalization and the subsequent lengthening of product lead times increases the urgency of improving the efficiency and control of these supply chains. This study investigates how a manufacturing company, VDL ETG, can improve their response to fluctuations in the customer demand.

VDL ETG is active in the manufacturing and assembly of complex technological products and modules for businesses. They mainly produce modules for the lithography industry, but their customer base covers many industries. The strong economic cycle within the lithography market has a big impact on the demand of the modules VDL ETG produces. As their products are expensive, these fluctuations in demand result in high cost to the supply chain.

This project focuses on one of the causes of high inventory cost, being the uncertainty in customer delivery dates and the method that VDL ETG deals with it. The inventory investment was perceived as rather high and the instability of schedules, resulting from rescheduling, leads to a high planning workload. Improving the rescheduling policy could reduce costs by reducing buffers within the supply chain or reducing the costs associated with schedule instability.

We investigate the improvement of the rescheduling policy using mathematical modeling and simulation of the VDL ETG case. Based upon these results, knowledge on this (re)scheduling problem is extended and an implementation plan to VDL ETG is provided, such that it can reduce the cost they face as a result of customer delivery date uncertainty.

The following chapters are structured in the following way: chapter 2 and 3 describe the problem context, analysis and problem selection. The research questions that will be answered are also stated in this chapter. Chapter 4 provides a literature review and chapter 5 describes the methods that we will use to answer the research questions. Data analysis and results are provided in chapters 6 and 7. Finally, chapter 8 concludes with a discussion and recommendations.

2 PROBLEM CONTEXT

In order to get a proper view on the problem, one needs to know the context. This chapter describes the company, business environment, the supply chain of VDL ETG and the different roles associated with the supply chain. It is almost entirely based upon the first part of “A roadmap to the improvement of VDL ETG’s supply chain efficiency & control” by Kamps and Arts (2014).

2.1 COMPANY AND BUSINESS ENVIRONMENT

The VDL Enabling Technologies Group (ETG) is active in the field of technological complex make-to-order manufacturing of mechatronic (sub)systems (modules). Among their competitive edges are the manufacturing of ‘critical parts’, assembly and cleaning. This is reflected in their mission statement:

“To reach global leadership as tier-one contract manufacturing partner, by outperforming in delivering mechatronic solutions”.

VDL ETG serves a small group of customers and manufactures about fifty different modules, which are organized in projects (new modules; production is not yet standardized) and programs (existing modules; production is standardized). Every module consists of several components of which about the majority of the module sales value is purchased, but a significant part is manufactured.

VDL Enabling Technologies Group (VDL ETG) is part of the large international, family owned business VDL Group. The VDL Group consists of more than 83 companies, with over 10,000 employees working in 19 different countries around the world. It is a collection of flexible, independently operating companies, each with their own specialism. The VDL Group focuses on the development, production and sales of semi-finished products, busses and complex end-products, and on assembly of cars (VDL Group, 2014). VDL ETG started in 1900 as Philips Machinefabrieken and during the 20th century it became a worldwide operating company, supplying integrated systems and solutions to Philips as well as to other companies. In 2000, the name changed into Philips Enabling Technologies Group and in 2006 it was taken over by the VDL Group (VDL ETG, 2014).

VDL ETG has different divisions, with general management being located at the headquarters in Eindhoven Acht. The company has a special division named VDL ETG Research, focusing on engineering and prototyping. The division VDL ETG Technology & Development takes care of the product and technology development. In addition to these, there is a special division called VDL ETG Projects, which focuses on producing one-off, customer specific modules and systems. Finally, the company offers its main serial production and assembling services characterized by high complexity and low volumes, being performed in four different locations: VDL ETG Almelo, VDL ETG Eindhoven, VDL ETG Singapore and VDL ETG Suzhou. Unless stated otherwise, when using the term VDL ETG, we refer to VDL ETG Eindhoven (Acht). The other three production sites, each with their own characteristics and planning and control structures, are outside the scope of this project. Because the supply of modules for the lithography industry represents a major part of the turnover of VDL ETG, the company is highly subject to the economic cycle in their demand pattern.

2.2 SUPPLY CHAIN MATERIAL FLOW

This section discusses first the regular production chain, followed by the reverse logistics chain and a description of the use (and cost) of inventory as buffer in the supply chain.

Components are either produced internally or sourced. Production of components is done by the 'Parts' unit which has an own planning unit. This unit is organized as a job-shop. Employees working at Parts are specialists; trained for one or a few machines. Planning of Parts is done based upon an MRP system in which all components for a module are planned to be finished at the same moment. 'Operational procurement' handles the procurement of components. When components arrive, assembly starts at the 'Systems' unit, followed by shipment. Planning of Systems is done Just-In-Time (JIT), but with a safety time of one week, and unlimited capacity. This is done since the assembly capacity can be scaled up due to the nature of the work. However, transitions of capacity at Systems cannot be done quickly; therefore, capacity constraints are present over short planning horizons. The assembly and shipment activities are coordinated by integral planning. This planning unit also releases orders towards 'Planning Parts' and operational procurement. Finally, order management deals with customer communication.

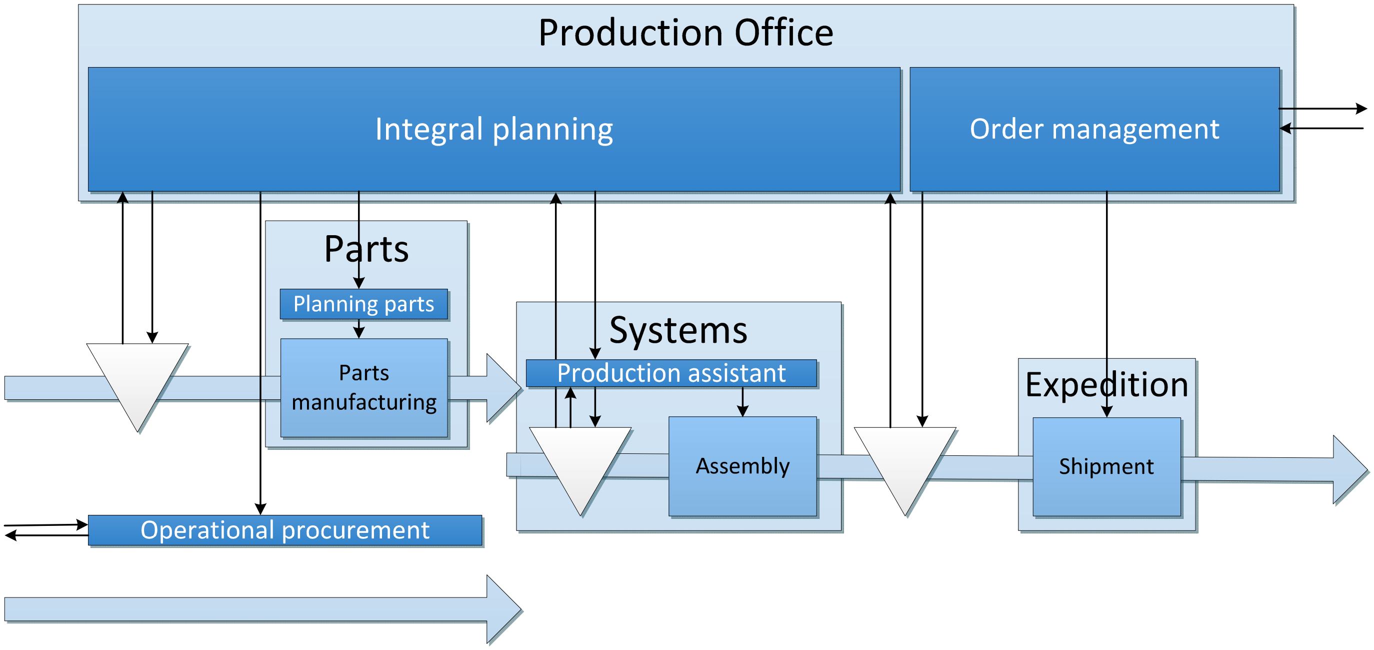


Figure 8: VDL ETG internal supply chain and planning units

The customer order decoupling point (CODP) lies at different places for different chains. Some modules have an assembly-to-order (ATO) structure, while others use a make-to-order (MTO) structure. In the first case, the CODP lies before assembly; in the case of MTO, the CODP is before VDL ETG. As components are often unique for a module, it is uncommon that components are used in multiple chains.

For ATO chains, (collaborative) forecasting is used. Based upon these forecasts, orders are given to operational procurement and parts manufacturing. Components demand for MTO chains is calculated by BaaN using a JIT-alike system (safety time is present). EOQ is used to determine optimal series for parts in ATO chains; JIT is not entirely implemented. Integral planners approve orders towards operational procurement and Parts, these decisions are based upon the component forecast of BaaN. Shipment activities are different for different chains (programs). Due to the low volume of outbound logistics, this does not seem to be a complex task.

'Repair Spare parts & Service' (RS&S) is a unit that deals with the repair of parts and modules and the production of spare parts (Figure 2). Its demand for components is often overlapping with that of the regular production. In those cases, there is contact between RS&S and integral planning and when possible, integral planning releases inventory towards RS&S. When components cannot be obtained from stock, RS&S fulfils the same role as integral planning does for regular production, initiating the procurement and parts manufacturing. RS&S operations are often not forecasted; in some cases, customers agree upon the creation of a safety stock for a component that has a long lead time and a rather high repair demand. This is only done after agreement with the customer, as the costs of the safety stock are charged to the customer (Kwanten, 2014).

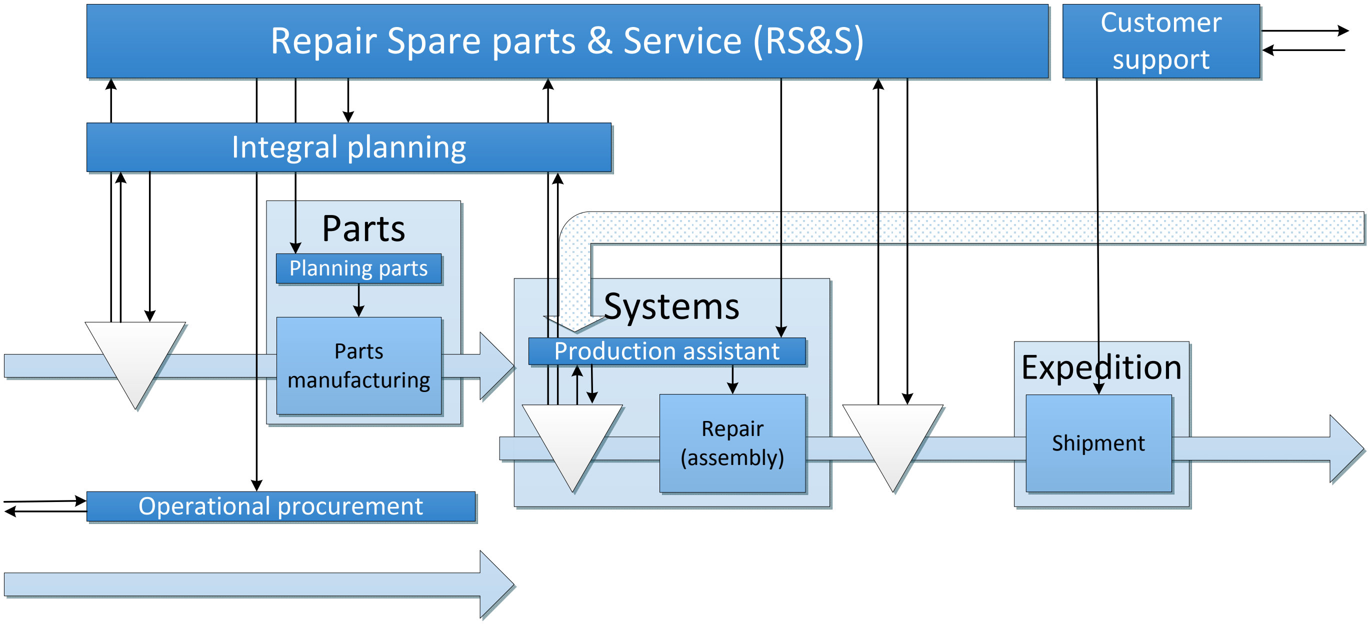


Figure 9: VDL ETG repair supply chain and planning units

The RS&S chain is of significant size; it represents a small part of the sales volume of VDL ETG. Due to higher margins on these products, the contribution to the profit of VDL ETG is higher (VDL ETG, 2014). The magnitude of the reverse logistics volume varies much for the different chains.

The production planning is performed by the Production Office ('Productiebureau'), which consists of the functions order management and integral planning. Integral planning is responsible for the production plan ('Productieplan'); 'Order management' is responsible for the communication with customers. The production plan states the delivery amounts and dates of a module; schedules of the production of Systems; and initiates the detailed planning of parts and the procurement. The production plan is based upon a demand plan ('Vraagplan') of the customer. Procurement and the communication with suppliers are performed by the unit operational procurement ('Operationele inkoop'); the planning of the parts is done by a separate planning unit (Planning Parts).

It is not uncommon that clients alter a delivery moment (i.e. change the demand plan). Furthermore suppliers sometimes cannot deliver at the agreed delivery date (possibly due to a rejection of a product). Both could lead to a rescheduling of the production. This is currently done using the ‘Herplanningstool’ (rescheduling tool), a custom-made connection to the BaaN database. Rescheduling is done in the same way as the regular scheduling (JIT), but with new information. Rescheduling (‘herplanning’) a module can only be done effectively when the assembly of that module has not started yet. When assembly has started, delaying it has a high price, as planning does not have any tools to influence the process at that point; bringing forward a delivery date is almost impossible or only possible for a small change in the date. Changes in the demand plan can lead to rescheduling, but this is not always the case. In those cases, a request for a demand shift is either rejected or the planning is not altered (and products will be held in stock).

2.2.1 INVENTORY BUFFERING AND COST

Buffering in the supply chain of VDL ETG is done mainly by time and inventory. Since modules are rather expensive, holding inventory of those is a costly way of buffering, though it can be efficient for cheaper components. Buffering in time is expensive as well (due to opportunity cost of capital of work-in-progress). Buffering in capacity is not effective at Parts due to high capacity (machine) costs and long routings. At Systems, buffering in capacity is used (planning is done assuming infinite capacity), as capacity is flexible (both cross-flexibility of employees and access to temporary workers).

VDL ETG buffers by inventory using safety time or safety stock. Sometimes safety stock is explicitly required by one of their customers (consignment stock of components) and for some components safety time and safety stock is used to buffer against lead time variance of suppliers. In the last case, MT approval is required. Next to this, inventory of VDL ETG consists of components waiting to be assembled within the cleanroom and inventory due to order quantities. Inventory of VDL ETG is exposed to risk of loss, as module designs could change over time and some components then become redundant. Finally, management can choose to start the production before the order has arrived; a so-called director order (directie order), which is done to reduce throughput time. This also contributes to an inventory of components or finished modules.

The inventory cost comes from mainly two drivers; opportunity cost of capital and risk of loss due to mainly module redesigns. Opportunity cost of capital is rather high due to the expensive modules and components. There is much storage space; there are no practical (relevant) physical restrictions on the inventory level.

2.3 SUPPLY CHAIN PROCESSES AND ROLES

The supply chain described in the previous section has many actors. Here, we describe how the information and actions related to an order propagate through different parties in the supply chain. In addition, the tasks of different roles are provided.

2.3.1 SWIM LANE DIAGRAM

In order to indicate the time dependencies between these different processes performed by different actors, we have constructed a so called swim lane diagram. This diagram is shown in Figure 10. Note that the diagram shows the regular decisions which are taken, including a special part which represents the optional occurrence of rescheduling activities. In this diagram, we focus on the decision functions which are important for the control of information and material in the supply chain, i.e. we focus on planning, control and release decisions. Execution processes, e.g. component manufacturing or assembling activities, are therefore excluded from this diagram. Control starts by the order acceptance decision function performed by an order manager (contact with customer), and ends at the moment the order manager releases the order for shipping, i.e. the process flow ends again at the point of contact with the customer.

