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Eindhoven University of Technology, February 2015

Modeling the trade-off between outcome- and process-performance of a human scheduler

by

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BSc. Industrial Engineering and Innovation Sciences – TU/e 2013

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In partial fulfillment of the requirements for the degree of

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in Operations Management and Logistics

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ABSTRACT

In production planning and scheduling, human decision makers are ultimately responsible for the efficiency of a schedule. Literature on production scheduling is known for its neatness and optimal solutions in the planned process, whereas the efficiency of the planning process in itself is still far from optimal. The contribution of this report is the explicit definition of the trade-off between efficiency of the planned process (outcome performance), and efficiency of the process by which a schedule is generate (process performance). Both types of performance are combined in one quantitative simulation model, showing that substantial cost savings can be made by choosing the appropriate review frequency. This thesis provides profound recommendations, and a new angle on scheduling efficiency with a broad application in (production-) planning and scheduling environments.

MANAGEMENT SUMMARY

This report is the result of a master thesis project, executed at The Dow Chemical Company, Terneuzen. The scope of the research consists of the scheduling department responsible for the polyol integrated supply chain. Polyol is manufactured at Dow's plant in Terneuzen through a batch process on multiple reactors.

PROBLEM STATEMENT

Within the BPSC in Terneuzen, daily production scheduling activities are performed by a group of 50+ schedulers for different Dow businesses. Historically, these businesses have developed their own scheduling methodologies and procedures, supported by customized and unique scheduling support systems based on Excel. The centralization of scheduling activities within the BPSC Terneuzen provides the opportunity to harmonize scheduling procedures within the BPSC, across businesses. With the implementation of the SAP ECC system there is the opportunity to streamline and optimize scheduling processes across businesses, including a higher use of scheduling capabilities provided by the ECC system compared to scheduling solutions used outside ECC. This optimization will drive to lower cost of transition of schedulers between businesses (shorter training period), easier backup solutions and better decision taking based on the integrated ECC systems, and also to a higher efficiency and value of the scheduling activities.

BUSINESS MODEL

Before jumping into standardization of the current work processes, this business model defines both scheduling performance, and a schedulers' task. Based on interviews and observations within scope, we have found that the especially the bulk polyol schedulers face different stakeholders, having different opinions on the definition of scheduling performance, scheduling responsibilities, and the way in which the scheduling tasks is supposed to be executed. Generally, two categories can be distinguished. On one hand are the Dow employees, who are responsible for the efficiency of the production process. These stakeholders value the so-called *outcome performance* (which refers to the quality of the schedule), and want a scheduler to update their schedule as frequently as needed to meet as many orders as possible on the requested delivery dates. Performance indicators valued by these employees are the service level (% of orders delivered on time) and the inventory holding costs (or meeting the end-of-month inventory target). On the other hand are the BPSC employees, who are responsible for the efficiency of the process by which schedules are created (*process performance*). These schedulers value steady plans, created along standardized, and efficient scheduling methods. Performance indicators which are perceived to be most important by these employees are the reliability and timeliness of the initial schedule release.

The business model drawn from this situation description is depicted in Figure 1, showing that the focus on either outcome or process performance is driven by the scheduler's review frequency. It should be noted that Figure 1 considers a trade-off, implying that gaining quality on outcome performance involves losing quality on process performance (and vice versa). The remainder of this research has focused on optimizing this trade-off.

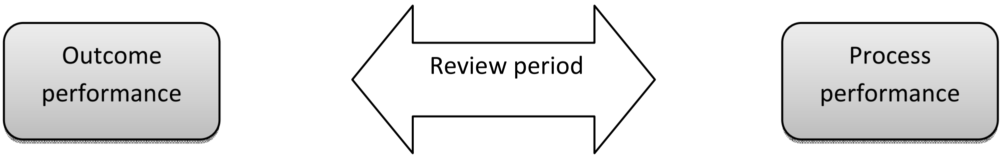


FIGURE 1: THE TRADE-OFF BETWEEN OUTCOME AND PROCESS PERFORMANCE

In the current situation, schedulers spend a lot of time providing information to stakeholders and answering questions. The importance of this role (referred to as the *informational role*), was also underlined by the fact that all employees indicate the quality of communication as the most important objective of a scheduler. The task of a scheduler at Dow is exception-driven. The most frequently occurring exception is an exception on ATP (Available to Promise) order acceptance, which causes schedulers to update their plan frequently.

OPTIMIZATION OF THE BUSINESS MODEL

The trade-off between process and outcome performance of the polyol schedulers is quantified and analyzed by use of two independent simulation models. The results from the model for outcome performance, using a make-to-stock-policy (left graph in Figure 2), show that decreasing the review period is beneficial, since a higher percentage of demand can be known and the demand pattern through the month is followed more accurately. The demand pattern follows a seasonal pattern through the month. Most demand (70%) of demand occurs in the first two weeks of the month, as a result of the currently used payment terms.

The opposite conclusion arises, based on the model for process performance (right graph in Figure2). This model shows that increasing the review period is beneficial, while this lowers the total workload for a scheduler and the relative amount of time spent in the informational role.

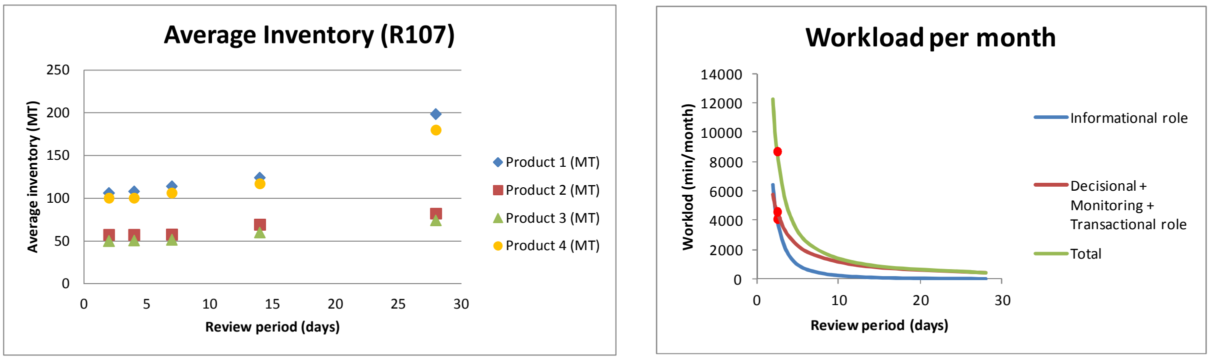


FIGURE 2: LEFT, THE AVERAGE INVENTORY AS A FUNCTION OF THE REVIEW PERIOD. RIGHT, THE WORKLOAD OF A SCHEDULER AS A FUNCTION OF THE REVIEW PERIOD.

The findings from these simulation models thus confirm the trade-off between process and outcome performance and quantify the effect of changing the review period on both. Other conclusions that can be drawn from the individual models are the fact that outcome performance has an upper limit for higher review frequencies (i.e. it cannot be increased more by increasing the review period more). From the perspective of process performance, we have found that it is more efficient to decrease the review frequency than to look for better support in the scheduling task. This is especially true for a short review periods, which are currently used at Dow.

For the optimization of this business model, we combine both simulation models into one overall cost function, leading to the graph in Figure 3. It should be noted that this graph only represents an example for a single reactor. The results for all other reactors are attached in Appendix L of this thesis. The red dot in Figure 3 indicates the current review period of approximately 2 days, showing that this review frequency is far above the optimal level. The graph shows the potential benefit of the optimizing the business function, taking into account both types of performance for scheduling.

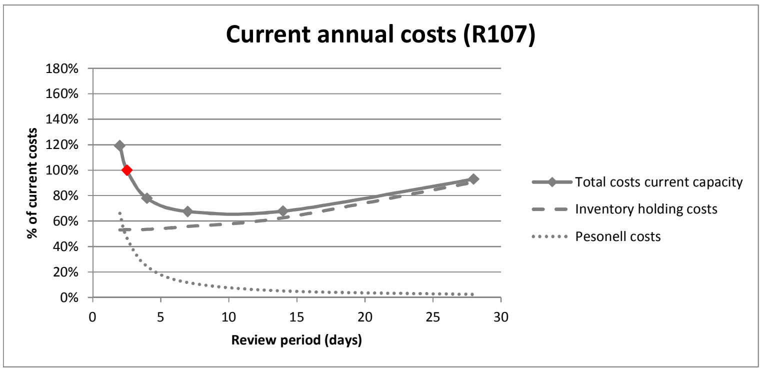


FIGURE 3: OPTIMIZATION OF THE COST FUNCTION FOR THE TRADE-OFF BETWEEN OUTCOME AND PROCESS PERFORMANCE.