All the processes in Figure 10 consist of one or more detailed decision functions, each having its own input, control and output variable(s), along with associated control mechanisms. A detailed overview of each of the decision functions is made in the confidential company version of this report, using the IDEF0 notation.

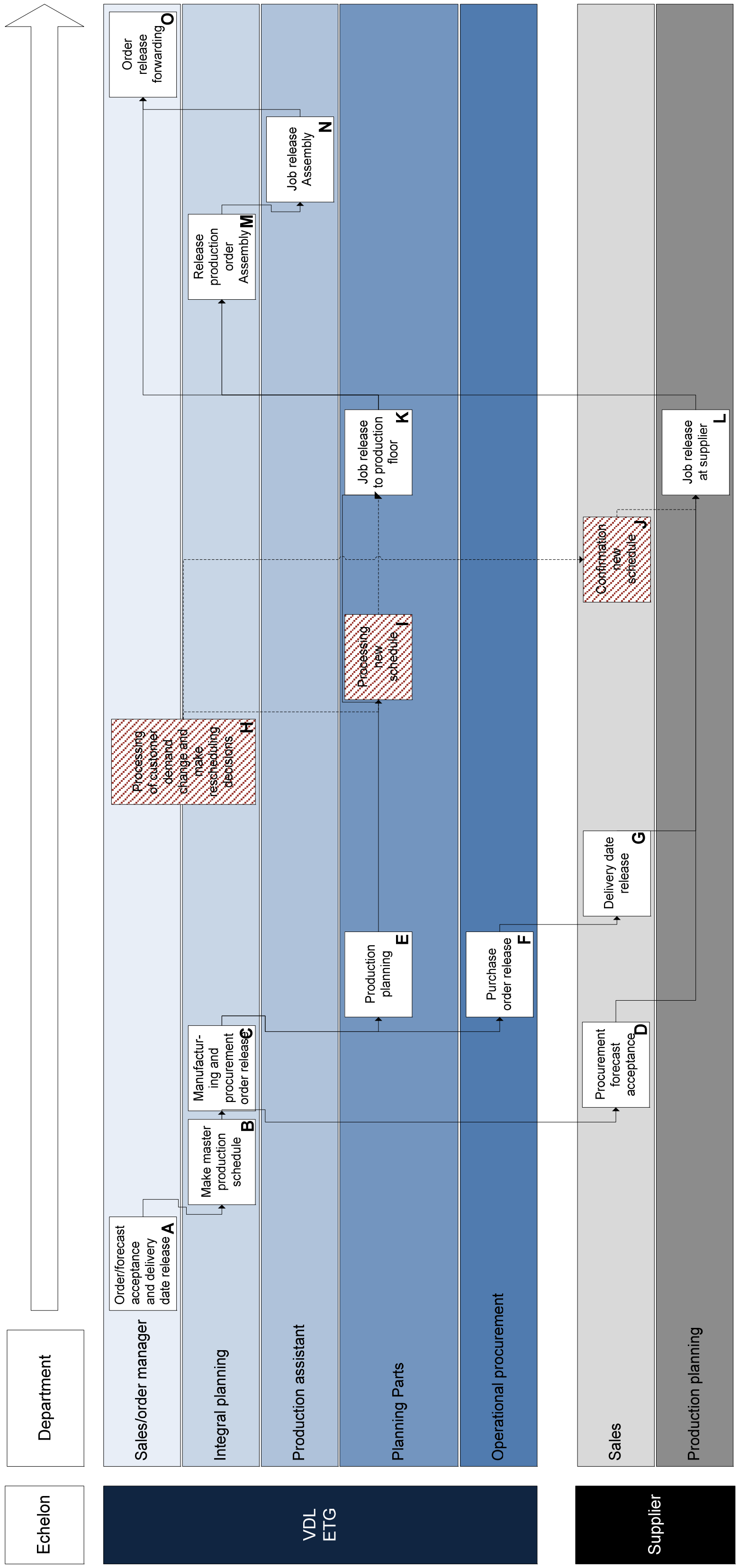


Figure 10: Swim lane diagram

3 FRAMEWORK AND PROBLEM STATEMENT

One of the main goals of this thesis is to solve a business problem. To ensure a solution provided actually solves a problem of the organization, a problem analysis is required. Since several other (thesis) projects will take place at VDL ETG on this topic, we have designed a roadmap to cover the several projects and ensure that the projects together improve the ultimate goal of the projects; improve the supply chain efficiency and control of VDL ETG. In the public version of this thesis, only the problem background and the process is discussed. A detailed description is provided in "A roadmap to the improvement of VDL ETG's supply chain efficiency & control" by Kamps and Arts (2014).

3.1 PROBLEM BACKGROUND

The environment of VDL ETG results in a supply chain that is hard to manage. We have identified nine sources that increase the supply chain complexity at VDL ETG. These nine are:

- Complex BOM structures (many, unique components that are used in one module);
- Low move rates and short life cycles;
- Demand date uncertainty (customers can advance or delay delivery dates);
- Capacity restrictions at Parts;
- Relevant yield issues (products can be rejected during the production process);
- Variance in supplier lead times (suppliers are unreliable on delivery dates);
- Throughput time is longer than customer lead time;
- High value of components; and
- High, early customized products (chains are MTO or ATO organized).

These nine are graphically shown in Figure 11. Although these individual features do not necessarily need to a complex supply chain, the combination results in the complexity.

Figure 11: Supply chain complexity at VDL ETG

Within VDL ETG, inventory costs and work in progress seemed high. This is related to high value of components and possibly to the uncertainties in yield; lead time uncertainty; and demand date uncertainty. Furthermore, the burden of control is high: this is probably related to the early customization, complex BOM and short product life cycles. Finally, the slow adaption speed to higher production rates is low, which is probably related to short life cycles and capacity restrictions.

These four issues are extensively discussed with several actors within the supply chain at VDL ETG.

3.2 PROCESS OF THE ROADMAP DEVELOPMENT

First, the most important problems of VDL ETG were listed using interviews of key stakeholders. These are “Low responsiveness”, “Large investment in work in progress”, “High inventory cost”, and “High planning workload”. In a group discussion, the root-causes were found for these problems. Based upon a cause-and-effect diagram and a quantitative problem validation, projects were developed to solve these problems. These projects were prioritized and positioned in time. This resulted in a roadmap to a more efficient and controllable supply chain.

3.3 PROJECT SELECTION AND RESEARCH QUESTION

As the rescheduling problem has no preceding; the impact to VDL ETG is rather high compared to the effort; and as VDL ETG indicated they would like to start with this, this problem as chosen as first project. Subsequently the rescheduling problem will be addressed in this thesis.

The goal of this project is to extend scientific knowledge on rescheduling methods and to improve the rescheduling method of VDL ETG. The achieving of this goal will be done by answering a series of questions, which are formulated in the subsections below.

3.3.1 RESEARCH QUESTION

The research question that this thesis project will answer is:

What rescheduling policy at Integral Planning reduces the rescheduling and inventory costs of VDL ETG?

3.3.2 SUBQUESTIONS

The first question answered in this projected is:

1. *What are key issues in the supply chain of VDL ETG and what are the causes?*

To determine the optimal rescheduling policy, we will answer the following subquestions in this thesis project:

2. *What are the costs of rescheduling, i.e. the costs of modifying the planning of Systems?*
3. *What are the costs of the choice not to reschedule?*
4. *Which factors have to be included in a choice which components to reschedule?*
5. *Which rescheduling methods are applicable for this rescheduling decision?*
6. *Which of these methods results in the lowest total costs?*
7. *How should VDL ETG implement this rescheduling method?*

4 LITERATURE REVIEW

To answer the research questions stated earlier, literature on the relevant topics is studied. This chapter first discusses the structure of supply chains and the customer order decoupling point and elaborates about rescheduling environments and methods.

4.1 SUPPLY CHAIN STRUCTURE

Most products and services that are consumed today are not made by a single company. This is often performed by big and complex supply chains, consisting of many organizations. A supply chain is defined, in line with Mentzer et al. (2001), as *"a set of three or more entities (organizations or individuals) directly involved in the upstream and downstream flows of products, services, finances, and/or information from a source to a customer"*. The goals of supply chains are "minimizing costs", "maximizing customer value and satisfaction", and/or "maximizing competitive advantages" (Mentzer, et al., 2001).

4.1.1 GOODS AND INFORMATION FLOWS

A supply chain primarily consists of a flow of goods downstream and a flow of information (mainly) upstream. Huang, Lau and Mak (2003) classify four different categories of supply chain structures: serial, divergent, convergent and network. A comparable distinction is made by Ernst and Kamrad (2000); but they do only differentiate three steps: manufacturing, assembly and packaging. Their framework is provided in Figure 12 below.

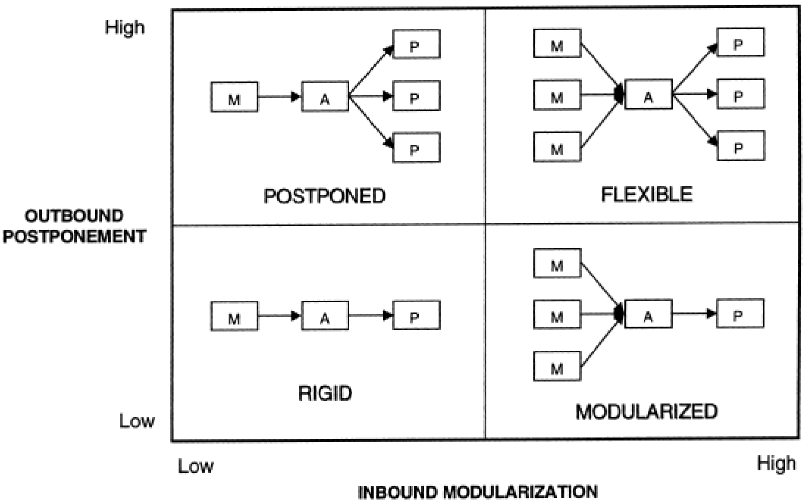


Figure 12: Framework for supply chain structures, obtained from Ernst and Kamrad (2000, p. 500).

Especially in the high-tech environment, many products consist of various components and provide either a few or one final product. Therefore, these supply chains are either classified as flexible or modularized. To coordinate the flow of goods, much information is needed at different levels and entities. One of the most important characteristics within a supply chain, that determines the structure of information flows, is the customer order decoupling point (CODP). All operations after the CODP (stream downward) are initiated once demand has arrived, and therefore pull-driven. The operations before the CODP (stream upward) are based upon forecasts and therefore push-driven.

Figure 13 shows the position of the CODP for different supply chain structures.

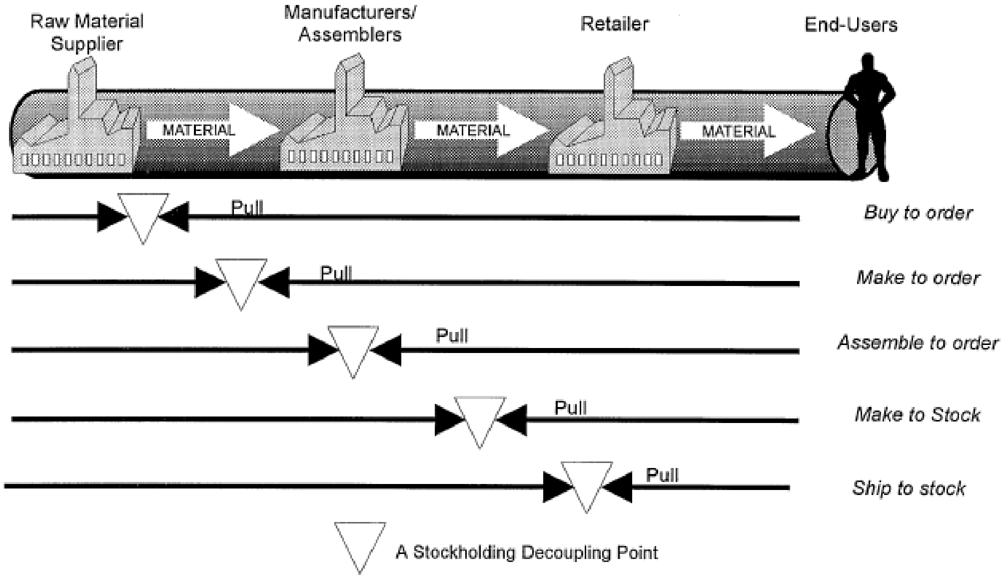


Figure 13: Different supply chain structures and the position of the decoupling point, based upon Naylor, Naim and Berry (1999)

Supply chains with a make-to-stock or ship-to-stock structure are driven by forecasts, which give stability and enable higher efficiency. On the contrary, supply chains with buy-to-order or make-to-order are driven by customer demand, and therefore need to be responsive (Fisher, 1997). Within companies, there exist several methods of material coordination, both pull (Just-In-Time, JIT) and push oriented (MRP). In JIT, demand progresses sequentially through a company or even a supply chain when demand arrives; the MRP II is based on a master production schedule, which is based upon planned lead times; orders are pushed through the system based upon these planned lead times, regardless of the actual demand in the next operation (Nahmias, 2009).

4.2 RESCHEDULING METHODS

Manufacturing companies encounter various sources of uncertainty, such as yield issues or supplier reliability. In some cases, companies can reduce the occurrence of a disruption associated with these sources of uncertainty (reduce the probability). Most are though not within the locus of control of the company, and cannot efficiently be brought within. In those cases, companies can reduce their exposure to unexpected events. This reduction of exposure can be done in the production schedule.

Uncertainty causes schedules to become inefficient as new information arrives. Rescheduling is a means of dealing with the uncertainty by using new information as it arrives. This section gives a definition on rescheduling and a framework of rescheduling environments, strategies and methods (4.2.1); provides measures of rescheduling performance (4.2.2); and compares several rescheduling methods (4.2.3).

4.2.1 DEFINITION AND FRAMEWORK

A common definition of rescheduling is *"the process of updating an existing production schedule in response to disruptions or other changes"* (Vieira, Herrmann, & Lin, 2003, p. 41). A production schedule is a planning that allocates resources to jobs in line with predefined goals. These goals could be defined in terms of tardiness; the number of orders delivered on time; and/or costs. Rescheduling is only needed when disruptions occur. We define a disruption as a random event that lead to a change in the expected processing or lead time. A basic view on rescheduling is provided by Grubbström and Tang (2000), displayed in Figure 14 below. When a disruption occurs, a choice whether or not to reschedule has to be made. In the case of rescheduling this leads to system nervousness (or instability). When schedules are remained intact, service level can decrease or inventory can increase. Both decisions could lead to higher cost, and subsequently a decrease in profit (which is not explicitly stated in Figure 14).

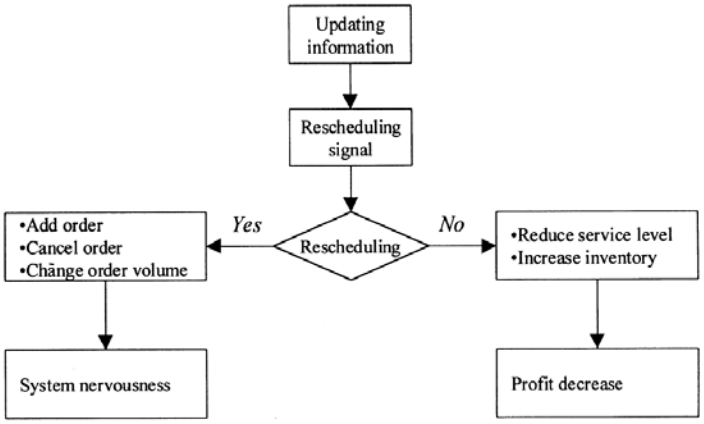


Figure 14: The rescheduling decision-making and the trade-off between different options (Grubbström & Tang, 2000).

Vieira, Herrmann, and Lin (2003) introduce a rescheduling framework to classify different rescheduling environments, strategies and methods. This framework is, in an adapted form, provided in Figure 15. Other authors also provide scheduling frameworks, such as Pinedo (2012), but the focus often lies on environments where capacity has an important role. In the scope of this project the emphasis is on Systems (with no relevant capacity restrictions) and the abstraction of capacity problems in the supply side is done via lead time deviations; therefore capacity (and thus order prioritizing) is not discussed in this framework.

The environments are either static or dynamic; the set of jobs is either finite (the set of jobs considered in a schedule is fixed) or infinite (the environment receives changes in the set of jobs when the schedule is made). Within static environments, all information is either known (deterministic) or there is uncertainty (stochastic). In dynamic environments, three variants are distinguished: no arrival variability; arrival variability; and variability in both arrival and routing (process flow variability).

Strategies can be divided into dynamic and predictive-reactive. Dynamic scheduling does not use a scheduling of individual jobs, but heuristics like dispatching rules that give priorities to jobs. Predictive-reactive has two steps; generating a production schedule and updating it in a response to a disruption. This rescheduling can be done on a periodic basis; when new information arrives (event-driven) or periodic and on special disruptions (hybrid).

The methods for rescheduling can be split into: methods that are used before disruptions occur (schedule generation) or when disruptions arrive (dynamic). The first contains the design of schedules that are robust against (minor) disruptions. The latter gives several methods for the adaption of the schedule. Subsection 4.2.3 will describe possible rescheduling methods in more detail and will provide a comparison on efficiency of rescheduling in different contexts.

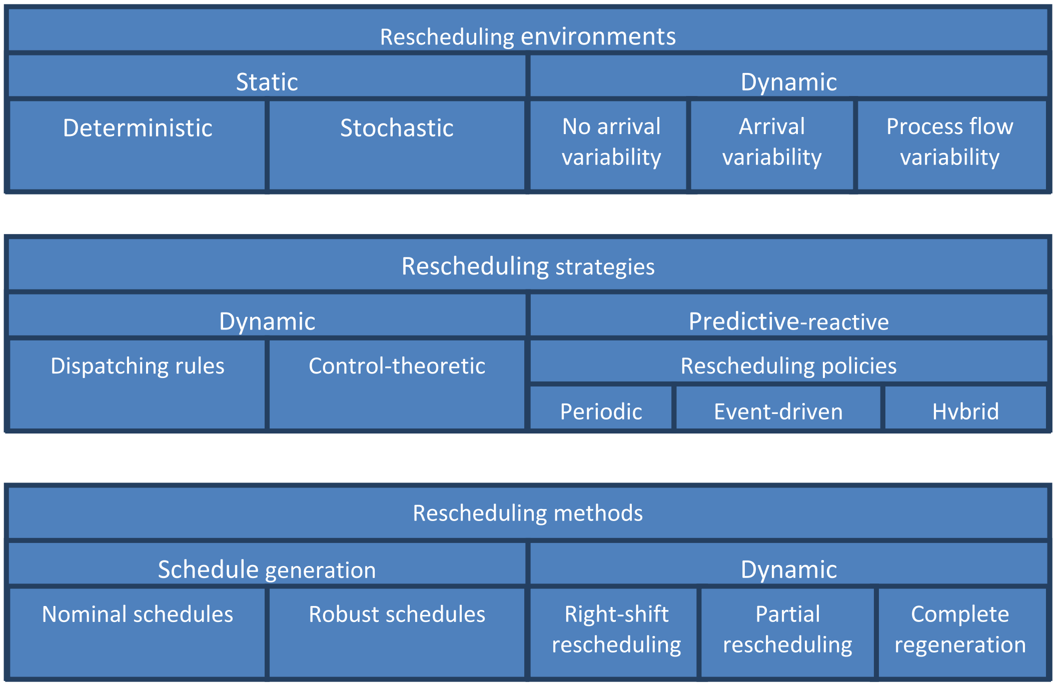


Figure 15: Framework of rescheduling environments, strategies and methods, based upon (Vieira, Herrmann, & Lin, 2003).

4.2.2 MEASURES OF PERFORMANCE OF RESCHEDULING

Measures of rescheduling can be separated into three groups: schedule stability, schedule efficiency and rescheduling cost (Vieira, Herrmann, & Lin, 2003). In this definition, the rescheduling cost are the cost of the rescheduling process, not of the costs (or cost reductions) associated with the execution of a new schedule. This latter is categorized as schedule efficiency.

When a planning often changes, it does not present much predictability. In the context of MRP, this is called “scheduling nervousness”. It is often defined as the number of changes that are made to a schedule during its execution (Vieira, Herrmann, & Lin, 2003). Few revisions imply high schedule stability.

The schedule efficiency is about the minimization of costs that occur at the implementation of the schedule. These costs either come from jobs starting too early (inventory holding cost); work-in-progress (holding cost); and jobs finishing too late (tardiness). Shafaei and Brunn (1999) provide a comprehensive cost function for the modeling of scheduling efficiency.

Finally, rescheduling cost could also be relevant. However, since the increase in digital planning tools available for planners, differences between rescheduling methods might be lower as schedules often are not calculated manually anymore. Computational efficiency still plays a role in the duration of a computation, as scheduling problems are NP-complete (Garey, Johnson, & Sethi, 1976). Costs of mitigating to a new schedule, and the costs associated with the mitigation are included. A major part of the rescheduling costs will be independent of the new schedule, but only on the decision to reschedule.

4.2.3 RESCHEDULING METHODS

The methods discussed above perform different on the different measures discussed in subsection 4.2.2. Furthermore, their performance differs per environment. We will compare the five methods on 77 problems which are also used by Abumaizar and Svestka (1997), combined with the results of Katragjini, Vallada and Ruiz (2013).

Comparison of rescheduling methods (Abumaizar & Svestka, 1997), (Katragjini, Vallada, & Ruiz, 2013)			
	Schedule stability	**Schedule efficiency**	**Rescheduling cost**
Nominal scheduling	++	--	++
Robust scheduling (Iterative Apparent Tardiness Cost)	++	+/-	+
Right shift rescheduling	-	-	++
Partial rescheduling (Affected Operations Rescheduling)	+	+	+
Partial rescheduling (Iterated Greedy)	+/-	+	-/+
Regeneration rescheduling	--	++	+

5 METHODOLOGY AND SCOPE

The approach used in this project is based upon the regulative circle of Van Strien (1997). This method is described in the first section of this chapter; the second gives a delimitation of the scope.

5.1 REGULATIVE CYCLE

Figure 16 below shows a modified version of the regulative circle of Van Strien (1997). The regulative circle shows the high-level approach of a business problem-solving project (the orgininal regulative cycle does not contain the problem set and roadmap and problem selection) (Van Strien, 1997).

A project starts with a set of problems (a problem mess), from this mess, one (or more) problems are obtained (Van Strien, 1997; Van Aken, Berends, & Van der Bij, 2007). In this project, multiple problems are identified and a roadmap is constructed to address these problems with the ultimate goal to improve the supply chain efficiency and control of VDL ETG.

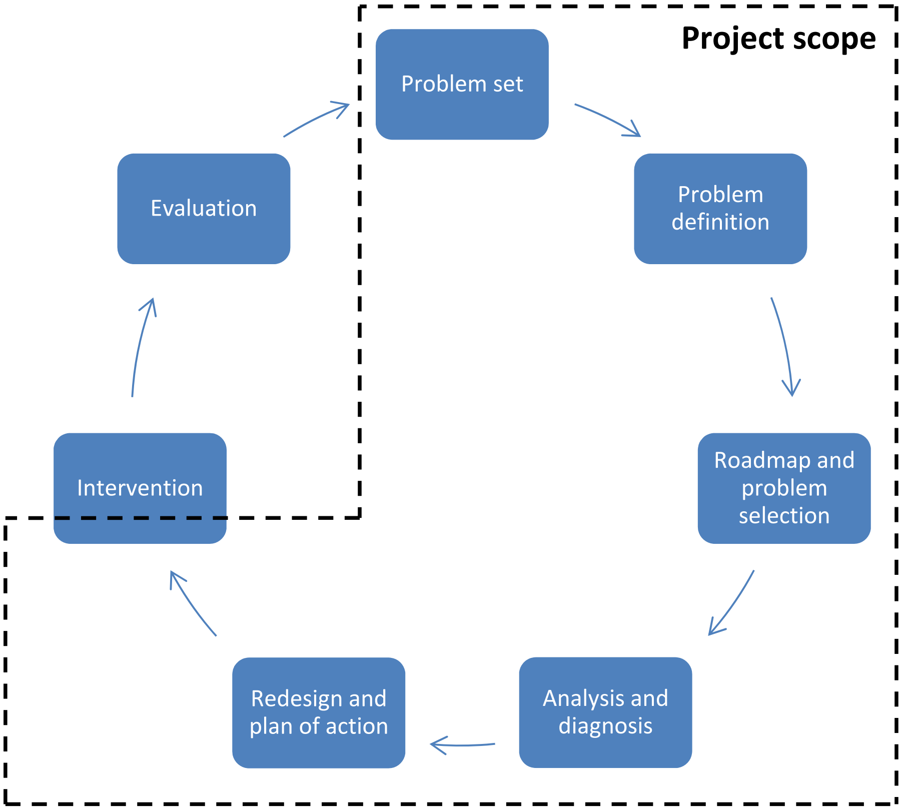


Figure 16: A modified version of the regulative circle of Van Strien (1997)

The transition from a problem set to a problem definition was the first step of this project, and is described in chapter 3. Based upon this problem, a roadmap has been developed that has the goal to improve the supply chain efficiency and control. The analysis phase aims to identify and quantify all relevant factors influencing the rescheduling cost, covering both schedule stability and efficiency. Furthermore, other factors influencing the effectiveness of rescheduling will be identified (and quantified) in this phase. The redesign consists of a comparison of different rescheduling methods and policies; the development and solution of a formal model of the rescheduling problem; and the development of a simulation model to optimize the rescheduling policy. Finally, the introduction of the new rescheduling policies will mark the completion of the project.

5.2 SCOPE OF PROJECT

The rescheduling in the context of VDL ETG is different in nature than a regular job-shop rescheduling, as not all required resources lie within the locus of control of integral planning. Therefore, the rescheduling optimization of the suppliers of Systems is not considered within the scope of this project as it cannot be implemented by VDL ETG. Next to that, these decisions (the supplier rescheduling) are more like the regular job-shop rescheduling problems as described by Vieira, Herrmann and Lin (2003), and are therefore different in nature than rescheduling in flow-shop environments with supply uncertainty. The variability from suppliers is however included to incorporate this uncertainty in the decision making process. Given that supplier variance is one of the reasons of the buffer stocks, it is relevant in the decision making process.

Figure 17 shows the project scope within the supply chain of VDL ETG, the reverse logistics stream (Repair Spare parts & Service, RS&S) is excluded from the scope, as rescheduling decisions are mainly present in the regular production. Furthermore, rescheduling within production units is also not considered. The scope is delimited to the integral planning and the information that it sends and receives. Finally, only the Eindhoven site is included in the scope; other manufacturing locations are excluded.

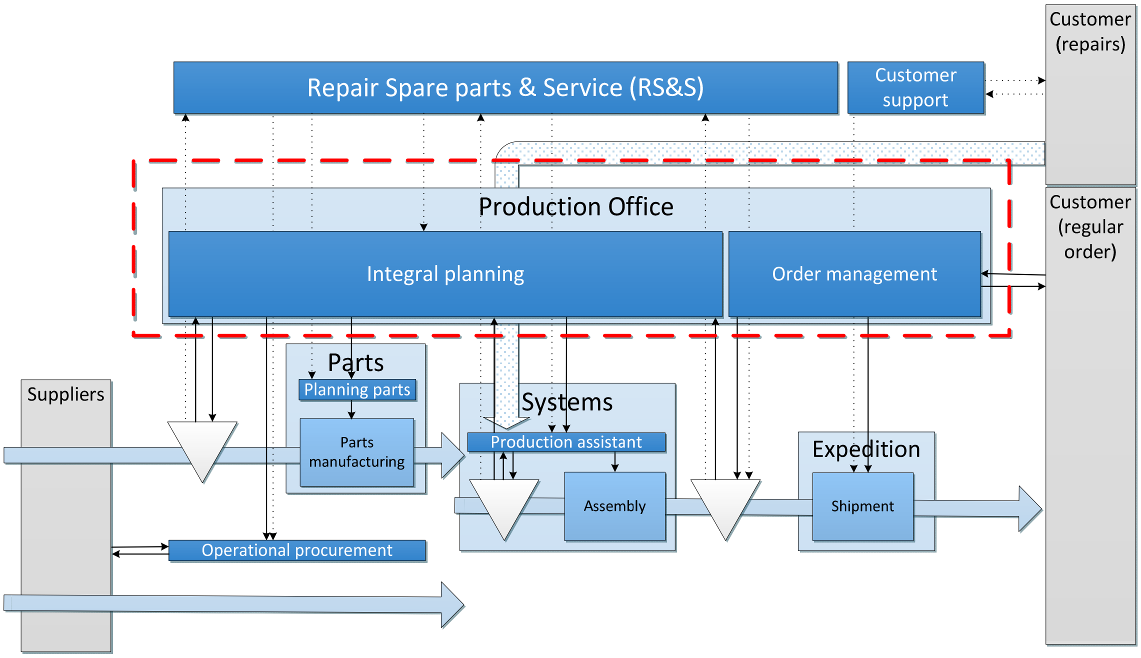


Figure 17: Supply chain of VDL ETG and project scope, based upon Kamps and Arts (2014).

6 DATA ANALYSIS

6.1 ANALYSIS OF RESCHEDULING, HOLDING AND TARDINESS COST

6.1.1 MEASURABILITY OF RESCHEDULING COST

In several studies, rescheduling is measured as a separate optimization variable or a constraint rather than via cost, for example as the number of changes or the sum of the differences in order start dates (Vieira, Herrmann, & Lin, 2003), (Cowling, 2001). Measuring schedule instability directly via cost is uncommon, because a translation is not obvious. De Kok and Inderfurth (1997) describe this issue:

> *“In many cases these consequences [of rescheduling] cannot be valued in terms of cost or lost profits, since relevant replanning expenses depend on time-varying availability of planning capacity, which can hardly be valued with respect to its contribution to a company's earnings. The same holds for the impairment of performance that short-term production control is facing due to quickly altering production decisions. Additionally, the loss of goodwill towards the planning system or the planning department generating a negative contribution to the behavior of people engaged in developing and executing production plans can never be expressed in money.” (De Kok & Inderfurth, 1997, p. 56)*

The first two arguments mentioned by De Kok and Inderfurth (1997) (time-varying availability of planning capacity that is hard to value and the valuation of the impairment of performance of production control) hold for short horizons. With regard to the first argument; any reduction in the requirement of planning capacity cannot always be valorized due to the varying availability, but on long-horizons this cost reduction can be captured. The impairment of performance could be measured by the loss of machine time due to setup costs. Finally, we state that any loss of goodwill towards the planning system is not primarily caused by its instability, but on the understanding of operators about the dynamic environment and the consequences it has on the schedule stability. Subsequently, we conclude that an expected cost reduction can be obtained from a reduction in schedule instability such that it represents reality to a proper extent.

6.1.2 FACTORS OF RESCHEDULING COST

Several factors contribute to the cost of rescheduling, such as planning, inventory and procurement costs. This analysis is structured in line with Figure 18 below. Costs are associated with the decisions themselves, or with the outcomes (schedule efficiency and stability). The costs of the planning decisions are given in the company version of this report. The outcome of the rescheduling decision is to either reschedule assembly or not.