Other results that have been found through interviews and the simulation model are the fact that the inventory capacity for polyol at Dow is very limited. The simulation results show that inventory is too limited to schedule, using a make-to-stock policy with a 95% service level, even in case the review period is very short. As a result, a lot of orders cannot be delivered on the requested delivery date. In order to increase the service level to external customers, Customer Sales Representatives (CSRs) work around the ATP order acceptance function. This causes schedulers to update their schedule on a high frequency, see Figure 4. Additionally, the usage of end-of-month inventory targets forces the opposite behavior of the inventory minimizing strategy for a fixed service level. The fact that schedulers decrease their inventory before the end of the month, results in a low service level in the beginning of next month, were demand is high.

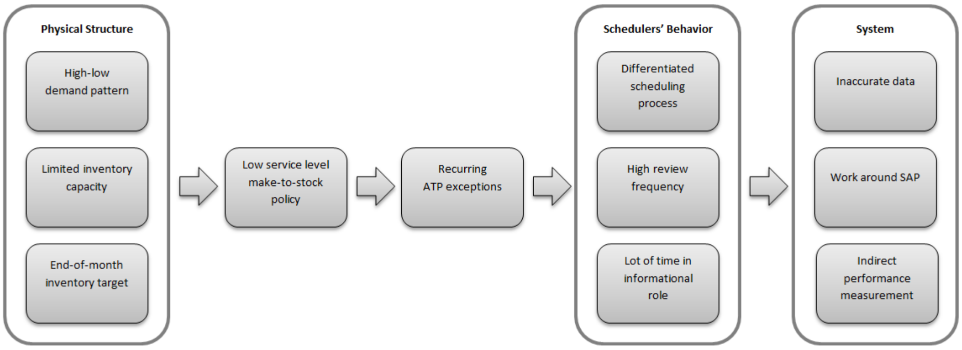


FIGURE 4: THE RELATION BETWEEN LIMITED STORAGE CAPACITY, ATP EXCEPTIONS AND A HIGH REVIEW FREQUENCY.

The last part of this thesis has looked into whether it is beneficial to increase storage capacity by use of additional hired storage containers for a fixed payment per day. The result of this analysis is shown in the graph in Figure 5, which again shows an example for a single reactor.

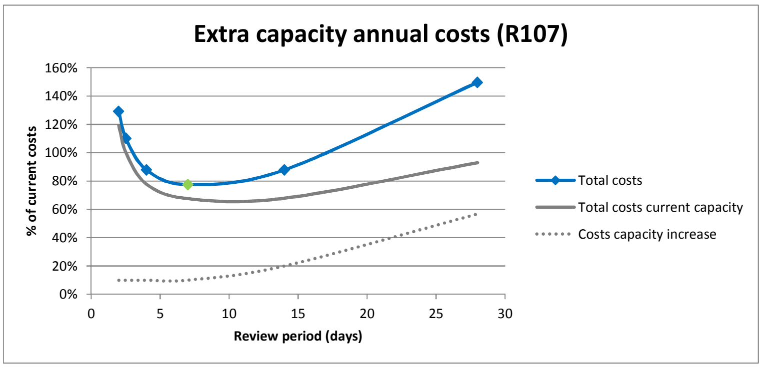


FIGURE 5: THE COST FUNCTION OF THE BUSINESS CASE, INCLUDING THE COSTS OF CAPACITY INCREASE.

Similar results for the other reactors have shown that the capacity increase is profitable for reactors 103, 104, 105, 107, 110, and the CPP reactor. For reactor 101 the capacity is already sufficient. For reactors 113, 114, and 115, the cost of capacity increase outweighs gains in scheduling performance. The expected gain of flattening the seasonal pattern in demand (by changing the payment terms) is equal to a rough estimate of 20%.

If we follow the line of reasoning from Figure 4 once again, increasing the inventory capacity where needed, spreading the demand pattern and/or reporting average inventories instead of end-of-month targets, enables opportunities to increase the service level for bulk polyol, while simultaneously scheduling according to a make-to-stock-policy with dynamic re-order levels. An increase in service level eliminates the need for a high number of ATP exceptions, which subsequently creates opportunities to change a schedulers' behavior: The scheduling process can be consolidated, the review frequency can be decreased, and schedulers can spend less time communicating to stakeholders. The change in review period is associated with an expected saving in overall costs for the business function, equal to 26%. As a result, the SAP system can be used, data can be tracked, and performance can be directly measured. Moreover, backing-up colleagues becomes easier and schedulers can be transferred across business.

LIST OF RECOMMENDATIONS FOR BPSC, THE DOW CHEMICAL COMPANY

- *Acknowledge the trade-off between process and outcome performance for the scheduling function*
- *Increase storage capacity for bulk polyol*
- *Reconsider the end-of-next-month payment terms, and monitor average inventory instead of end-of-month inventory*
- *Increase the service level for bulk polyol, while using a make-to-stock policy, and observing ATP agreements more strictly*
- *Decrease the review frequency for scheduling*
- *If the inventory capacity is not increased, then consider ATP exceptions as the main responsibility of a scheduler instead of treating it as an exception*

PREFACE

This thesis is the result of a graduation project which I conducted at The Dow Chemical Company. I wrote this thesis in partial fulfillment of the requirements for the degree of Master of Science in Operations Management and Logistics at Eindhoven University of Technology. I am very grateful that I have been able to engage in this study and for all the opportunities it has given me, both within and outside the curriculum. Below I would like to express my gratitude to everybody who supported me through this thesis project, and though the past years of studies.

First of all, I would like to thank The Dow Chemical Company, for giving me the opportunity to write my thesis at one of the world leading chemical companies. The past six months have given interesting insights in the practice that belongs to everything I have learned previously. Special thanks to Martijn Veringa, for his guidance within Dow, for linking me to the right people for the right bits and pieces of information, and for his ever-present interest in updates on my project. My thanks also go to everybody who provided information or made time to discuss my findings. In particular I would like to thank the team of polyol schedulers and planners, Peter van Egerschot, and Geerten van Dijk.

Second, I want to express my gratitude to my supervisors at Eindhoven University of Technology. My first supervisor, Jan Fransoo, for always asking the right questions about the separate parts of my research and sending me in the right direction towards one overall story. I never left one of our meetings without an overflow of new ideas or research directions that could be further investigated. I would also like to thank Maxi Udenio, who always made time to discuss underlying details about my simulation model, and who taught me how to write less like 'one of you Dutch guys'. And third, thanks to Josette Gevers, for being my second supervisor with a total different angle on this research topic. Thanks for your insights on human behavior and helping me to explain my research methodologies better.

Last, I would like to express my gratitude to everybody most important to me personally. None of this would have been possible without my family and friends dragging me through good and bad times over the past eight years. Special thanks to my parents, for their loving, generous, (and financial) support. Congratulations on (almost) achieving the third MSc.-title within one family; you are halfway now! Special thanks to Arno, Bart, and Mark, for their sense of humor and relativistic ability. Good luck on the road to becoming TU/e graduate number four, five, and six within this family. Special thanks to my friends, who helped me making my student life the best I could have wished for. I have learned a lot from every single one of you and you have been always there for me when I needed anything. And last but most surely not least, Timo. Thank you for being my tower of strength and for giving me a lot more to look forward to.

Linda Tiemersma

Eindhoven, February 2015

Table of CONTENTS

1 INTRODUCTION

In this report we present the results of a master thesis. This thesis was executed as collaboration between Eindhoven University of Technology and The Dow Chemical Company (Dow hereafter). The aim of this report is twofold: first, to contribute to scientific knowledge on the human factor in planning and scheduling, and second, to enhance the overall performance of Dow's production scheduling department, within the scope of this research.

Production scheduling is an important function for the operational performance of a company's supply chain. A traditional view on the scheduling function, both in academia and in industry, is that the scheduling function consists of allocating tasks to resources in time. However, it is increasingly argued that there is a need for having an enlarged view on this scheduling function. Schedulers in real-life fulfill a diverse number of roles and are required to not only schedule, but be able to deal with exceptions, and identify and anticipate on problems. As a result, scheduling performance is currently measured by making use of a dispersion of performance metrics. These performance indicators can roughly be split into two categories, i.e. *outcome performance* (referring to the quality of the actual plan) and *process performance* (referring to the quality of the process in which plans are generated). Although decision support systems have focused on increasing outcome performance, there is a huge potential to increase the efficiency of the planning process itself (Berglund, Guinery, & Karltun (2011); Fransoo, Wäfler, & Wilson (2011); Larco, Fransoo, & Wiers (2012); MacCarthy & Wilson (2001); Snoo, Wezel, & Jorna (2011)).