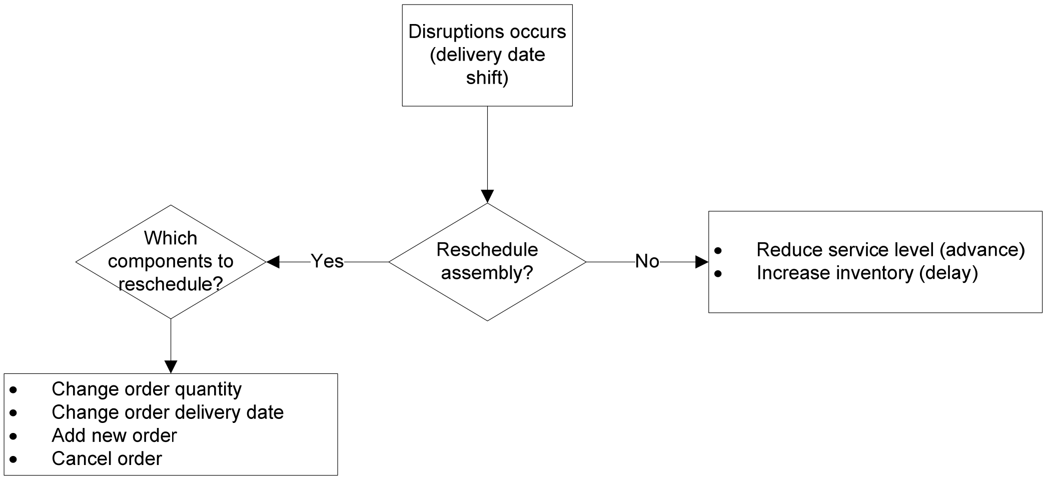


Figure 18: Reschedule decision framework, obtained from Kamps (2014)

6.2 ANALYSIS OF SUPPLY AND DEMAND UNCERTAINTY

6.2.1 DATA ANALYSIS METHOD DELIVERY DATE UNCERTAINTY

The first data on delivery date uncertainty was based upon rescheduling from VDL ETG towards suppliers. This is however an indirect and incomplete measure of the uncertainty VDL ETG faces from customers. Therefore, eventlog data from BaaN has been used on the field “Externe leverdatum” (external delivery date). This is often (but not always) changed when a customer indicates a delivery date shift. The dataset does not contain any missing values. The absence of missing values is plausible as all fields are generated by the ERP system.

Data was validated using interviews with order managers. This resulted in the removal of some observations. The exact procedure is stated in the company version of this thesis.

Based on this dataset, expected values and variance of the delivery date change are obtained and probability distributions are fitted. Due to the nature of the data (high degree of symmetry, fat tails, very broad horizon), the Lognormal and Laplace distributions are fitted and tested using quantile plots. On the number of reschedules per order, a geometric and a Poisson distribution have been fitted. The geometric distribution lies most in line with first observations as the data has a finite horizon on the left side (at least 0 reschedules), and the additional rescheduling message seems to behave like a Bernoulli trial.

6.2.2 RESULTS DELIVERY DATE UNCERTAINTY

Due to confidentiality, only an impression of the results is provided in this section. Detailed information can be found in the company version of this thesis.

Figure 19 below shows the occurrence of rescheduling messages with the corresponding advance or delay. The pattern has a no values at 0, as an unaltered delivery date is not a rescheduling.

Figure 19: Number of rescheduling messages with difference compared to previous external delivery date (in weeks). Blue represents the effective differences (final requested delivery date compared to earliest requested delivery date).

Orders that are rescheduled once, have a high probability to be rescheduled again. Figure 20 shows the frequency of rescheduling messages on orders. A distinction is made between effective and ineffective rescheduling; a series of rescheduling messages is ineffective when at least two messages direct in an opposite direction (e.g. one advance and one delay).

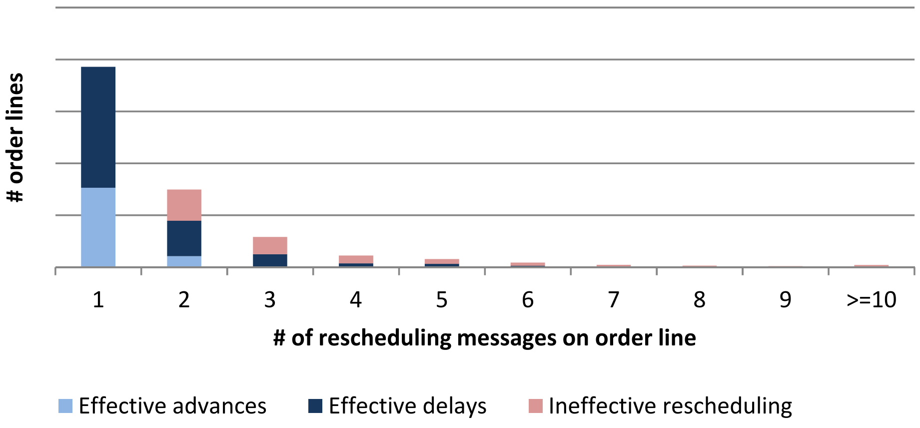


Figure 20: Frequency of number of rescheduling messages per order, splitted on effectiveness of rescheduling

Finally, the time between a rescheduling message and the old (and new) delivery date was investigated. This concept is illustrated in Figure 21. Figure 22 shows the difference between the moment of rescheduling and the previous delivery date; Figure 23 shows the difference with the new delivery date. Dark blue marks delays compared to the original delivery date; light blue indicates advances.

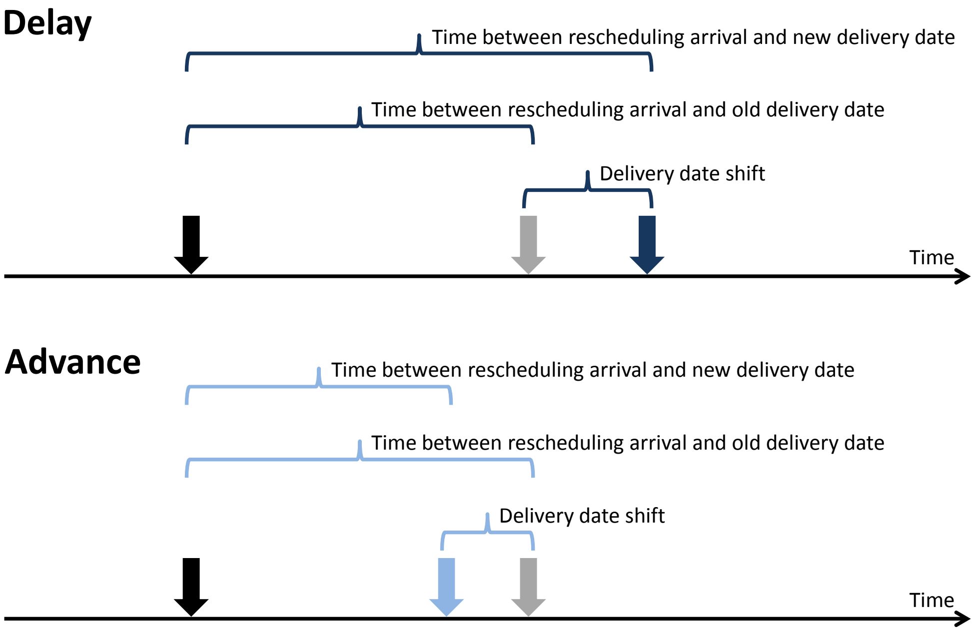


Figure 21: Graphical representation of the concepts delivery date shift and time between rescheduling arrival, and until old and new delivery date

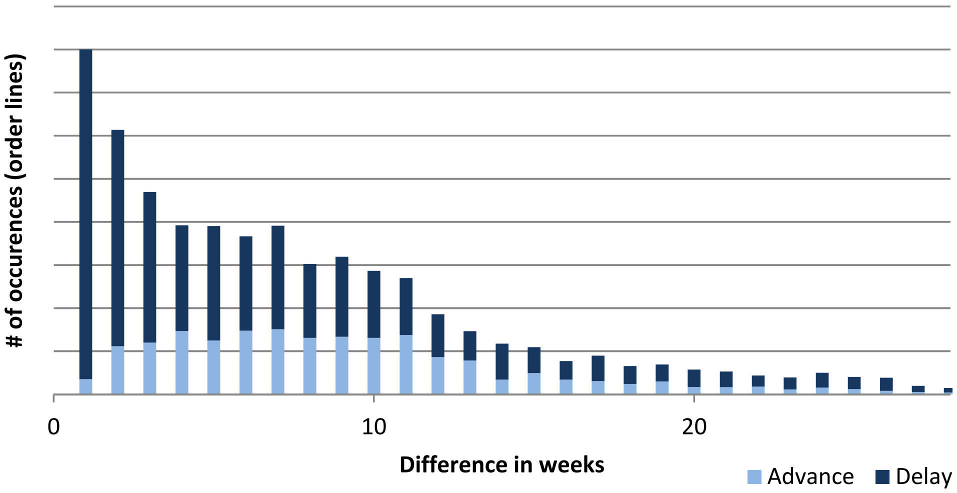


Figure 22: Difference in weeks between moment of rescheduling and previous delivery date

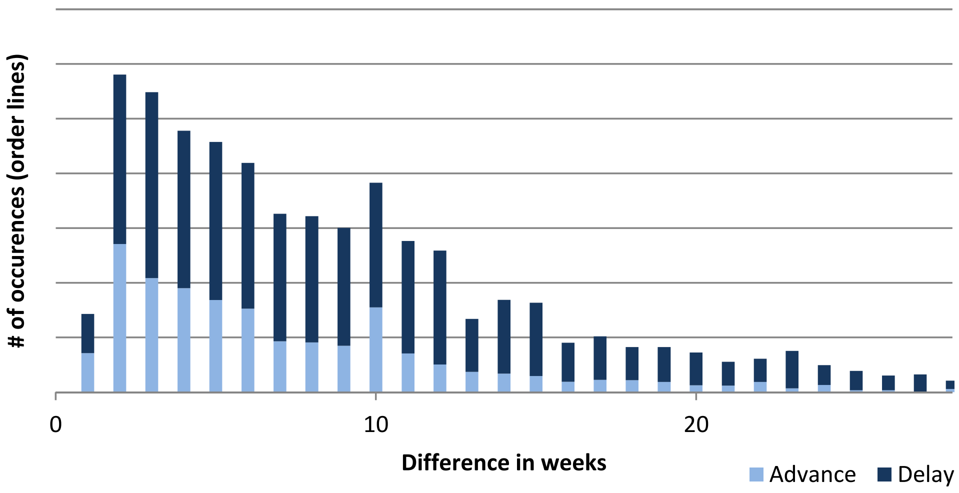


Figure 23: Difference in weeks between moment of rescheduling and new delivery date

6.2.3 SUMMARY OF SUPPLY AND DEMAND UNCERTAINTY

The magnitude, timing and frequency of rescheduling message have to be included to estimate the savings of alternative rescheduling policies. Furthermore, the supply uncertainty (in both leadtime and yield) has to be included, as it has an impact on both the effectiveness of safety stock and safety time and on the effectiveness of rescheduling methods. Table 1 below shows for these factors the mean and variance as well as the distribution that fits the data. The distribution of the data is omitted from this public version; the fitting method is provided in Appendix D.

Table 1: Selected factors with statistics and fitted distribution.

Factor	Typical value mean	Distribution fit
External delivery date shift (in weeks)	1 - 4	Double lognormal
Time between old delivery date and moment of rescheduling (in weeks)	5 - 10	Exponential
Time between new delivery date and moment of rescheduling (in weeks)	5 - 15	Lognormal
Number of rescheduling messages per order	0 - 5	Geometric
CLIP deviation suppliers (in days)	-10 - 10	Logistic
CLIP deviation Parts (in days)	-10 - 10	Logistic
Yield	0.99 – 0.9999	Bernoulli

7 MODELS AND RESULTS

Using the information obtained in the data analysis, this chapter elaborates about analytical and simulation models and their results. First, the analytical models are described for both static scheduling and dynamic rescheduling, followed by the results from these models. Section 7.4 provides an explanation of the simulation and this chapter concludes with the simulation results and sensitivity analysis.

7.1 ANALYTICAL MODEL STATIC SCHEDULING

Within the comparison of rescheduling methods, described in section 4.2, 'robust schedules' was one of the most promising two. The goal of this static scheduling method is to minimize the costs associated by using buffers efficiently. It is in essence not a method of rescheduling, but a method to avoid rescheduling. Within the context of the static scheduling models, all assumptions stated in appendix C are made.

7.1.1 SIMPLE MODEL

The simple static scheduling problem is characterized by:

- a stochastic delivery date change function (f_{DD}, F_{DD});
- a deterministic leadtime and holding cost for every component;
- a deterministic leadtime for assembly;
- a deterministic holding cost for finished modules; and
- a deterministic tardiness cost per day.

As leadtimes and the magnitude of demand are given, there is no reason to buffer within the chain; only at the end. Therefore, only the delivery date change, tardiness and holding cost are required. The problem can therefore be described by the set: $\{f_{DD}, c_{holding}, c_{tardiness}\}$. This simplification implicitly makes the assumption that a delivery date change is observed at the delivery moment, while in reality it often arrives several weeks earlier. An earlier arrival of the message would give possible benefits of holding inventory within the chain; assembly could for example be started later. This would however create a situation that actively responds upon delivery date changes. Given the purpose of the model (reducing schedule fluctuations created by rescheduling messages), this assumption is justified.

The goal of the model is the minimization of cost, which is a trade-off between expected holding and expected tardiness cost. Figure 24 shows this tradeoff graphically; when modules are finished earlier, expected tardiness cost are reduced, but holding cost increase. On the other hand, when modules are finished later, expected tardiness cost increase and expected holding cost decrease. Within the context of this problem we state that safety stock can be seen as a safety time equal to the inter-arrival times of orders, and we will subsequently only consider safety time as design parameter (T), as it is more suitable for volatile MTO chains.

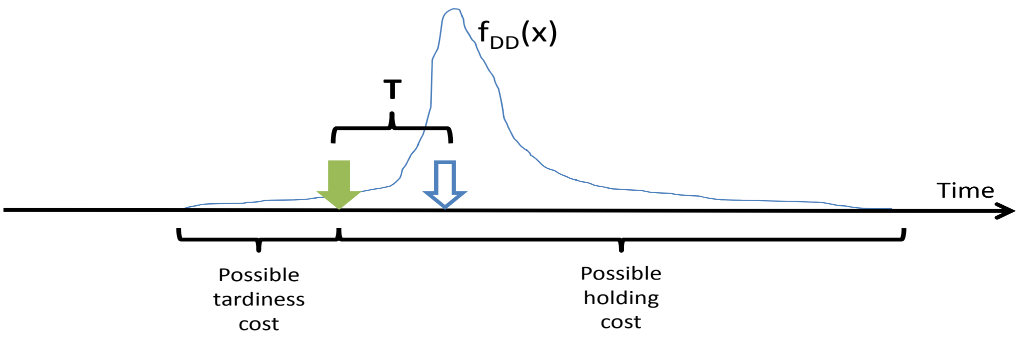


Figure 24: Trade-off between holding and tardiness cost on the probability density function of delivery date change

Although Figure 24 suggests that the delivery moment has a continuous nature, it actually is discrete, as only dates are communicated. Nonetheless, we will model it as a continuous random variable in line with a regular newsvendor problem.

$$C(T) = c_{tardiness}\int_{-\infty}^{\infty} max\{0, T - x\}\, f_{DD}(x)dx + c_{holding}\int_{-\infty}^{\infty} max\{0, x - T\}\, f_{DD}(x)dx$$

Tardiness costs are incurred when the delivery date will be shifted before the moment that the module is finished, while holding cost come from modules that are finished earlier than delivery date. As it is a newsvendor problem, the optimal safety time (T*, shown in Figure 24) can be derived in the following way:

$$C(T) = c_{tardiness}\int_{-\infty}^{T} (T - x) f_{DD}(x)dx + c_{holding}\int_{T}^{\infty} (\mathrm{x} - T) f_{DD}(x)dx$$

$$\begin{aligned}\frac{dC(T)}{dT} = {} & c_{tardiness}\left[\int_{-\infty}^{T}(1)f_{DD}(x)dx + (T - T)f_{DD}(T)(1) - (T - \infty)f_{DD}(-\infty)(0)\right] \\ & + c_{holding}\left[\int_{T}^{\infty}(-1)f_{DD}(x)dx + (\infty - T)f_{DD}(\infty)(0) - (T - T)f_{DD}(T)(1)\right]\end{aligned}$$

$$\frac{dC(T)}{dT} = c_{tardiness}\int_{-\infty}^{T} f_{DD}(x)dx + c_{holding}\int_{T}^{\infty} -f_{DD}(x)dx$$

$$\frac{dC(T)}{dT} = c_{tardiness}F_{DD}(T) - c_{holding}\big(1 - F_{DD}(T)\big)$$

$$\frac{dC(T)}{dT} = \big(c_{tardiness} + c_{holding}\big)F_{DD}(T) - c_{holding}$$

$$\big(c_{tardiness} + c_{holding}\big)F_{DD}(T^{*}) - c_{holding} = 0$$

$$F_{DD}(T^{*}) = \frac{c_{holding}}{c_{tardiness} + c_{holding}}$$

$$T^{*} = F_{DD}^{-1}\left(\frac{c_{holding}}{c_{tardiness} + c_{holding}}\right)$$

The problem should be solved for every end-item as their holding cost and delivery date distributions are different.