In this report we contribute to science by explicitly defining and quantifying the trade-off between outcome performance and process performance of a human scheduler. Besides that, we design a model for optimizing the scheduling function (in particular the review frequency) based on an overall cost function. And last, we reflect the implications of our optimization results for the organizational structure, schedulers' responsibilities, the availability and use of IT, and business requirements.

Dow's starting point for this research was to improve scheduling performance by primarily standardizing processes and the use of IT. Although the latter seems to be the most straightforward goal, simply standardizing the current way of working overlooks possible bottlenecks and improvement directions. Therefore, this research contributes to an increase in Dow's scheduling performance by giving insight in the drivers for current processes and opportunities to consolidate and enhance the current way of working.

The outline of this paper is as follows: In chapter 2 and 3 we introduce the problem based on previous literature and a case description respectively. Chapter 4 defines the research outline, including the research questions and methodologies. An empirical investigation on performance indicators, scheduling tasks and drivers for the current processes at Dow, is discussed in Chapter 5. This chapter also defines boundaries and decision variables for two simulation models in Chapter 6. In this chapter we look into a model for outcome performance, a model for process performance and a value case for combining both perspectives. Chapter 7 looks into process redesign and organizational changes based on the found optimal solution in Chapter 6. A discussion of the results and limitations of the empirical investigation and simulation model are the focus of Chapter 7 whereas Chapter 8 lists conclusions and recommendations. Chapters 9, 10, and 11 can be used as a reference for literature, variables, definitions, and abbreviations, while reading this report.

2 LITERATURE REVIEW

From a scientific point of view, the goal of any research is to bridge a gap within the existing knowledge by analyzing testable explanations and predictions. In this case, we aim to contribute to the knowledge on behavioral operations in planning and scheduling. For a full literature review on behavior of human planners, we refer to Tiemersma (2014). In this report, we explore the root causes and effects of existing gap between theory and practice in this specific scientific field. In this chapter we summarize the findings from previous work, and outline the motivation and goals for our proposed research.

2.1 RELATED WORK

Planning and scheduling refer to the (manufacturing) management processes by which resources and production capacity are optimally allocated to meet demand. Planning and scheduling play an important role in performance enhancement in any operation. The process is characterized by complex trade-offs between competing priorities, factorial dependence, a large solution space, and a dynamic environment. The human decision makers, performing the planning or scheduling task are referred to as planners and schedulers.

From empirical findings in literature, it is clear that the contribution of planners and schedulers and the importance of understanding their roles and activities within an organization cannot be underestimated. Their core value is the ability to be flexible, to predict disturbances and to cope with uncertain dynamic environments. Even though both companies and researchers acknowledge the importance of these human decision makers, a gap exists between scientific knowledge or research literature and organizational practice in planning and scheduling (Berglund, Guinery, & Karltun (2011); Fransoo, Wäfler, & Wilson (2011)). Root causes for this gap, can be summarized in the following 4 main categories:

1. The complexity of the planning and scheduling task has increased over the past decades. However, there is relatively poor understanding what the implications are of increased task complexity in planning and scheduling operations (MacCarthy & Wilson (2001); McKay & Wiers (1999)).
2. Planning and scheduling have been analyzed from three fundamentally different viewpoints: i.e. technical, contextual, and cognitive dimensions. *Technical* factors are mostly analyzed from an axiomatic approach, in which the production planning problem is represented as a formal, usually mathematical model. *Context* focused research is the research on production control decisions from an empirical process perspective, organizational, or extra-organizational perspective. The *cognitive* view has the object to fully document the decision making process within the mind of the production planner (Buxey (1989); Cegarra J. (2008); Crawford & Wiers (2001) Fransoo, Wäfler, & Wilson (2011); MacCarthy & Liu (1993); Wezel & Jorna (2009)).
3. Planning and scheduling performance is often defined in terms of service levels, tardiness, or inventory and setup costs (*outcome performance*), however, objective measurement of the scheduling task in organizations must account for the process by which plans are generated and executed (*process performance*). A planners' task includes both the relatively systematic role of planning, as well as the complex role of exception management and rescheduling (Jackson, MacCarthy, & Wilson (2004); Neely (2005); Snoo, Wezel, & Jorna (2011)).
4. Generally spoken, operations management is a design-oriented science, focusing on relevant research, real-life problem solving and optimization of processes. Planning and scheduling uses a mathematical approach of problems on one hand, or field studies for specific situations on the other hand. In contrast, research in the field of behavioral sciences is generally more rigorous. Studies are often carried out in a laboratory, aiming to operate in controlled situations and with numerous individuals in order to make it possible to attain statistical significance. Both types of research have benefits and

limitations in applicability or generalizability (Hodgkinson & Rousseau (2009); Katok (2011); McKay & Wiers (1999)).

Besides the above defined research gap, we will use a study conducted by Larco, Fransoo, and Wiers (2012), who analyzed the same scope within the same organization, as a starting point for this research. Larco, et. al. (2012) studied this scheduling department, based on performance indicators as distinguished by De Snoo, Wezel, & Jorna (2011): i.e. *outcome performance* and *process performance* (see bullet 3 above), and in terms of the roles a taks can support, based on the classification found in Jackson, MacCarthy, and Wilson (2004): The *decisional role*, monitoring *role, informational role,* and *transactional role*. The decisional role includes scheduling and re-scheduling activities for a given horizion. The monitoring role complements the decsional role and consists of monitoring stocks, demand fluctuations, new customer orders and the execution of production orders so that the scheduler may asses the need for re-scheduling. The informational role includes providing and collecting information from external parties. Finally, the transactional role infovoles the follow-up of prescribed procedures of the firm, such as creating a delivery note. The detailed findings in Larco, Fransoo, and Wiers' (2012) paper will be part of chapters 5 and 6 of this thesis and are attached in Appendix F.

2.2 MOTIVATION AND GOALS

The motivation for research on the human factor in planning and scheduling is to increase the performance of the scheduling business function within organizations. The identification of the gap between theory and practice in Tiemersma (2014) has raised interesting starting points for future research on the human contribution to planning and scheduling efficiency. Great progress can be made by bringing together multiple perspectives while simultaneously combining different research methods and performance metrics. For the specific case of this report, these scientific goals can be summarized as:

1. The goal of this research is to define case-specific performance indicators for both process and outcome performance of a human scheduler. In order to design metrics for planning and scheduling performance, explicit research into performance criteria is needed.
2. The second aim is to explicitly define the trade-off between process and outcome performance and thereby contribute to a generalizable model for the optimization of the scheduling task. We aim at bringing together the mathematical and axiomatic approach from planning and scheduling theory and the more rigorous research style of behavioral science, this research will use field data to analyze schedulers' behavior.
3. The next goal within the research field referred to as 'behavior of human planners' is to optimize the use of decision support systems. An unanswered question is how to balance the human input and system output in order to increase usefulness and scheduling efficiency. Our goal is to analyze the discrepancy between system methods and actual human actions in a real-life situation. Besides that, we will look into a specific definition of the scheduler's task in a real life situation, drivers for the complexity of this task, and decision support systems can contribute to these tasks.

We will use these goals, combined with goals from the Case Description in Chapter 3 as basis for the Research Outline in Chapter 4.

3 CASE DESCRIPTION

The research as described in this thesis has been executed at the Business Process Service Center (BPSC) of The Dow Chemical Company, Terneuzen, The Netherlands. This chapter will give insights in how the collaboration between The Dow Chemical Company (Dow) and Eindhoven University of Technology (TU/e) came about. We will start this chapter with a problem statement, motivation and goals for this research, as have been defined by Dow before the start of the project. In order to address these questions more specifically, we need some insights in the processes at Dow. The remainder of this chapter will thus present the organizational processes in a nutshell, before summarizing practical goals. These goals, combined with the goals in Chapter 2 will guide as a stepping stone towards the research outline in Chapter 4.

3.1 PROBLEM STATEMENT

The opportunity- (or problem-) statement from Dow's point of view has been described in the project Charter (Shields, van Egerschot, & van Dijk, 2014):

"Within the BPSC in Terneuzen, daily production scheduling activities are performed by a group of 50+ schedulers for different Dow businesses. Historically, these businesses have developed their own scheduling methodologies and procedures, supported by customized and unique scheduling support systems based on Excel.

The centralization of scheduling activities within the BPSC Terneuzen provides the opportunity to harmonize scheduling procedures within the BPSC, across businesses. With the implementation of the SAP ECC system there is the opportunity to streamline and optimize scheduling processes across businesses, including a higher use of scheduling capabilities provided by the ECC system compared to scheduling solutions used outside ECC.