7.1.2 ADVANCED MODEL

In comparison to the simple model presented in the previous section, the advanced model solves the problem consisting of:

- a stochastic delivery date change function (f_{DD}, F_{DD});
- a stochastic leadtime for every component and assembly (including an implicit stochastic yield for some components); (f_{LT}, F_{LT})
- a deterministic ordering (setup) cost for components;
- a deterministic holding cost for components and modules; and
- a deterministic tardiness cost per day.

Setup cost introduces the requirement for a lot size decision as an there exists a trade-off between setup and holding cost. Since ordering larger order quantities (i.e. larger than 1) only increases cycle stock (and not safety stock), cycle stock decisions can be made locally. It then is only important to notice that order quantities are at least as large as, and a multiple of, order levels in a higher assembly stage. The algorithm of Federgruen and Zheng (1992) could be used to incorporate the lot sizing decision. Subsequently, a base-stock policy is analyzed first.

Summarizing, we first analyze this system as a base-stock policy with a single stock location with a stochastic leadtime and delivery date. Next, we extend the problem to a multi-echelon assembly environment. Finally, the lot sizing decision will be added using the algorithm of Federgruen and Zheng (1992). Figure 25 below provides an illustration of this approach.

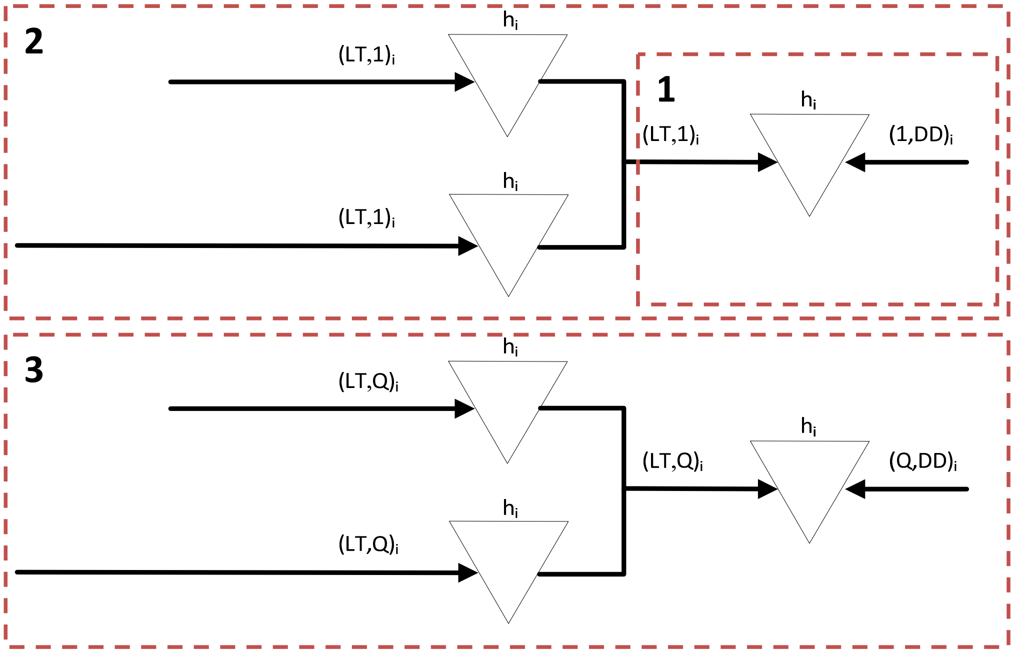


Figure 25: Approach of advanced model, first studying one location, then a multi-echelon environment and finally lot-size decisions are included

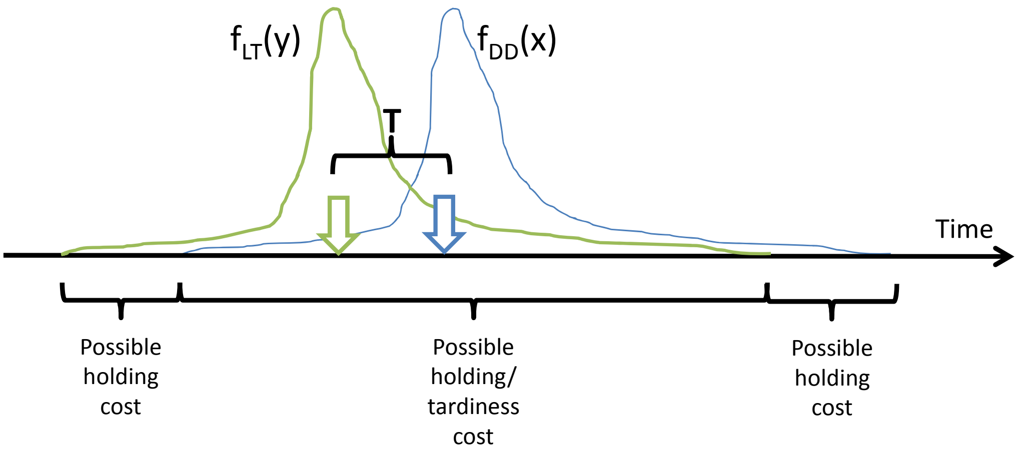


Figure 26: Trade-off between holding and tardiness cost on the probability density function of delivery date change and product leadtime

When a module is finished before the delivery date, holding costs are incurred; when it is finished after the delivery date, it results in tardiness costs as illustrated in Figure 26 above.

$$C(T) = c_{tardiness} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} max\{0, T + y - x\} f_{DD}(x) f_{LT}(y) dxdy \\ + c_{holding} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} max\{0, x - y - T\} f_{DD}(x) f_{LT}(y) dxdy$$

$$C(T) = c_{tardiness} \int_{-\infty}^{\infty} \int_{-\infty}^{T+y} (T + y - x) f_{DD}(x) f_{LT}(y) dxdy \\ + c_{holding} \int_{-\infty}^{\infty} \int_{T+y}^{\infty} (x - y - T) f_{DD}(x) f_{LT}(y) dxdy$$

$$\frac{dC(T)}{dT} = c_{tardiness} \int_{-\infty}^{\infty} \left[\int_{-\infty}^{T+y} (1) f_{DD}(x) f_{LT}(y) dx + \big(T + y - (T + y)\big) f_{DD}(T + y) f_{LT}(y)(1) \\ - (T + y - \infty) f_{DD}(-\infty) f_{LT}(y)(0) \right] dy \\ + c_{holding} \int_{-\infty}^{\infty} \left[\int_{T+y}^{\infty} (-1) f_{DD}(x) f_{LT}(y) dx + (\infty - (T + y)) f_{DD}(\infty) f_{LT}(y)(0) \\ - \big((T + y) - (T + y)\big) f_{DD}(T + y) f_{LT}(y)(1) \right] dy$$

$$\frac{dC(T)}{dT} = c_{tardiness} \int_{-\infty}^{\infty} \left[\int_{-\infty}^{T+y} f_{DD}(x) f_{LT}(y) dx \right] dy + c_{holding} \int_{-\infty}^{\infty} \left[\int_{T+y}^{\infty} -f_{DD}(x) f_{LT}(y) dx \right] dy$$

This equation cannot be solved analytically in this form. A transformation to a discrete probability distribution is possible with regard to the environment. That would allow a solution using a convolution sum, but would still require specific distribution to be used. Therefore, we provide an alternative method of calculating the optimal safety time. A difference function z is defined as x-y (the moment of demand occurrence minus the moment of delivery); a negative value of z subsequently indicates tardiness. This is shown graphically in Figure 27 below.

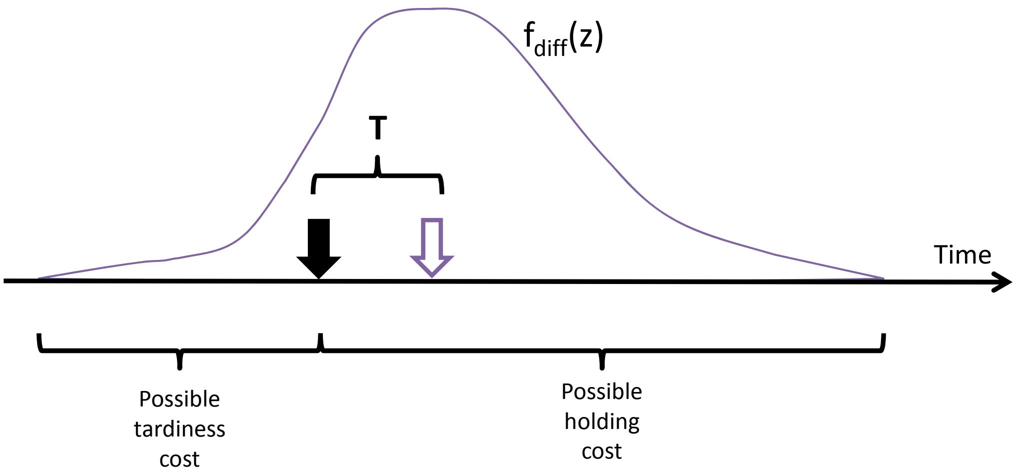


Figure 27: Trade-off between holding and tardiness cost on the probability density function of the difference between date of product readiness and customer demand

The probability density function of this difference equals the following (a proof that the function is a probability density function is provided in Appendix E):

$$f_{diff}(z) = \int_{-\infty}^{\infty} f_{DD}(x) f_{LT}(x-z)dx$$

Then, the cost function can be rewritten as:

$$C(T) = c_{tardiness} \int_{-\infty}^{\infty} max\{0, T-z\} f_{diff}(z)dz + c_{holding} \int_{-\infty}^{\infty} max\{0, z-T\} f_{diff}(z)dz$$

$$C(T) = c_{tardiness} \int_{-\infty}^{T} (T-z) f_{diff}(z)dz + c_{holding} \int_{T}^{\infty} (z-T) f_{diff}(z)dz$$

As this is a newsvendor problem, the optimal T is given by the following equation (the proof is shown in section 7.1.1):

$$T^* = F_{diff}^{-1}\left(\frac{c_{holding}}{c_{tardiness} + c_{holding}}\right)$$

This is in line with the result in section 7.1.1, where leadtime is assumed to be deterministic and the difference function subsequently is defined by the delivery date function alone.

Although the difference function might not be obtained as easily as the leadtime and delivery date shifts separately, it can be observed. When both are related (and thus assumption B4 is violated), the use of the difference is even better than assuming that leadtime and delivery date are independent in using them separately.

The decision at lower assembly stages is the amount of safety time to use there, such that safety time at the module can be reduced. This implies a shift of probability mass in the difference function (z) of the module to the right (which implies a reduction of safety time at module level; a decrease of T). Safety time at component level is many times cheaper than safety time at module level (p_{module}/p_{comp}), but does not buffer against the leadtime variances of other components or assembly itself. There exists a tradeoff between the safety time at module and component level. The additional cost of safety time at an earlier (stream upward) location in the system equals:

$$C\left(T_{comp}\right) = hp_{comp}T_{comp} - hp_{module}(T_{old} - T_{new})$$

$$\begin{aligned} C\left(T_{comp}\right) = hp_{comp}T_{comp} & \\ & - hp_{module}\left(F_{diff(OLD)}^{-1}\left(\frac{c_{holding}}{c_{tardiness} + c_{holding}}\right)\right. \\ & \left. - F_{diff(NEW)}^{-1}\left(\frac{c_{holding}}{c_{tardiness} + c_{holding}}\right)\right) \end{aligned}$$

This equation has no solution, as the cumulative distribution function (in general) does not have an inverse. It does however exist for specific distributions, but even when using these, the probability mass shift driven by the introduction of safety time earlier in the system, cannot be combined in this term. Therefore, an iterative approach is used.

The iterative approach uses the following algorithm:

1. Sort predecessors of assembly on leadtime variance (descending).
2. Select first (next) component.
3. Add one day of safety time to LT of component.
4. Calculate all safety time requirements at higher levels and check whether this is profitable, go to 3, if not remove one day of safety time and go to 5.
5. Select new component, if all components are investigated; select all predecessors of all components with added safety time, sort them descending on leadtime variance and go to 2. If no new levels exist or no safety time was added in the previous step, stop algorithm.

This algorithm would lead to an optimal length of safety time at different components.

Finally, the lot-sizing decision needs to be incorporated in the problem. This was aimed to be done using the algorithm of Federgruen and Zheng, as described in their paper “An efficient algorithm for computing an optimal (r,Q) policy in continuous review stochastic inventory systems” (1992). They however discuss (r,Q) policies, while the MTO/ATO environment can be typically modeled by an (s, Q) model. An EOQ policy using echelon holding cost (the incremental holding cost) and setup cost would be a good base to determine lot sizes. Furthermore, lower echelons should at least order the quantity and a multiple of a higher level.

7.2 ANALYTICAL MODEL DYNAMIC RESCHEDULING

Next to a robust scheduling method, dynamic partial rescheduling seemed a good method in both stability and schedule efficiency (section 4.2). The goal of dynamic rescheduling is to minimize the costs associated with rescheduling by acting reactive on delivery date changes when they arrive. Subsequently, buffer reduction in the supply chain is possible as rescheduling deals with a part of the variance.

The analysis of the dynamic rescheduling method is done separately for delays and advances as both can be recognized upon arrival of a rescheduling message. In both cases, all assumptions stated in appendix C are made.

The following sets of components are defined in the context of dynamic rescheduling:

$$S_{comp} = S_{arrived} \cup S_{order} \cup S_{not\ ordered}$$

$$S_{comp} = S_{arrived} \cup S_{advanced} \cup S_{not\ advanced}$$

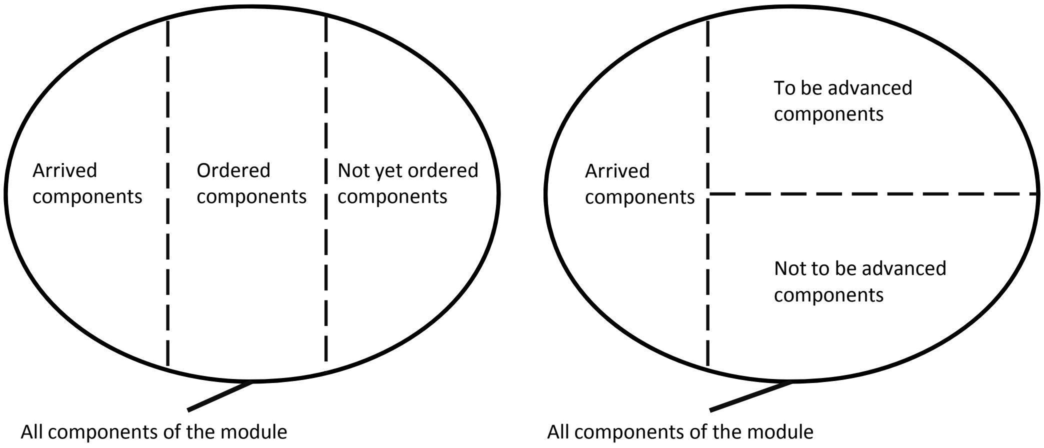


Figure 28: Sets of components used in the analysis of dynamic rescheduling

Components of the module considered in a rescheduling message are either already in stock at VDL ETG; ordered at suppliers; or not yet ordered at suppliers. Components in the last two categories can also be distinguished as components that need to be advanced and components that do not need to be advanced; orders that are not yet ordered could be advanced when ordered, in case an order is required within regular leadtime.