This optimization will drive to lower cost of transition of schedulers between businesses (shorter training period), easier backup solutions and better decision taking based on the integrated ECC systems, and also to a higher efficiency and value of the scheduling activities."

Before we specify what the above implies for the research goals, we throw a quick glance at Dow's processes and the scope of our research.

3.2 PROCESS DESCRIPTION

In this section we follow the as-is situation at Dow, in which this research is executed. Insight in the context of the scheduler will increase the understanding of the above mentioned goals and upcoming analyses. In this paragraph we will start with a wide scope and description of the company and its products, before zooming in on specific processes related to the scheduler's task.

3.2.1 THE DOW CHEMICAL COMPANY

Dow's integrated, market-driven, industry-leading portfolio of specialty chemical, advanced materials, agro sciences and plastics businesses delivers a broad range of technology-based products and solutions to customers in approximately 180 countries and in high growth sectors such as packaging, electronics, water, coatings and agriculture. In 2013, Dow had annual sales of more than $57 billion and employed approximately 53,000 people worldwide. The Company's more than 6,000 products are manufactured at 201 sites in 36 countries across the globe (Dow, 2014).

3.2.2 POLYOL INTEGRATED SUPPLY CHAIN

Part of the advanced materials produced at Dow, fall into the category referred to as 'Polyols'. This category of products and its manufacturing are the focus of our research. Dow is the world's largest producer of propylene oxide and polyether polyols, key components used in the production of polyurethanes. Dow's polyurethanes business offers one of the industries' broadest product lines for rigid foams, flexible foams, adhesives, sealants, coatings, elastomers, agrifibers and many other applications. The primary application for polyols is the manufacture of flexible or rigid polyurethane foams. Polyurethanes are used in nearly every aspect of daily life: furniture, bedding, seating of cars, soles, thermo insulation for refrigerators and buildings, wood substitutes, packaging, and coasting are only a few common examples of its use in all day life (Dow Answercenter, 2014).

Manufacturing of polyol at Dow's plant in Terneuzen is part of the polyol integrated supply chain as is shown in Figure 1.

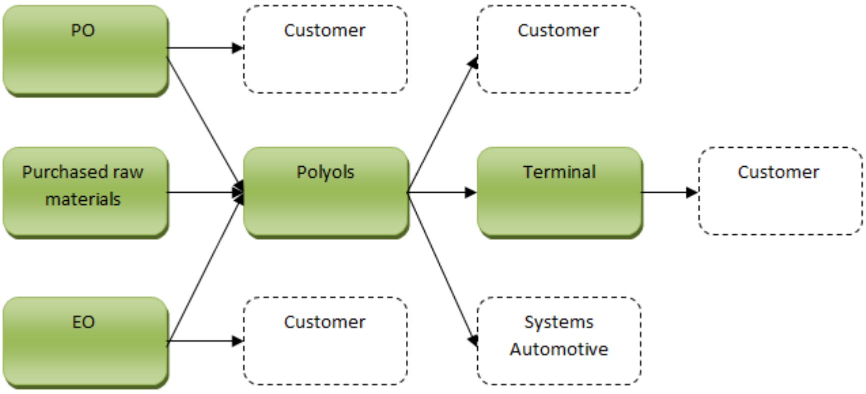


FIGURE 1: POLYOL INTEGRATED SUPPLY CHAIN, DOW TERNEUZEN.

As can be seen in Figure 1 above, polyol production uses three different sources of raw materials: PO (Propylene Oxide), EO (Ethylene Oxide) and other purchased raw materials. The production of PO is a continuous process at another Dow plant in Stade, Germany. PO is shipped from Stade to Terneuzen by boat and is kept in a number of storage tanks. EO, which is also produced in a continuous process, is produced at the plant in Terneuzen and is connected to the polyol plant with a pipeline. As we see in the Figure 1, PO and EO are also directly sold to third parties. The lead-time (i.e. time between placement of a customer order and delivery of the same order) of these products is equal to 2 days.

The polyol plant consists of 16 reactors and 6 finishing trains (see Attachment I). The first step of the production process takes place in a batch reactor. In these reactors, PO or EO reacts with an initiator. The reaction runs under elevated temperature and pressure and is strongly exothermic. When the reaction is complete, the polyol products are separated from byproducts and water by means of precipitation and distillation. The latter step is executed on a finishing train. Every reactor has a unique list of products (referred to as 'reactor grades' with a unique GMID-code) that can be manufactured on that specific reactor. The production of these reactor grades is also referred to as 'bulk production'. Bulk polyol is stored in inventory tanks. The bulk inventory can be sold directly to customers (lead-time: 2 days), used as a raw material for the systems automotive plant (outside of scope), or send to the terminal. The terminal is responsible for drumming of polyol. 'Drumming' refers to the process in which polyol is packaged in a drum or Intermediate Bulk Container (IBC). These filled drums or IBC's are directly sold to external parties with a lead time of 14 days. In case bulk polyol is sold without being drummed, it is loaded into containers or trucks and is shipped directly to the customer via road or sea transport.

3.2.3 BUSINESS PROCESS SERVICE CENTER

The production scheduling function within Dow, is part of the Business Process Service Center (BPSC). (At the time of this study, production scheduling was part of BPSC, and production planning was part of Dow. Starting on March 1st, 2015, production scheduling will be moved back to Dow). The BPSC is a fast growing independent organization providing tailor-made services to Dow businesses and joint ventures. The provided services are generally standardized processes including logistic services, administrative services, billing, procurement and production scheduling. The world-wide BPSC-network consists of offices in Midland, Sao Paulo, Mumbai, Shanghai, Tianjin and Terneuzen.

BPSC Terneuzen was founded as an independent part of Dow in 2012, and has grown to a center with over 500 employees since then. BPSC Terneuzen provides services to Dow businesses and joint ventures in Europe, the Middle-East and Africa (EMEA).

3.2.4 PRODUCTION SCHEDULING

Production schedulers at BPSC Terneuzen are responsible for sequencing and production order release within the day-to-day production plan, based on a monthly production forecast, inventory-targets, and/or actual demand. In order to meet the committed delivery dates or service levels, production schedulers decide on sequencing, production quantities run rates and inventory levels. Decisions are made, taking into account a differing set of constraints and variances. Table 1 shows an overview of the responsibilities per production scheduler. It should be noted that most tasks refer to steps in Figure 1 or reactors in Attachment 1.

TABLE 1: RESPONSIBILITIES PER SCHEDULER.

Schedulers			
Scheduler	Train(s)	Reactor(s)	Other
1	T4	R112, R113, R105 (initiators)	Off-spec
2		CPP	Blends
3	T1B	R106, R107, R110	CP1421
4	T5, T3	R112, R114, R115	Formulations
5	T1A, T2	R101, R102, R103, R109, R108, R111	
6			Raw Materials
7			PO
8			EO

First, we will have a look at the tasks in Table 1 that have not been mentioned before. Reactor 105 (scheduler 1) produces initiators for all the other reactors. Initiators are, like the name suggests, needed to initiate the reaction between PO, EO and other raw materials. The responsibilities listed in the 'other' column of Table 1 are the following: Off-spec is any finished good which does not meet the requirement or passes a best-before date. These goods need to be changed or sold under specified conditions. Blends and formulations are mixtures of different finished goods (mixed in containers or reactors respectively), which have to be mixed before they can be sold. CP1421 is a product which is produced at Dow Stade, but for which drumming is done in Terneuzen. As we see in Table 1, every scheduler has a specific task. And even though every scheduler has his/her back-up employee, this increases the difficulty of back-up in case of absence of one of the schedulers. This has been indicated in the problem statement as one of the main challenges Dow currently faces.

In Figure 2, an overview of the polyol scheduling process is shown. An enlarged version of the process map is attached in Appendix B. We walk through this process step by step. First, we see that an aggregate planning is made for the upcoming years, based on a demand forecast. With the aggregate planning as input, the production planners for PO, EO, and polyol are responsible for the capacity planning over a horizon from 3 months to 1 year. The CPP scheduler is responsible for the sequencing and release of production orders and orders for drumming, whereas for the other products drumming is sequenced at the drumming plant. Order acceptance is done by a Customer Sales Representative (CSR). Orders are accepted, using an Available-to-Promise (ATP) methodology. ATP is a business function that provides a response to customer order enquiries, based on resource availability. It generates available quantities of the requested product, and delivery due dates. Therefore, ATP supports order promising and fulfillment, aiming to manage demand and match it to production plans. ATP as it is used at Dow, accepts order in case stock is available or production is scheduled before the requested delivery date.

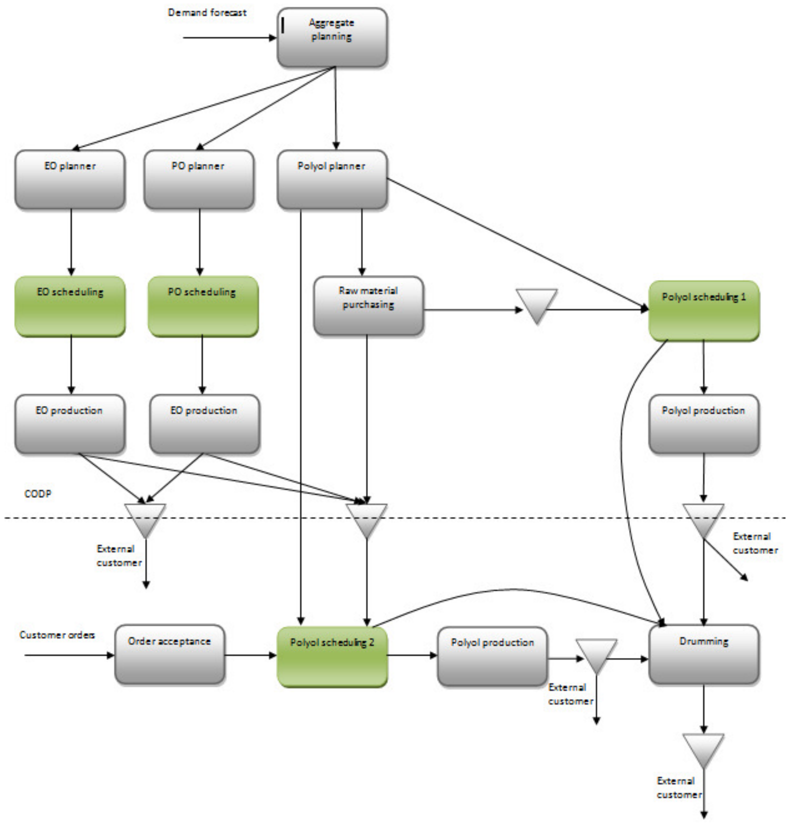


FIGURE 2: PRODUCTION PLANNING, SCHEDULING, AND PRODUCTION PROCESS, POLYOL, BPSC TERNEUZEN.

It should be noted that the picture above shows ‘Polyol Scheduling’ twice. This is the case, because employees do not give one unambiguous answer to the question whether bulk scheduling is done on a make-to-stock or a make-to-order basis. For some reactor grades schedulers argue to schedule on a make-to-stock basis; i.e. the production scheduler uses a policy for inventory control and releases production orders, based on the finished goods inventory level and demand forecast. On the other hand, polyol has a number of reactor grades which are produced on a make-to-order basis; i.e. the production scheduler keeps track of actual accepted demand, and releases production orders, based on this actual demand. The stock-point after production is in that case a buffer to maintain certain flexibility in the production dates. The dotted line, marked as CODP (Customer Order Decoupling Point), marks the split between the make-to-stock and the make-to-order process. In the current situation, schedulers decide individually which (combinations of) scheduling method(s) they use (per product).

Formulations, blends, and drumming of polyol are done on a make-to-order basis, based on order releases by a scheduler. Furthermore, PO, EO and Polyol can be transferred to the customer in containers, IBCs, or bulk via road, water, railways, or a pipeline, which are the responsibilities of the logistics department.

Production planners decide on end-of-month inventory target per stock point within the process in Figure 2. Appendix C shows an overview of which planner sets the inventory target per product per stock point.

3.3 SCOPE

Given the productions scheduling process at Dow, BPSC, Terneuzen, the boundaries of the scope of this research are drawn. The scope of this research will limit to the scheduling function and more specific to the team of schedulers for polyol, located in Terneuzen. Our scope thus consists of scheduler 1 to 8 in Table 1. The same scope is highlighted in green in Figures 1 and 2.

3.4 MOTIVATION AND GOALS

We recapture the motivation of this research as was stated in Dow's Project Charter (Shields, van Egerschot, van Dijk, 2014): The aim of this study is to seek for standardization in work-processes and use of IT systems (e.g. SAP), for the polyol-scheduling department at Dow, BPSC, Terneuzen. Logically, processes should be standardized in such a way that the value of scheduling activities is maximized and decisions are made in the best possible way. The standardization has the additional advantage of driving lower cost of transition of schedulers between businesses and easier back-up.

In summary, Dow wants to increase the schedulers' process performance without lowering outcome performance, which leads us to the following research goals:

1. The goal of this research is to define case-specific performance indicators for both process and outcome performance of a human scheduler. In order to define the value of scheduling activities, we need to define scheduling performance first.
2. The second practical goal of our research is to define what the drivers are for a differentiated scheduling process and which (sub-)tasks can be defined and consolidated. Every (sub-) task has different performance indicators and different performance maximizing processes. As argued before, we aim to find an optimal balance between process and outcome performance.
3. The last goal of our research is to analyze how the organizational structure and the use of IT can support the optimization of the previously defined performance indicators within the previously defined tasks.

4 RESEARCH OUTLINE

Based on the goals and objectives from the Literature Review in chapter 2 and the objectives from the Case Description in chapter 3, we will define specific research questions and methodologies to answer these questions in this chapter.

4.1 RESEARCH QUESTIONS

The overall question of this study is "*How to maximize performance of a human scheduler, taking into account both process and outcome performance?*". In order to answer this question, we subdivide it into 4 questions:

1. **How can scheduling performance at Dow, BPSC be defined?**

As has been highlighted in Chapters 2 and 3, one cause of the gap between scientists and practitioners is the use of fundamentally different measures for planning and scheduling performance. Consequently, it is not clear whether scheduling performs poorly, adequately, or even good in any given situation. In order to design performance measurement systems for scheduling, explicit research into performance criteria is needed (MacCarthy & Wilson (2001); Snoo, Wezel, & Jorna (2011)). A general performance model for scheduling at BPSC enables opportunities to consolidate the scheduling process in a way that contributes to the overall value of scheduling activities.

2. **What are the drivers for a differentiated scheduling process?**
    a. **Which sub-tasks can be determined based on organizational drivers for differentiated scheduling processes?**
    b. **What is the role of a scheduler per defined scheduling (sub-)task?**

Insights in the drivers of complexity of the scheduling task, provide us with insights into which part of the scheduling process should be different, in order to meet business specific requirements. This also leads to directives to consolidate the schedulers' work processes, information availability, use of IT-systems, and case-specific performance indicators per scheduling task. Additionally, possible drivers for a differentiated scheduling process might not contribute to higher scheduling performance and can thus be eliminated. In research question 2B we take a next step into defining what a scheduler should be doing in the ideal situation. This is based on the underlying tasks and performance indicators as have been defined in research questions 1 and 2A.

3. **How can the overall performance of a scheduler be quantitatively modelled?**
    a. **What drives the trade-off between process and outcome performance of a scheduler?**
    b. **What quantitative model can be defined to model a scheduler's outcome performance?**
    c. **What quantitative model can be defined to model a scheduler's process performance?**
    d. **How can the behavior of a human scheduler be optimized taking into account both outcome and process performance?**

The overall goal defined by Dow (see Chapter 3) is to increase the efficiency of the scheduling process, without affecting the outcome performance. Currently, literature does not offer a model incorporating both process and outcome performance indicators and does not explicitly define the trade-off (Larco, Wiers, & Fransoo (2013); Snoo, Wezel, & Jorna (2011)). The model we define to optimize the value of scheduling tasks, will take both types of performance metrics into account. Besides that, we quantify the effect of leaning more towards the either the outcome- or the process- performance side. While answering research question 3D we look into how schedulers behavior can contribute to both types of performance.

4. **How can the current situation be redesigned in order to increase the overall performance of a scheduler?**
    a. **How can the optimal solution, found in the previous research questions, be implemented at Dow, BPSC?**
    b. **How does the redesigned situation contribute to standardization of processes and IT support?**

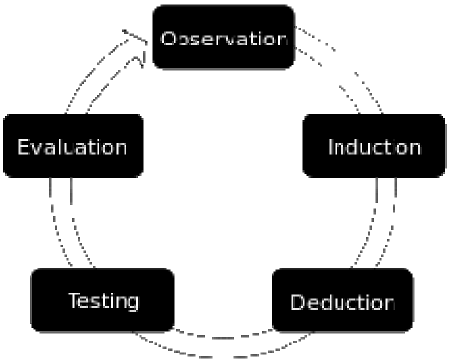
Since the current behavior of schedulers at Dow might not be the best behavior to maximize the scores on previously defined performance indicators, changes are needed. Our last research question will therefore reflect on aimed changes in the organizational structure and on how IT can be used to support the scheduler's role. By answering this fourth research question we take a step back to have an overview of the organizational structure and how this can benefit to the performance maximizing behavior we defined in research question 3.