7.2.1 ORDER DELAY

In case of a customer delay of an order, holding costs are reduced. The holding cost of components that are already ordered can only be reduced if those orders can be delayed. The holding cost of components that are not yet ordered and the added value of assembly can be reduced when assembly is postponed. When these savings exceed the costs of rescheduling, it is efficient to reschedule.

$$\mathit{expected\ savings}\ > \mathit{expected\ cost\ of\ rescheduling}$$

Given that new rescheduling messages are independent of the history (memoryless), the value of a rescheduling is assumed to be worthless if more message arrive on an order. Furthermore, given that capacity restrictions are omitted (assumption B3), other orders are not affected by a rescheduling decision.

$$\begin{aligned}
&\mathit{holding\ cost\ reduction\ of\ later\ arriving\ components}\\
&+\ \mathit{later\ addition\ of\ assembly\ value} * \mathit{probability\ of\ no\ additional\ rescheduling\ messages}\\
&+ 0 * \mathit{probability\ of\ at\ least\ one\ additional\ rescheduling\ message}\\
&> \mathit{expected\ fixed\ cost\ and\ expected\ component\ cost\ of\ rescheduling}
\end{aligned}$$

The probability of at least one additional rescheduling will disappear from the equation. The component cost of rescheduling are moved to the left side. Given that $\mathbb{P}(R = 0) > 0$, which is in line with observations (section 6.2), this equals:

$$\left(\sum_{i\in S_{order}\cup S_{not\,order}} max\left\{\Delta_{DD} * h * p_i - 1_{i\in S_{order}} * \frac{\mathbb{E}(c_{comp})}{\mathbb{P}(R=0)}, 0\right\} + \Delta_{DD} * h * \left(p_{module} - \left(\sum_{i\in S_{comp}} p_i\right)\right)\right) * \mathbb{P}(R=0) > E(c_{fixed})$$

$$\sum_{i\in S_{order}} max\left\{\Delta_{DD} * h * p_i - \frac{\mathbb{E}(c_{comp})}{\mathbb{P}(R=0)}, 0\right\} + \sum_{i\in S_{not\,order}} (\Delta_{DD} * h * p_i) + \Delta_{DD} * h * \left(p_{module} - \left(\sum_{i\in S_{comp}} p_i\right)\right) > \frac{\mathbb{E}(c_{fixed})}{\mathbb{P}(R=0)}$$

$$\sum_{i\in S_{order}} max\left\{\Delta_{DD} * h * p_i - \frac{\mathbb{E}(c_{comp})}{\mathbb{P}(R=0)}, 0\right\} + \Delta_{DD} * h * \left(p_{module} - \left(\sum_{i\in S_{comp}-S_{not\,order}} p_i\right)\right) > \frac{\mathbb{E}(c_{fixed})}{\mathbb{P}(R=0)}$$

Given that a procurement order will not be rescheduled when the cost of rescheduling exceeds the expected holding cost savings, such an order will not be rescheduled. This allows partial rescheduling. The equation above shows three elements; the possible savings; the certain savings; and the fixed rescheduling costs. An example of this decision is provided below.

For simplification purposes, a product structure of a bike is used, given in Figure 29 below.

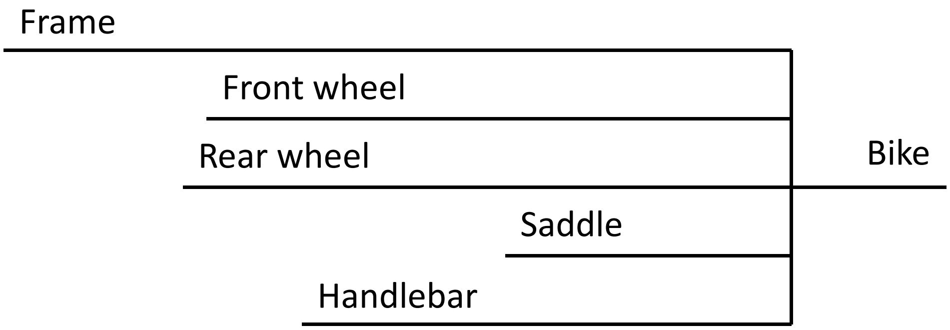


Figure 29: Product structure and lead times of bike (example)

Just after the front wheel has been ordered, a rescheduling message arrives to delay the order by two weeks. At that moment, the frame is already delivered (due uncertainty and high safety time).

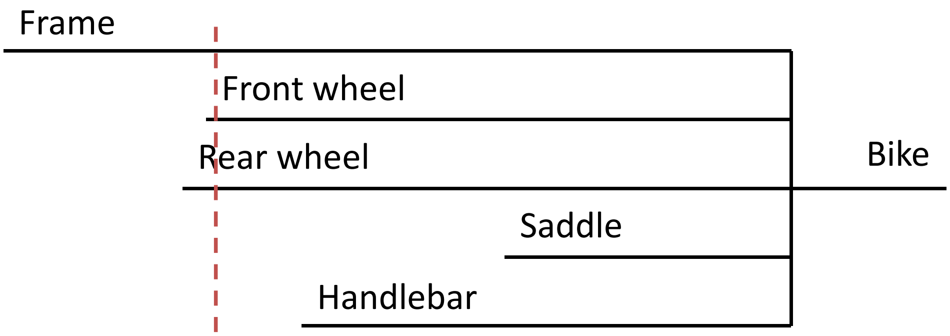


Figure 30: Product structure and lead times of bike (example)

The choice is to reschedule or not, and in case of a rescheduling, which components to reschedule. Clearly, the frame cannot be rescheduled, as it is arrived. The (echelon) holding costs of the frame have to be incurred anyway, and can be seen as sunk cost. Therefore, this component (within $S_{arrived}$) is not considered in the decision. The saddle, handlebar and assembly can be rescheduled easily (no orders are sent yet). If the (holding cost) savings of the rescheduling of assembly are higher than the rescheduling cost, rescheduling should be done.

$$\Delta_{DD} * h * \left(p_{module} - \left(\sum_{i \in S_{comp} - S_{not\ order}} p_i\right)\right) > \frac{\mathbb{E}(c_{fixed})}{\mathbb{P}(R = 0)}$$

Additional savings could be made when the front and rear wheel can be rescheduled (to make sure they arrive at the same moment as the new start of the assembly), to reduce inventory holding cost.

$$\sum_{i \in S_{order}} max\left\{\Delta_{DD} * h * p_i - \frac{\mathbb{E}(c_{comp})}{\mathbb{P}(R = 0)}, 0\right\}$$

7.2.2 ORDER ADVANCE

In case of an advance of an order, holding cost and tardiness cost are reduced. The holding cost of components that are already in stock can be reduced. When these savings exceed the costs of rescheduling, it is efficient to reschedule.

$$expected\ savings\ > expected\ cost\ of\ rescheduling$$

$$tardiness\ cost\ reduction + holding\ cost\ reduction\ > expected\ cost\ of\ rescheduling$$

$$\left(\mathbb{E}(c_{tardfixed}) + \sum_{i \in S_{arrived}} (\Delta_{DD} * h * p_i)\right) * \mathbb{P}(R = 0) > \mathbb{E}(c_{fixed}) + \mathbb{E}(c_{comp}) * (|S_{advanced}|)$$

$$\mathbb{E}(c_{tardfixed}) + \sum_{i \in S_{arrived}} (\Delta_{DD} * h * p_i) > \frac{\mathbb{E}(c_{fixed})}{\mathbb{P}(R = 0)} + \sum_{i \in S_{advanced}} \left(\frac{\mathbb{E}(c_{comp})}{\mathbb{P}(R = 0)}\right)$$

$$\mathbb{E}(c_{tardfixed}) + \Delta_{DD} * h \left(\sum_{i \in S_{arrived}} p_i\right) > \frac{\mathbb{E}(c_{fixed})}{\mathbb{P}(R = 0)} + \sum_{i \in S_{advanced}} \left(\frac{\mathbb{E}(c_{comp})}{\mathbb{P}(R = 0)}\right)$$

Advances are clearly harder to perform as all components need to be in time to perform an efficient rescheduling; if not all components can be rescheduled, any component rescheduling will be useless.

In practice, VDL ETG aims to maximize its customer proposition, and subsequently advances orders when it is possible. Subsequently, the tardiness costs are in practice that large that the equation above holds. The same example used in the previous section, is used to illustrate this method. Just after the front wheel has been ordered, a rescheduling message arrives to advance the order by a week. At that moment, the frame is already been delivered (due uncertainty and high safety time).

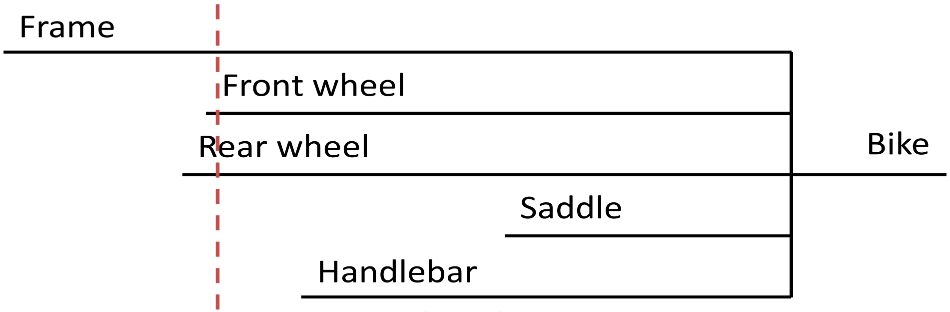


Figure 31: Product structure and lead times of bike (example)

The choice is to reschedule or not, and in case of a rescheduling, which components to reschedule. In this case, the frame and saddle will not give issues (the saddle is planned to be ordered in a few weeks), and rescheduling will even reduce the holding cost of the frame. If the cost of advancing the wheels and handlebar is worth the reduction of the tardiness and the reduction of holding cost, rescheduling should be done.

$$\mathbb{E}(c_{tardfixed}) + \Delta_{DD} * h \left(\sum_{i \in S_{arrived}} p_i\right) > \frac{\mathbb{E}(c_{fixed})}{\mathbb{P}(R = 0)} + \sum_{i \in S_{advanced}} \left(\frac{\mathbb{E}(c_{comp})}{\mathbb{P}(R = 0)}\right)$$

7.3 QUALITATIVE RESULTS MATHEMATICAL ANALYSIS

For both the static and dynamic method, the impact of various changes to the environment are derived from the equations. For each variable, the direction of the change is mentioned. The size of a change is discussed at the simulation results and sensitivity analysis (sections 7.5 and 7.6).

7.3.1 STATIC

The following relationships can be derived from the analytical equations on static scheduling. Total cost increase when:

- Leadtime variance increases (more variance implies more safety time, thus higher cost)
- Yield decreases (lower yield, more supply uncertainty, thus higher cost)
- Number of delivery day shifts increases (more shifts imply most often larger deviations, and higher tardiness cost)
- Magnitude of shifts increases (bigger shifts results in higher cost)
- Component and module prices increase (higher prices imply higher holding cost)
- Holding cost rate increases (higher rate leads to higher holding cost)
- Tardiness cost increase (higher tardiness cost results in more safety time, thus higher cost)

7.3.2 DYNAMIC

The following relationships can be derived from the analytical equations on dynamic rescheduling. Total cost increase when:

- Leadtime variance increases (more variance implies more safety time, thus higher cost)
- Yield decreases (lower yield, more supply uncertainty, thus higher cost)
- Number of delivery day shifts increases (more shifts result in higher cost)
- Magnitude of shifts increases (bigger shifts results in higher cost)
- Time between message receipt and planned delivery decreases (more time results in lower cost)
- Component and module prices increase (higher prices imply higher holding cost)
- Holding cost rate increases (higher rate leads to higher holding cost)
- Tardiness cost increase (higher tardiness cost results in more safety time, thus higher cost)
- Rescheduling cost increase (higher rescheduling cost would lead to either higher tardiness or higher rescheduling cost)
- Maximum advancement factor decreases (lower factor implies a restriction on the rescheduling possibilities, and thus higher cost)

7.4 SIMULATION MODELS

The goal of the simulation is identical to the analytical approach discussed in the previous chapter; cost minimization. Simulation will be performed for the simple as well as for the advanced model, to make a good comparison with the dynamic rescheduling method. Given that the latter only deals with delivery date uncertainty, only a comparison with the simple model is fair. Another fair comparison could be made when safety time is added at the dynamic model to deal with the supply uncertainty; in this case, a comparison with the advanced model can be made.

This chapter will first introduce the simulation environment that is also used to model the dynamic method, and then discuss the simple and advanced model.

7.4.1 SIMULATION ENVIRONMENT

The simulation covers the production and demand processes of one type of module over a given period of time. The composition of the module can be generated (with a given number of assembly levels and branches per level) or user-defined. Furthermore, the length of the simulation and the move rate can be chosen. As all events (and performance measures) are related to an order line, the entire lifecycle of the order lines is simulated. This makes a startup period not required (performance of order lines is mutually independent).

For all modules and components, the realized leadtime and yield are generated based upon either a probability distribution (stochastic) or a constant (deterministic). Furthermore, the algorithm generates the delivery date changes for modules.

Finally, the user enters values for the different constants, such as rescheduling cost and the holding cost rate.

The simulation gives, for each rescheduling method, the following performance measures as output:

- number of rescheduled order lines;
- average inventory investment of components (based upon the average time per order line);
- average inventory investment of modules (based upon the average time per order line);
- number of tardy order lines;
- average tardiness per order line;
- total rescheduling cost;
- total holding cost;
- total tardiness cost; and
- total cost (sum of rescheduling, holding and tardiness cost).

Next to the performance measures of the different methods, the simulation includes a sensitivity analysis on all input variables.

7.4.2 DESIGN OF SIMULATION

Figure 32 below shows the simulation design. The user can rebuild the simulation, perform a new stochastic drawing, and calculate the performance of the methods discussed. Between the actual calculations of the performance, a validation layer is build, which gets the required data from the sheets. Furthermore, when parameters of stochastic variables are modified, the calculation of the performance of methods triggers automatically a new stochastic drawing. The same holds for the rebuilding of the environment.