4.2 METHODOLOGIES

This section explains the research methods we use to answer the research questions as defined above. Overall, we will use two different research methods, i.e. empirical investigation and simulation modeling. An in-detail description of the research process is treated in the in Chapter 5 and Chapter 6.

4.2.1 EMPIRICAL INVESTIGATION

The first part of our research is an empirical investigation of the current scheduling tasks. Empirical research is a way of gaining knowledge by means of direct and indirect observations and experience, in this case in a qualitative manner. The empirical research methodology will be used to answer research questions 1 and 2. This type of research follows the empirical cycle as was defined by de Groot (1969).



1. Observation: The collecting and organization of empirical facts; Forming hypothesis.
2. Induction: Formulating hypothesis.
3. Deduction: Deducting consequences of hypothesis as testable predictions.
4. Testing: Testing the hypothesis with new empirical material.
5. Evaluation: Evaluating the outcome of testing

FIGURE 3: EMPIRICAL RESEARCH CYCLE (GROOT, 1969)

4.2.2 SIMULATION MODELING

For research question 3, we use a quantitative research method for research: i.e. simulation modeling. The aim of simulation modeling is to gain insight in how specific actions relate to a specific outcome. The goal is to improve the practice in the future by evaluating results from a mathematical model (Fransoo & Bertrand, 2002). For the design of the quantitative model, we use the research model from Mitro et. al. (1974).

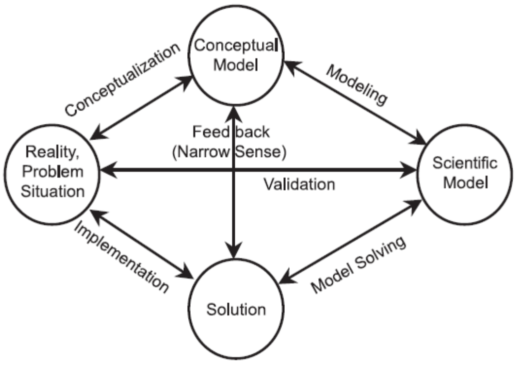


FIGURE 4: QUANTITATIVE RESEARCH MODEL (FRANSOO & BERTRAND, 2002).

5 EMPIRICAL INVESTIGATION

The first part of our research is an empirical investigation of the current scheduling tasks within scope. In this chapter we give an in-detail description of the methodologies used, we analyze results and draw conclusions based on the first research question.

5.1 PERFORMANCE METRICS

Since one of the goals of our research is to increase scheduling efficiency and the value of scheduling activities, we should define what scheduling efficiency is, and when the value of activities is high. Thus, we should define performance indicators for scheduling at BPSC, captured in the research question:

How can scheduling performance at Dow, BPSC be defined? (RQ 1)

5.1.1 METHOD

Performance indicators for planning and scheduling have been defined in previous studies (De Snoo, Wezel & Jorna, 2011). Logically, these performance indicators are the base line for our empirical investigation on scheduling performance indicators at Dow. To analyze the perceived relative importance of these previously defined performance indicators, we use expert opinions. Planners, schedulers, the team-leader, and a work-process specialist rank the performance indicators on a 1 to 15 scale based on its (perceived) relative importance. Additional information is gathered through observations and semi-structured interviews with the same employees.

5.1.2 RESULTS AND ANALYSIS

From interviews it follows that in the current situation at BPSC, scheduling performance is indirectly measured. It is complaint driven (no complaints is good, complaints is not good) and evaluated by the schedulers' team leader once every 6 months using a 360° feedback system. The stakeholders providing feedback about the scheduler's performance are depicted in Figure 5. It should be noted that different stakeholders have different priorities in a schedulers behavior. E.g.: an higher inventory level lowers the risk of lost sales, which is good, according to a customer sales representative. On the other hand, a planner sets inventory targets for the same scheduler and generally values a lower inventory level. This trade-off highlights the need for an overall optmization of scheduling peformance. The 360° feedback system also reviews a scheduler on process performance, e.g. speed of schedule adaption and communcation quality.

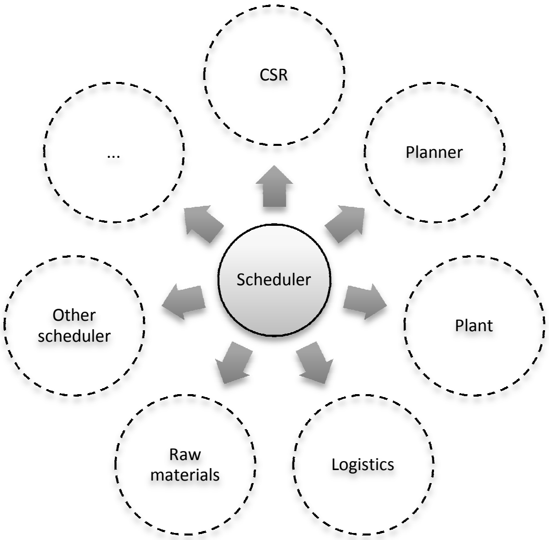
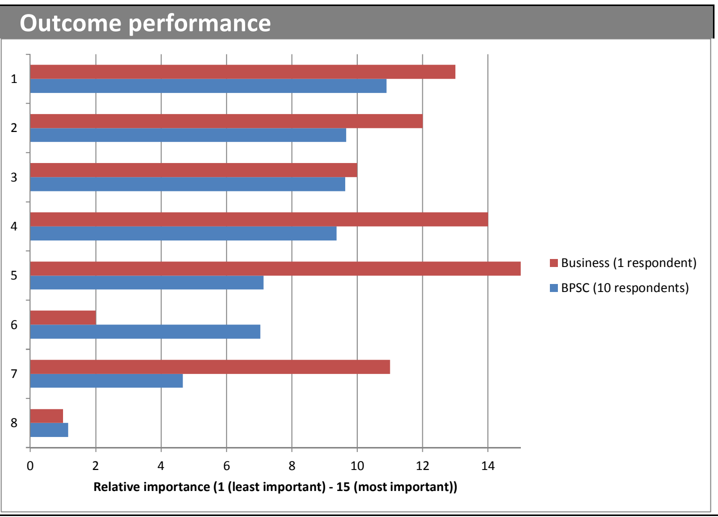


FIGURE 5: SCHEDULER'S STAKEHOLDERS

Direct performance indicators for scheduling have been defined in literature. According to these previous studies the objective of schedulers is twofold: first, to produce high quality schedules and second, to provide timely feedback about the schedule to stakeholders in the organization. These goals and associated performance measures have been identified by De Snoo, Wezel, and Jorna (2011) who explicitly distinguish between outcome and process performance. In general, the more complex the scheduling task, the higher the importance of outcome performance for scheduling. For both types of performance, we discussed performance indicators with schedulers and their team-leader, to end up with a situation specific list of objectives. These specific objectives have subsequently been ranked by 11 employees: 8 schedulers, 1 team-leader, 1 work-process specialist (all BPSC employees) and the polyol planner (Dow employee). In Figure 4 we have split the results in results from BPSC and results from Dow, even though the latter consists of only one respondent.

Outcome performance

1. Fulfillment of committed delivery dates (i.e. service level)
2. Minimization of schedule errors
3. Information completeness
4. Minimization of lost sales
5. Fulfillment of inventory targets
6. Information presentation and clarity
7. Minimization of cost of execution of the schedule (e.g. minimization of changeovers)
8. Fulfillment of preferences and wishes of employees using the schedules



Process performance

1. Communication quality
2. Timeliness of initial schedule release
3. Reliability of initial schedule
4. Flexibility of schedule adaption
5. Speed of schedule adaption
6. Cost and efficiency of the schedulilng process
7. Harmonization quality

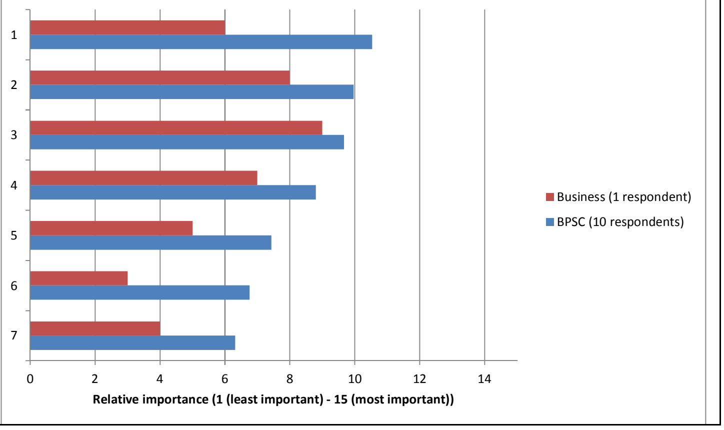


FIGURE 6: PERCEIVED IMPORTANCE OF PERFORMANCE INDICATORS.

First of all, it should be noted that there is a clear difference between the (average) ranking of BPSC employees versus the (*N=1*) ranking of the Dow planner. Where the perceived relative importance of the schedulers, their team-leader and a work-process specialist is that process performance should be prioritized over outcome performance, the planner indicates outcome performance as the primary goal for a scheduler. These results match schedulers' intuition that employees in Figure 5, who are resposible for the outcome performance of a schedule (e.g. planners and CSRs who are Dow employees) value outcome performance more, whereas BPSC employees, who are responsible for the efficient execution of the scheduling task, value process performance more. Based on de Snoo's (2002) findings, we would expect the rating for outcome performane in this situation to be higher than process performance. De Snoo has shown that in a relatively straightforward scheduling environment, outcome performance is generally the main focus of schedulers. Based on De Snoo's criteria, this situation is not a high uncertainty environment (i.e. stress-shop (Wiers, Larco & Fransoo (1997)), and can consequently focus on outcome performance.

Second, we should note that a number of performance indicators are mutually related and a higher score on one performance indicator can imply a lower score on the other performance indicator (i.e. a trade-off). For example: keeping more inventory reduces the risk of an out-of-stock situation and increases thus the performance on the fulfillment of delivery dates, whereas it increases the risk of not meeting the inventory target. Another example is the relation between reliability of the initial schedule release and flexibility of schedule adaption. The more flexible a schedule can be adapted (higher outcome perfomance), the less reliable and timely the initial schedule release can be (lower process performance). This highlights the importance of agreement on- and the availability of- information about the objectives in order to aim for high performance.

During the interviews with schedulers we have found that in case of conflicting objectives (as in the two examples above), the prioritization of objectives is unclear. Moreover, all schedulers underline that their current workprocesses are characterized by a high number of exceptions on the defined work processes (e.g. ATP order acceptance). In the current situation, there is no fixed service level that should be met (according to the schedulers: "*all orders should be delivered on time*"), and there are no guidelines on the circumstances under which a schedule should, or should not be changed in case additional demand occurs. This indistinctness also emerges in the currently executed IPS project (a project aiming at an increase in performance by high frequency data tracking). The project-leaders suggested to track the number of orders a CSR requests to accept against agreed ATP standards. The ongoing discussion is whether a high change frequency in the scheduler (high flexibility) is good, or a low number of changes should be the desired situation (less work and high efficiency). This explicit trade-off will be part of further investigation in the simulation model in Chapter 6.

Third, we notice that whereas most performance indicators have relatively clear mectrics, the performance indicators 'communication quality' and 'information completeness' are ranked high, but do not have a very straightforward metric. A more in-depth discussion we have found that these indicators are rooted in two important objectives for a scheduler. First, it is important for a scheduler to provide all information to related parties, especially in case changes are made in the short-term schedule. This performance indicator can be measured with the number of times a stakeholder missed information or the number of times a (related) employee needs to gather needed information. And second, it is important for a scheduler to be responsive in answering a stakeholders' questions. This performance indicator has already been defined in earlier research at Dow's BPSC (Larco, Fransoo, & Wiers, 2012) as the maximum allowed duration between a question and an answer.

A lot of data which can be used to measure scheduling performance is supposed to be captured within the recently implemented SAP system (SAP ERP is Enterprise Resource Planning software which incorporates the key business functions of an organization (SAP, 2015)). Dow implemented the most recent version, SAP ECC, in May 2014). Unfortunately, we have found that this data does not in all cases represent the content as is suggested by the name of a particular field. For example, inventory levels in the system are inaccurate, changes are made against ATP rules which are not entered as a rush order, and only demand that is eventually delivered is tracked in the system (no lost sales). As a result of the inaccurate information, schedulers fear to be judged on incorrect information.

For the last and probably most interesting conclusions from our first research question, we need to look into the theoretical background of the scheduling role. Jackson, MacCarthy, and Wilson (2004) discerned different roles of schedulers: The *decisional role*, monitoring *role, informational role,* and *transactional role*. The decisional role includes scheduling and re-scheduling activities for a given horizion. The monitoring role complements the decsional role and consists of monitoring stocks, demand fluctuations, new customer orders and the execution of production orders so that the scheduler may asses the need for re-scheduling. The informational role includes providing and collecting information from external parties. Finally, the transactional role infovoles the follow-up of prescribed procedures of the firm, such as creating a delivery note. Larco, et. al. (2012) executed a time study at the same department within BPSC and found that schedulers spend most of their time (>54%) in their informational role. This is also reflected in the performance indicators which are rated as most important. In interviews, schedulers pinpoint lack of clarity in the management structure of logistics systems (i.e. who decides what, based on which information and priorities, at which frequency, using a push or pull system, etc.) as a the most important driver for spending time in this role. Frequently, they are asked to explain and underpin decisions they have made in addition to a long list of requests for information from an unknown problem owner. This informational role highly influences the daily behavior of a scheduler (Larco, Fransoo, & Wiers, 2012).

For the remainder of this research, we will focus on the performance indicators with the highest perceived importance for both Dow and BPSC. These perormance indicators are the service level (% of orders delivered on time), and inventory targets or inventory holding costs for outcome peroformance and timeliness and reliability of initial schedule release for process performance. In addition, the communication quality and the amount of time schedulers spend in the informational role, will be part of further investigation. Previously, research at Dow has been done on the optimization of outcome indicators (e.g. optimal inventory levels, optimal number of setups etc.), even though decision makers on different levels are not aware of all balances. From this line of reasoning, the main contribution of our research is to add process performance to the scope and define the trade-off between outcome and process performance in order to find an optimal balance in the daily activities of a scheduler.

5.1.3 CONCLUSIONS REGARDING PERFORMANCE INDICATORS

- Currently used performance metrics for scheduling at Dow's BPSC are indirect measures (e.g. # complaints, 360^{o}-feedback system)
- Currently, schedulers spend a lot of time in their informational role (time studies by Larco, Fransoo, Wiers, 2012), which is also reflected in the objectives they rank as most important

- Views on the relative importance of mutually dependent objectives are divided (e.g. outcome vs. process performance). A difference occurs between Dow and the BPSC:
  - Process performance (i.e. timeliness and reliability of initial schedule release) is ranked higher in terms of perceived importance than outcome performance by schedulers at BPSC. This is in contrast to guidelines found in De Snoo (2002)
  - Outcome performance (i.e. service level and inventory costs) is ranked higher in terms of perceived importance than process performance by the interviewed Dow planner

- Confusion exists about the management structure of logistics systems and the scheduling task (who decides what, with which frequency, based on which information and priorities, pull vs. push system etc.). Schedulers pinpoint this as the root cause for the time they spend in the informational role

- (SAP) data frequently represents something else than is suggested by the name of the field (e.g. # rush orders, raw material availability) or the data is inaccurate
- Schedulers fear to be judged on (inaccurate) data

5.2 SCHEDULING TASKS

A second goal of this research is to understand the drivers for a differentiated scheduling process. Different schedulers can be working on different types of decisions based on the requirements, variances, and constraints within their scheduling tasks. Besides these clearly substantiated differences in roles, there might be drivers for a differentiated scheduling process which do not contribute to an increase in scheduling performance and can thus be eliminated. This leads us to the following question and sub-questions:

What are the drivers for a differentiated scheduling process? (RQ 2)

Which sub-tasks can be determined based on organizational drivers for differentiated scheduling processes? **(RQ 2A)**

What is the role of a scheduler per defined scheduling (sub-)task? **(RQ 2B)**

5.2.1 METHOD

Previous studies investigated characteristics for scheduling tasks and indicators which define the complexity of a scheduling task. The assumption is that scheduling tasks with similar complexity drivers can be executed roughly in the same way (Cegarra & Hoc (2008); McKay & Wiers (1999)). We will use these previous studies as a starting point to analyze the drivers for scheduling complexity per scheduler, per train, per reactor, or even per product. Most of the drivers for scheduling complexity will be based on historical data about the scheduling process. The missing parts of information will be based on the known work processes and schedulers' experience.