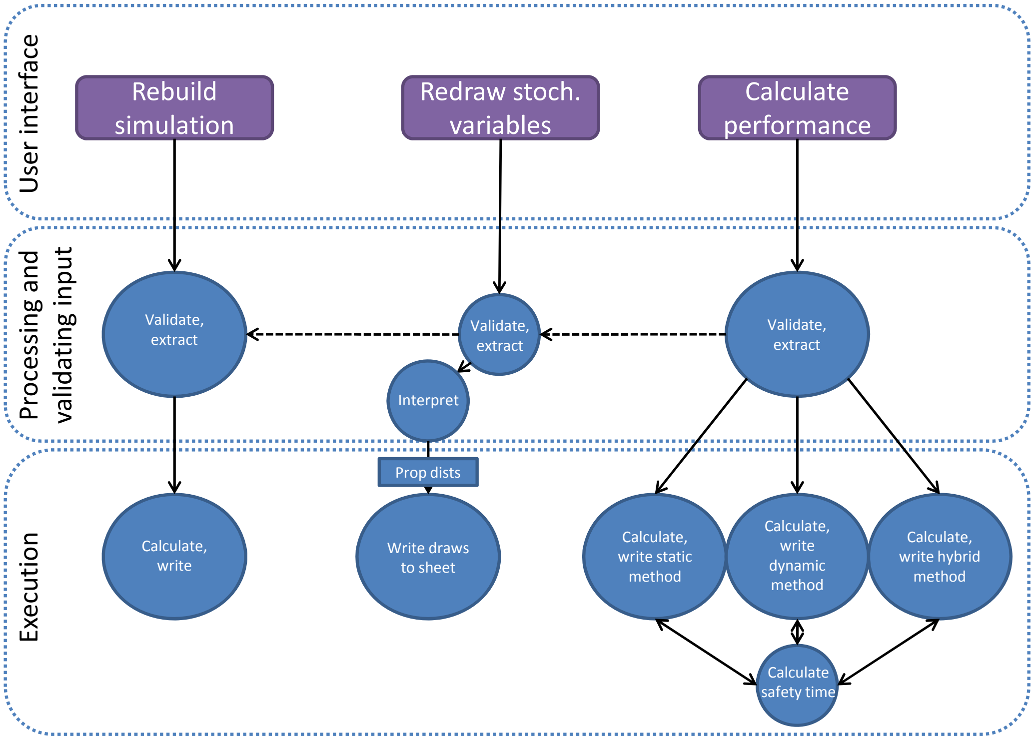


Figure 32: Design of simulation

7.4.3 CALCULATION OF RESULTS

The static algorithm iteratively calculates the cost for each module produced. The most important parameter is the amount of safety time at the module and different components. The safety time of the module is calculated using the result of section 7.1.2 using the difference function. The difference function is calculated using an independent stochastic sample from the same probability distributions as used for the calculation. After the calculation of the safety time of the module, the safety time is iteratively calculated for the various components. This is illustrated in Figure 33 below.

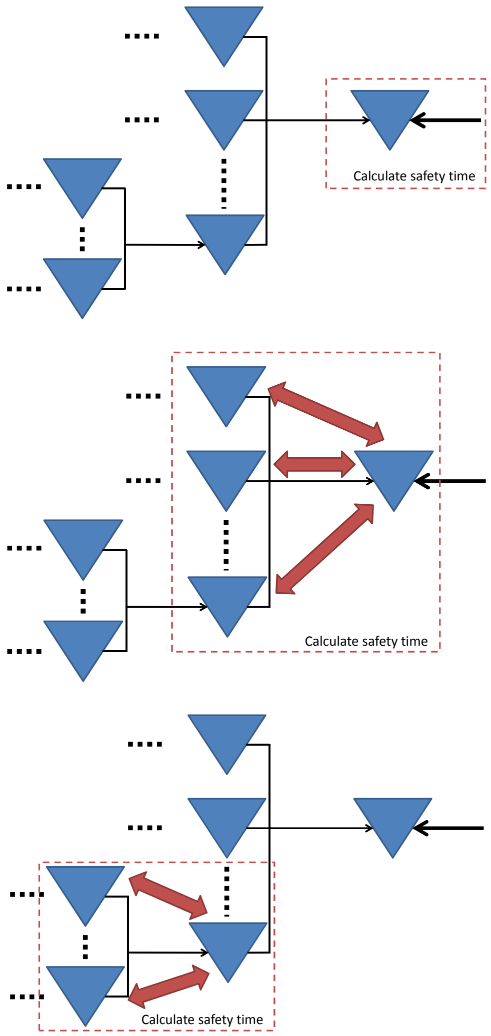


Figure 33: Iteratively distribution safety time between components

The cycle is repeated for every component that has predecessors. Safety time is moved as much as possible from a higher to a lower level such that the tardiness is not increased; next, safety time is removed from the predecessors until tardiness increases. This does not lead to an optimal solution, but its calculation time is only exponential to the levels of a product and not to the number of components (which depends exponential on levels and polynomial on branches). Using a greedy algorithm that moves safety time to allocate safety time to the component that leads to the most tardiness needs a continuous re-evaluation of the critical path, and has therefore a higher computational complexity (polynomial on components).

7.4.4 DYNAMIC RESCHEDULING

We simulate the dynamic rescheduling method in the same environment as the static rescheduling. Section 7.4.1 describes this environment.

The dynamic rescheduling model contains tardiness, holding and rescheduling cost as input variables (next to the stochasticity in delivery date and in the moment of arrival of the rescheduling messages). The choice whether or not to reschedule individual order lines is the design parameter in this problem.

The dynamic solution uses the same method to construct safety time; it is however only evaluated on supply variance, and not on demand variance.

Next, the dynamic solution also iterates on each module produced and considers each rescheduling message that arrives. On a rescheduling message, a decision is made whether or not to reschedule. This depends on the time of receipt; magnitude of rescheduling; holding and tardiness cost; and the status of the production. For advancements, it is considered to what degree a production time can be reduced via a predetermined maximum advancement factor.

7.5 RESULTS OF SIMULATION

The simulation is based upon the assembly of the a product of VDL ETG. The product structure, component prices, leadtime and move rate are identical to the real situation at VDL ETG. Supply and demand uncertainty are based upon VDL ETG averages as described in the data analysis (chapter 6). Lot sizing decisions have not been incorporated into this decision; this could be done via an EOQ model. The lot sizing decision does not influence the trade-off between a dynamic and static solution though. Due to the limited time available within this project, this decision has not been included.

The simulation length used is 3 years with a realistic move rate; a tradeoff to reduce noise and keep the computation time short. A comparison of the cost is provided in Figure 34 below.

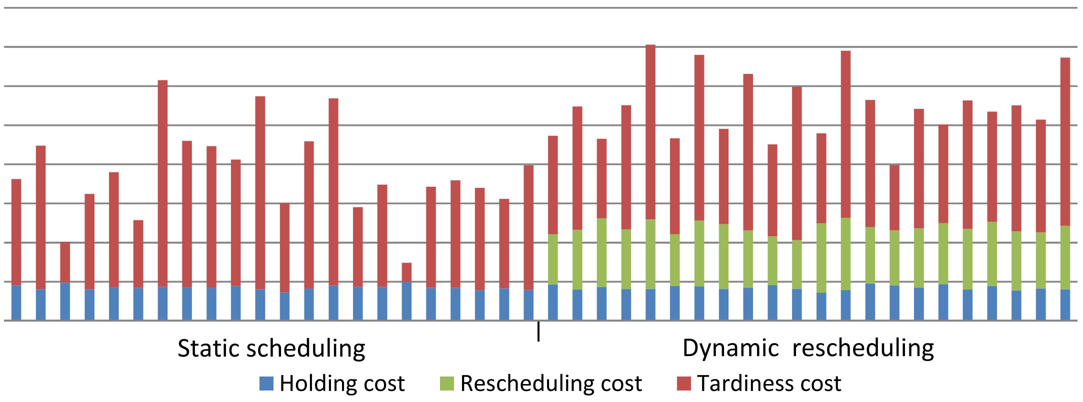


Figure 34: Comparison of costs of (re)scheduling methods

This comparison shows the static method to be much cheaper than the dynamic method. This is probably due to the low module price, which makes inventory holding rather cheap compared to rescheduling. Furthermore, the trade-off between tardiness and holding cost will drive a very high inventory level. Finally, the high supply uncertainty, to which a dynamic solution does buffer, but not reschedule, drives the difference in costs.

A better comparison could be made when actual component uncertainty (leadtime and yield) is added instead of the standardized (uncorrelated) values.

7.6 SENSITIVITY TESTS

Sensitivity analysis on the product discussed in the previous section, would be too time-intensive for the scope of this project. Therefore, a sensitivity analysis has been performed with a module consisting of seven components. For each of the stochastic variables, 50 simulations on a low and 50 on a high value of each dependent variable are performed. For the deterministic variables, 10 simulations were used with 8 runs, with an identical stochastic sample per 8 runs. The stochastic effect distorts the results of the comparisons at the variables as shown in Table 2 below; the 5% and 95% quantiles of 50 runs are very broad. A representation of quantiles is chosen instead of confidence intervals, because underlying distributions are not known, and normality is not evident.

Table 2: Sensitivity analysis on stochastic variables, 5%, 50% and 95 quantiles provided on 50 runs.

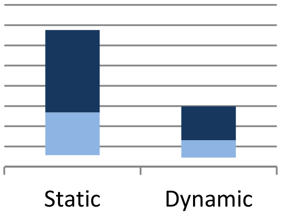
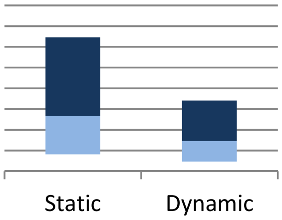
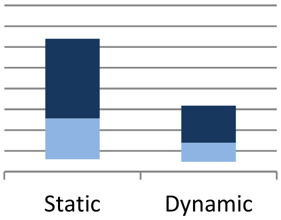
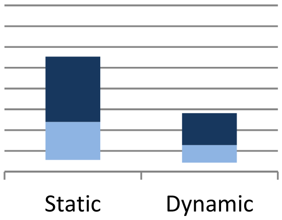
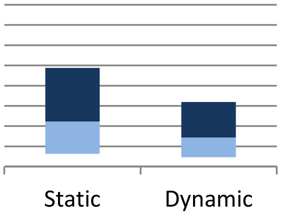
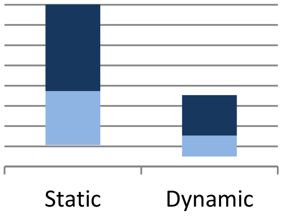
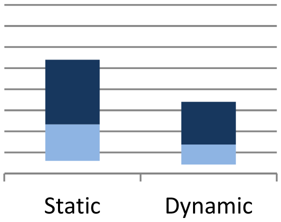
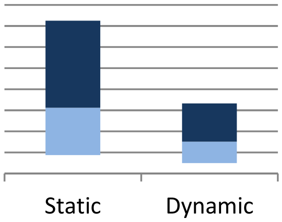
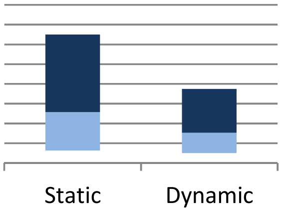
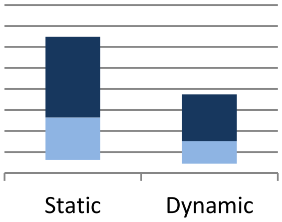
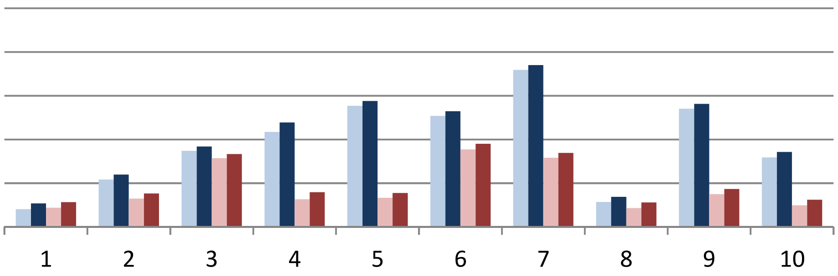
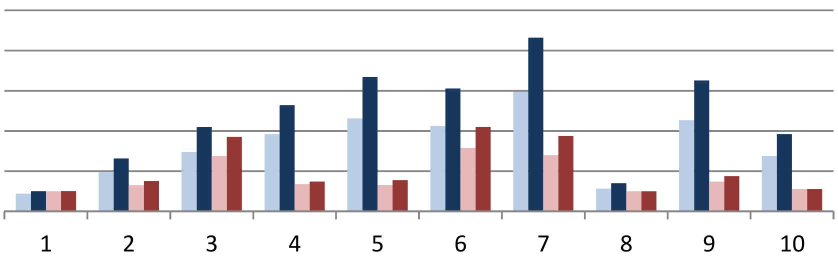
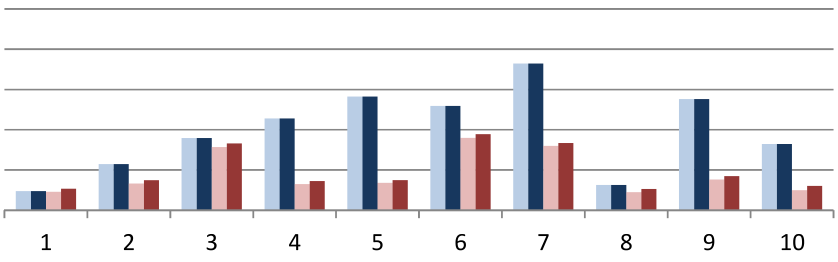
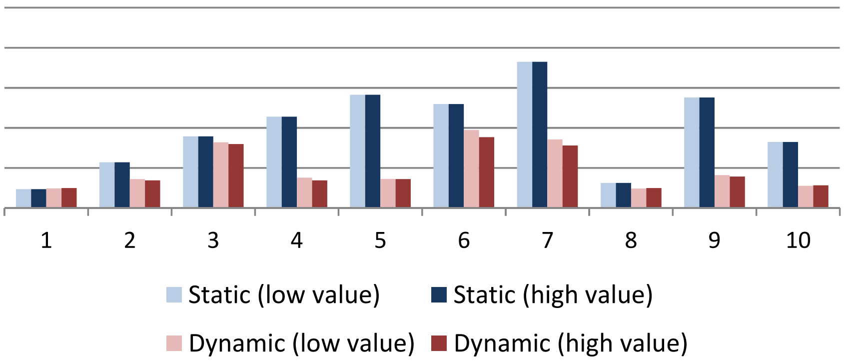
	Low (few)	High (many)
Leadtime variance		
Yield		
Rescheduling magnitude		
Rescheduling occurrence		
Time between message arrival and original delivery date		

Table 3: Sensitivity analysis on deterministic variables. For every combination, ten runs were performed. The same runs correspond with an identical stochastic sample.

	Runs
Holding cost rate	
Tardiness cost	
Rescheduling cost	
Maximum advancement factor	

A change in the stochastic variables has a major impact on the difference in costs of both methods; changes in the deterministic variables only show minor differences (Table 3). Tardiness cost shows the strongest effect, but this has to do with low component prices compared to the high (absolute) tardiness cost. When component prices increase, the impact of holding costs increases as well. The impact of differences in rescheduling cost and the advancement factor are zero for the static method, which is in line with intuition. It is important to denote that the estimations for the stochastic variables are less accurate than the measures on the deterministic variables, as mentioned in chapter 6.

All sensitivity tests show a strong favor for the dynamic method, this is due to the reduced product complexity that affects the supply uncertainty. The largest component of total cost is tardiness cost, the dynamic method cannot deal well with supply side uncertainty, and therefore a reduction of this uncertainty (due to a simple product structure) leads to a decrease in tardiness cost. This is in line with the sensitivity on leadtime deviation on the stochastic method, but not on the deterministic method. A better comparison could be made when a convolution of the underlying leadtime and yield uncertainty would be calculated, but this is time-intensive, and therefore not used. The insensitivity of the static method on leadtime variance is hard to explain (7.5 shows different results). One possible explanation is that the buffering against demand side uncertainty is that high, that minor differences at the supply side uncertainty do not influence the performance due to safety time already present.

8 CONCLUSION

In this chapter we reflect upon the scientific contribution, the methods we have used in the data analysis, and modeling part. Furthermore, we discuss the assumptions we have made. We conclude with recommendations to VDL ETG.

8.1 SCIENTIFIC CONTRIBUTION

The contribution to literature on (re)scheduling is twofold. First, it discusses a static scheduling method that incorporates both supply and demand side uncertainty in the safety time calculation at end-items and provides a method to iteratively calculate it for lower level items. Second, it makes an explicit, quantitative comparison between static scheduling and dynamic rescheduling in an ATO/MTO environment subject to delivery date uncertainty.

Algorithms that could calculate the safety time for lower component levels quicker would be a valuable extension to the results found in this thesis. The computational burden restricts the use for complex product structures.

8.2 DISCUSSION

An important part of the data analysis is based upon the rescheduling data from a BaaN eventlog. We have verified the use of that particular input field; order managers use it in most occasions to denote the actual new delivery date. However, for some product chains, it is used differently. This results in a measurement error in the delivery date shifts, which could influence the results. Next to the data on rescheduling, the data on rescheduling cost is estimated using interviews and work observations. Although triangulation has been used to maximize validity, much more work observations are needed to get statistical confidence. The limited time window of this project restricted this.

The assumptions on constant opportunity cost of capital and obsolescence are close to the reality. Cost of capital does not vary much and when modules are released for volume, obsolescence risk is mainly related to the amount of inventory and not to the product life cycle. The order quantities are however not predetermined (A2); planners make lot sizing decisions. This is though explicitly removed from the scope to focus on safety stock and safety time, which are independent of the lot sizing decision.

The modeling simplifications B2 and B3 hold in the VDL ETG environment; (the most problematic part of) yield is observed when problems are discovered at assembly. Other sources of yield result in leadtime differences, as new products can be manufactured more quickly at Parts or at suppliers. The assumptions B1 and B4 do not hold (yield is often dependent on batch sizes), but this complicated the modeling as the lot-sizing decision is excluded. Assumption B4: uncorrelated leadtime deviation, yield, and delivery date uncertainty is unrealistic. Leadtime variance is typically supplier-related, not only component-related. Furthermore, rescheduling messages are customer-related, not only module-related. Using all different distributions for components and covariances would take more time than is available in this project. However, the simulation tool is designed in a way that it could deal with these covariances, but it would take more than a week to obtain all covariances within a product; some hours to put it in the simulation tool; and several days to run the simulation.

Finally, the planning problem has an integral nature. This thesis provides tools to solve a part of the problem, but it is essential to keep the entire picture in mind. Where leadtime variance is much larger than delivery date uncertainty, a static scheduling method might be the best way to integrate dealing with uncertainty from both supply and demand side via safety time. A strong reduction in this uncertainty results in an environment where dynamic rescheduling is more efficient. The improvement of the supply chain via a series of (thesis) projects is good way to address the various challenges, but a proper integration of current results in coming projects seems essential to obtain major, lasting benefits for VDL ETG.

8.3 RECOMMENDATIONS TO VDL ETG

This thesis project aimed to serve two goals; to extend knowledge on rescheduling policies and to provide VDL ETG with recommendations to improve their rescheduling methods and subsequently reduce costs.

- First, we recommend VDL ETG to use the rescheduling delay directive to support the decision-making on received order delays. This tool provides planners with a reference level. Better rescheduling decisions could reduce holding and rescheduling cost.
- Next, the rescheduling tool developed could be used to compare static and dynamic (re)scheduling methods for various chains in estimating the desired inventory levels. However, as the next project within the roadmap explicitly investigates the safety stocks and safety times needed in different echelons, it is not recommended to alter safety times already, based on the results of this thesis.
- Within this thesis, we have mainly studied the trade-off between a static and a dynamic method based upon efficiency (cost). Although this is an important parameter, the increase in risk due to higher safety times or the reduction in reaction speed are also important aspects of the choice. One should study the tradeoff between this risk and the cost reductions before deciding upon the method.
- Static scheduling methods perform better in chains where rescheduling messages have a small magnitude, product structures are complex, and prices are rather low. Dynamic rescheduling can deal better with expensive products, simple product structures and big rescheduling shifts. Furthermore, dynamic rescheduling performs better when messages are received earlier.
- Due to the different performance on different supply chain characteristics, and the different nature of the various product groups of VDL ETG, a different implementation for different product groups is recommended.

Next to the recommendations on the optimal rescheduling method, the following recommendations are made to improve overall performance of the supply chain.

- This thesis is for a major part based upon rescheduling data from an eventlog. Although we know that it is a rather good approximation, it could valuable to collect the actual rescheduling data and subsequently improve the accuracy of the rescheduling methods.
- The supply chain uncertainty is high, and this leads to high buffers in components. Reduction of this uncertainty reduces the cost of any rescheduling method.
- Evaluation of the rescheduling delay directive on rescheduling should be done yearly to adjust for changes in holding costs, rescheduling cost and rescheduling occurrence.

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APPENDIX A: GLOSSARY

English term	Dutch term	Use within the scope of this project
CLIP	CLIP	Committed line item performance: measure of due date reliability used within VDL ETG; it measures the percentage of line items on the requested date
Components	Componenten	Part of module or component
Demand plan	Vraagplan	Delivery moments and quantity of modules required over a certain planning horizon
Director order	Directie order	Order not committed by a customer, initiated upon management approval to reduce lead times
ECLIP	ECLIP	Earlier than or at CLIP; identical to CLIP but includes all line items that are delivered earlier
Rescheduling tool	Herplanningstool	An Access-environment where an SQL-driven form can be filled out to initiate rescheduling through a link with the BaaN database
Integral planning	Integrale planning	Planning unit that coordinates goods flow within VDL ETG Acht and releases orders
Master production schedule (production plan)	Hoofdproductieplan (HPP) (productieplan)	Master production schedule as used within the MRP II framework; states the required manufacturing and procurement orders in time
Module	Module	End-item of VDL ETG's assembly operations, often a part of a product of the customer
New Product Introduction (NPI)	New Product Introduction (NPI)	Product chains that are not yet standardized (also called projects)
Order management	Order management	Unit that handles customer communication for release-for-volume chains
Operational procurement	Verwerving	Unit that handles the procurement of components bought at suppliers
Parts	Parts	The Parts manufacturing unit at VDL ETG Acht, includes also the 'Plaat' manufacturing unit unless otherwise mentioned
Planning Parts	Planning Parts	Unit that is responsible for the job-shop planning of Parts
Production Office	Productiebureau	Organizational entity including the integral planning and order management units
Production assistant	Productie-assistent	Person that initiates the order picking and releases orders towards the assembly at Systems
Production plan	Productieplan	See: master production schedule
Production order (PO)	Production order	Order stating a delivery date and quantity of a module or component
Project	Project	Financial accounting entity; every order and all costs are allocated to projects (one project can cover multiple orders)
Release for volume (R4V)	Release for volume	Production chains that are standardized (also called programs)
Repair Spare parts & Services (RS&S)	Repair Spare parts & Services	Unit that takes care of the planning of the reverse logistics and spare parts manufacturing
Systems	Systems	The assembly unit at VDL ETG Acht
VDL ETG	VDL ETG	VDL ETG Acht, the main manufacturing plant of the VDL Enabling Technologies Group, unless the entire group is explicitly mentioned

APPENDIX B: LIST OF SYMBOLS USED

In Table 4 below, the symbols used in this document are stated and explained.

Table 4: List of symbols used in this document

Symbol	Unit of measure	Explanation
D	Demand in products	Demand with an expected delivery date
dc	Delivery date change in days	Delivery date change in days
γ	Process output/input	Yield rate
h	Euro per time period	Holding cost rate for the investment in inventory per time period
K	Euro per setup (order)	Setup cost
L	Time in days	Lead time
p_i	Euro per time period	Penalty cost for tardiness (per time period) for job i
Q	# products	Amount ordered
S	Days/product	Schedule stability in absolute average difference in start and completion times

APPENDIX C: STATEMENT OF ASSUMPTIONS

The following assumptions are made within this project. A distinction is made for assumptions throughout the entire project and assumptions in the modeling part.

Assumptions within scope of the project:

A1. The opportunity cost of capital is constant over time;
Although the actual opportunity cost of capital fluctuates, it is hard to include this fluctuation and management decisions within VDL ETG are based upon a fixed, average opportunity cost of capital.

A2. Order quantities are predetermined; and
Although order quantities can be chosen by integral planners, it is assumed predetermined in the scope of this project.

A3. Obsolescence depends is only and completely related to the investment in inventory.
Although the risk of obsolescence normally has an exposure of the full value of the obsolete components, this risk is often mitigated as the loss is passed on to customers.

Assumptions in the modeling:

B1. Yield can be modeled as a percentage of the input;
In some processes at VDL ETG, the yield is one or two products per batch, independent of the batch size. Modeling as a percentage can represent this fairly well though, as batch sizes are predetermined.

B2. Yield is observed when a component is taken from the inventory;
Sometimes yield is observed earlier, but this would be the worst case scenario and does also happen at VDL ETG. Therefore this point in time is used.

B3. Capacity restrictions are negligible; and
This assumption holds for Systems, but Parts does have capacity restrictions. In the initial constraints capacity will not be included, but after the modeling, it will be verified whether proposed solutions are feasible for Parts.

B4. All sources of uncertainty are uncorrelated.
This states that leadtime variances, yield and rescheduling messages are uncorrelated to each other as well as over different modules.

APPENDIX D: DISTRIBUTION FITTING PROCEDURE

Below the SPSS syntax is stated, which is used to fit the data to probability distributions.

```
IF  (DelDateChange>0) PosDelDateChange=DelDateChange.
IF  (DelDateChange<0) NegDelDateChange=-DelDateChange.
IF  (InternalDDChange>0) PosInternalDDChange=InternalDDChange.
IF  (InternalDDChange<0) NegInternalDDChange=-InternalDDChange.
IF  (LTparts<-50) LTparts=$sysmis.
IF  (LTparts>50) LTparts=$sysmis.
IF  (LTsuppliers<-50) LTsuppliers=$sysmis.
IF  (LTsuppliers>50) LTsuppliers=$sysmis.
COMPUTE LTpartsShift = LTparts+51.
COMPUTE LTsuppliersShift = LTsuppliers+51.
COMPUTE PosDelDateChange=TRUNC((PosDelDateChange+6)/7,1).
COMPUTE NegDelDateChange=TRUNC((NegDelDateChange+6)/7,1).
COMPUTE PosInternalDDChange=TRUNC((PosInternalDDChange+6)/7,1).
COMPUTE NegInternalDDChange=TRUNC((NegInternalDDChange+6)/7,1).
COMPUTE DifTNewWeek=TRUNC((DifTNew+6)/7,1).
COMPUTE DifTOldWeek=TRUNC((DifTOld+6)/7,1).
COMPUTE DelDateChange=DelDateChange/7.
EXECUTE.

FREQUENCIES VARIABLES=DelDateChange PosDelDateChange NegDelDateChange DifTNewWeek
DifTOldWeek NumOfReschedules InternalDDChange PosInternalDDChange NegInternalDDChange
LTparts LTsuppliers
  /NTILES=4
  /STATISTICS=STDDEV VARIANCE MEAN MEDIAN MODE SUM SKEWNESS SESKEW KURTOSIS SEKURT
  /HISTOGRAM NORMAL
  /ORDER=ANALYSIS.

NPAR TESTS
  /K-S(NORMAL)=DelDateChange PosDelDateChange NegDelDateChange DifTNew DifTOld
NumOfReschedules InternalDDChange PosInternalDDChange NegInternalDDChange
  /K-S(UNIFORM)=DelDateChange PosDelDateChange NegDelDateChange DifTNew DifTOld
NumOfReschedules InternalDDChange PosInternalDDChange NegInternalDDChange
  /K-S(POISSON)=DelDateChange PosDelDateChange NegDelDateChange DifTNew DifTOld
NumOfReschedules InternalDDChange PosInternalDDChange NegInternalDDChange
  /K-S(EXPONENTIAL)=DelDateChange PosDelDateChange NegDelDateChange DifTNew DifTOld
NumOfReschedules InternalDDChange PosInternalDDChange NegInternalDDChange
  /MISSING ANALYSIS.
```

```
PPLOT
  /VARIABLES=LTsuppliersShift LTpartsShift
  /NOLOG
  /NOSTANDARDIZE
  /TYPE=Q-Q
  /FRACTION=BLOM
  /TIES=MEAN
  /DIST=LOGISTIC.

PPLOT
  /VARIABLES=DifTOldWeek
  /NOLOG
  /NOSTANDARDIZE
  /TYPE=Q-Q
  /FRACTION=BLOM
  /TIES=MEAN
  /DIST=EXP.

PPLOT
  /VARIABLES= PosDelDateChange NegDelDateChange PosInternalDDChange NegInternalDDChange
DifTNewWeek
  /NOSTANDARDIZE
  /TYPE=Q-Q
  /FRACTION=BLOM
  /TIES=MEAN
  /DIST=LNORMAL.

IF  (PosDelDateChange>0) TestDDChange=TRUNC((TRUNC((RV.LNORMAL(3.22,0.87)*7),1)-6)/7,1)+1.
IF  (NegDelDateChange>0) TestDDChange=-TRUNC((TRUNC((RV.LNORMAL(2.25,0.80)*7),1)-6)/7,1)-1.
IF  (PosInternalDDChange>0) TestIntDDChange=TRUNC((TRUNC((RV.LNORMAL(3.33,0.91)*7),1)-
6)/7,1)+1.
IF  (NegInternalDDChange>0) TestIntDDChange=-TRUNC((TRUNC((RV.LNORMAL(2.25,0.81)*7),1)-
6)/7,1)-1.
COMPUTE TestDTO=TRUNC(RV.EXP(0.12)+1,1).
COMPUTE TestDTN=TRUNC(RV.LNORMAL(7.22,0.833)+1,1).
COMPUTE TestLTparts = TRUNC(RV.LOGISTIC(47.79,5.214),1)-50.
COMPUTE TestLTsuppliers = TRUNC(RV.LOGISTIC(48.35,4.078),1)-50.
EXECUTE.
```

APPENDIX E: PROOF OF PROBABILITY DENSITY DIFFERENCE FUNCTION

With X a continuous random variable, a probability density function, $f_x(x)$, needs to satisfy two properties (Taboga, 2010), being:

1. Non-negativity: $f_x(x) \geq 0 \, for \, any \, x \, \epsilon \, \mathbb{R}$
2. Integral over $\mathbb{R}$ equals 1: $\int_{-\infty}^{\infty} f_x(x)dx = 1$

The difference function is defined as follows:

$$f_{diff}(z) = \int_{-\infty}^{\infty} f_{DD}(x) f_{LT}(x-z)dx$$

Given that f_{DD} and f_{LT} are both probability density functions, the following holds:

$$f_{DD}(x) \geq 0 \; and \; f_{LT}(x) \geq 0 \; for \; any \; x \, \epsilon \, \mathbb{R}$$

Subsequently,

$$f_{DD}(x) f_{LT}(x-z) \geq 0 \; for \; any \; x, z \, \epsilon \, \mathbb{R}$$

Thus:

$$f_{diff}(z) \geq 0 \; for \; any \; z \, \epsilon \, \mathbb{R}$$

This proves that the first property holds.

$$F_{diff}(\infty) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f_{DD}(x) f_{LT}(x-z)dx\,dz$$

Using the convolution property (Tonelli's theorem), this equals:

$$F_{diff}(\infty) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f_{DD}(x) f_{LT}(x-z)dz\,dx$$

As f_{DD} does not depend on z, this can be rewritten to:

$$F_{diff}(\infty) = \int_{-\infty}^{\infty} f_{DD}(x) \int_{-\infty}^{\infty} f_{LT}(x-z)dz\,dx$$

Introducing u as x-z gives:

$$u = x - z$$

$$F_{diff}(\infty) = \int_{-\infty}^{\infty} f_{DD}(x) * - \int_{-\infty}^{\infty} -f_{LT}(u)du\,dx$$

For any given $x \in (-\infty, \infty)$, the integral of u would result in 1, thus:

$$F_{diff}(\infty) = \int_{-\infty}^{\infty} f_{DD}(x) * 1\,dx$$

$$F_{diff}(\infty) = \int_{-\infty}^{\infty} f_{DD}(x)\,dx = 1$$

This shows that the second property applies as well, and that f_{diff} subsequently is a probability density function.

■