5.2.2 RESULTS AND ANALYSIS

From the literature (Tiemersma, 2014), we know that the scheduling task can be subdivided into two fundamentally different set of actions: The *routine-task*, which consists of making the actual schedule, and the *non-routine task*, which is defined by a lot of exceptions schedulers face daily (Rasmussen (1986); Sanderson (1991). The first type of decisions is made routinely, while the second type requires abstraction and the explicit design of a solution. Decision support systems (also the SAP ECC system, used at Dow) are primarily designed to support the scheduler's routine task, albeit that the actual planning is often only a small part of the schedulers' daily activities (schedulers approximate to spend 80% to 90% of their time considering exceptions). Keeping this in mind, we will analyze drivers for a differentiated process, both within the routine task, as for recurring exceptions. In discussions with schedulers we have found that, although they mainly consider exceptions, the most part of exceptions are recurring.

Literature has defined a list of drivers for scheduling complexity (Cegarra & Hoc (2008); McKay & Wiers (1999)), which are assumed to be substantiated reasons to differ the scheduling process. These drivers are: 1. Cycle synchronicity; 2. Process steadiness; 3. Process continuity; 4. Multiple objectives; 5. Contradictory objectives.

Based on the collected historical data on the demand distribution and variance of demand (for Bulk attached in Appendix D and an example of drumming attached in appendix E) in addition to the schedulers' experience, four categories of fundamentally different scheduling task can be distinguished at Dow's BPSC. The four categories are schematically shown in Figure 7, in which the size of the rectangle represents the workload (i.e. approximately 2 FTE for PO/EO, 1 FTE for raw materials, 4 FTE for bulk, 1 FTE for drumming/formulations/blends, mostly divided over multiple schedulers).

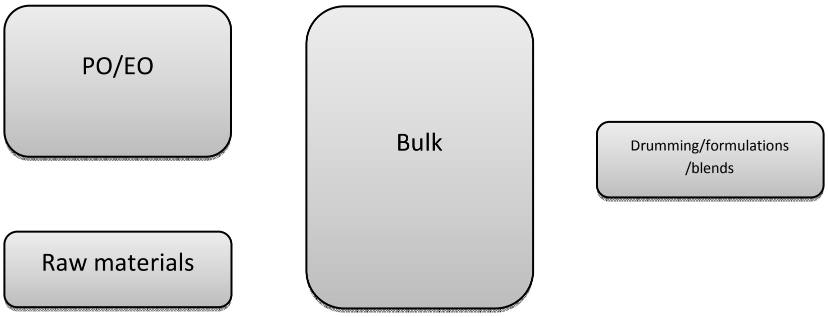


FIGURE 7: CATEGORIES OF SCHEDULING TASKS AT BPSC.

Per block in Figure 7, a scheduler has different responsibilities. The first block, is *PO/EO* scheduling, which is a continuous process, with an average demand around 100.000MT of PO and 5.000MT of EO per month. This demand has a coefficient of variance (CV hereafter) of 0,08 and 0,06 respectively. The PO and EO schedulers make decisions on the production speed and shipment quantities to the different stock points on specific moments in time. The second block is the purchasing of *raw materials* (other materials than EO and PO) for which decisions need to be made on order quantities and order timing. Demand for raw materials ranges from 1 to 200MT per month with a CV ranging from 0,01 to 0,5. The third block is the production of *bulk* polyol on a reactor. Polyol is manufactured as a batch process and schedulers decide on the sequencing and production quantities of products. This process has a CV in demand ranging from 0 to 1 and the demand quantities per product are attached in Appendix D (product names are confidential information and therefore replace by A to Z). The last block includes *drumming, blends and formulations*. This block has a longer lead-time than all the other blocks (14 days instead of 2 days) and produces on a purely make-to-order basis. It produces exact quantities for specific customers, with a CV in demand above 1 (see Appendix E for an example of packaged goods demand, CPP). The scheduler decides on the sequencing of orders. It should be noted that only the drumming of CPP is part of the schedulers' responsibilities. The other drumming decisions are made at the plant. In the current situation at BPSC, most schedulers have a couple of sub-tasks (e.g. bulk and drumming).

If we focus on the execution of the scheduling task within one block (Figure 7), the task is executed roughly the same. However, bulk production of polyol is an exception with a lot of different opinions on how the scheduling task should be executed and five different methods used by five different schedulers. As mentioned in Chapter 3, the overall question from Dow is whether these differences should exist and whether they have different economic results. Based the analysis above, we argue that the bulk scheduling task is roughly the same for all schedulers and can be executed roughly in the same way. Logically, details are different per reactor, product, etc. but we question the level of detail schedulers should take into account.

Observations and interviews with schedulers have also given insight in the recurring exceptions per block. The most striking observation is that the exact methodologies to make a schedule or to solve problems are not clearly defined and rules are not strictly observed. This causes schedulers to take into account all available information and make decisions mainly based on intuition and experience. As a result, it takes a lot of effort to understand, back-up, or learn a scheduling task. Besides that, a lot of communication between planners, schedulers, plant etc. is needed in order to make every schedule work and schedulers work around the IT system for exceptions the system is not designed for. It should be noted that this problem is most frequently mentioned for the scheduling of bulk polyol.

The above mentioned point can be taken one step further. The fact that the management structure of these logistic systems is unclear is one of the root causes for recurring exceptions within a schedulers' daily task. The most frequently occurring exception (for bulk production) is an exception on order acceptance (ATP). ATP only accepts order is case inventory is available or scheduled before the requested delivery date. Since customers frequently request a quantity or delivery date, which is not feasible according to ATP, a CSR ask a scheduler to update the short term schedule in order to meet demand. To get an insight in the frequency of this recurring exception, we look into data on bulk service levels in Appendix F. As can be seen in this Appendix, there is a huge difference (>20%) between OTC2e (service level based on requested delivery date) and OTC6i (service level based on confirmed delivery date), showing that customers frequently ask for a different delivery date than can be confirmed, causing an information stream between scheduler and CSR. The third column in the service level table shows that the service level for external order is higher than the average based on both internal and external orders, implying that schedulers prioritize individual orders. Schedulers confirm that they change the sequence of production if this increases the service level to external customers. The internal workflow to drumming has slack in the two week lead time for packed goods. The last conclusion that can be drawn, based on Appendix F is that the service levels are generally low.

The most fundamental difference between (bulk) schedulers task execution in the current situation is rooted in the way they treat the recurring exception that was highlighted above. Some of the bulk schedulers review their schedule once or even multiple times a day (schedulers 1, 2 and 4), focusing on increasing the outcome performance (e.g. service level to external customer) of this schedule. They keep track of every single change in production orders, run-rates etc. The other extreme are the schedulers (schedulers 3 and 5) who make a steady schedule (e.g. once per 2 weeks), based on the forecasted demand. These schedulers focus on an easy to understand schedule and higher process performance (e.g. reliability of the initial schedule release). An ongoing discussing exists within this group of schedulers about which review frequency is best. Currently, the policy used is driven by a scheduler's preference (e.g. whether a scheduler likes puzzle-solving).

In the remainder of this research we will analyze whether frequent updating (i.e. high outcome performance) or a steady schedule (i.e. high process performance) should be the focus for a bulk polyol scheduler in order to maximize scheduling performance.

5.2.3 CONCLUSIONS REGARDING THE SCHEDULING TASK

- There are both similarities and differences between (the complexity of) schedulers' tasks, which can be subdivided into four main categories; i.e. 1. EO/PO, 2. Raw materials, 3. Bulk, 4. Drumming/blends/formulations
- Currently, most schedulers at BPSC have a number of sub-tasks (e.g. bulk + drumming) with different complexity drivers

- Besides differentiated tasks rooted in different complexity drivers, the differentiated scheduling process for bulk production is also driven by:

    - Lack of clarity in the definition of a schedulers' task and the management structure of logics systems (push/pull, inventory policy, acceptance of rush orders etc.),
    - Lack of clarity in business requirements (level of flexibility, service level, etc.)
    - Different opinions on what a scheduler's responsibilities are and what schedulers like within their job (e.g. puzzle solving)

- The above mentioned drivers for a differentiated scheduling process also drive a high variability and high number of exceptions in a scheduler's daily task
- The high number of exceptions forces schedulers to work around the SAP system, which was primarily designed for support of the routine task. Moreover, it increases the workload in the informational role
- The most frequently occurring exception is an exception on ATP order acceptance, through which CSRs try to increase the service level to external customers

- A bulk schedulers' review frequency is a driver for a focus on either process or outcome performance. This trade-off will be optimized in the next chapter

6 SIMULATION MODEL

The second part of our research is an analytical model, optimizing the trade-off between outcome and process performance. For this part, we will narrow the scope to bulk scheduling. The previous chapter has highlighted that a differentiated scheduling process, without underpinned difference in the scheduling complexity, mainly occurs for this part of the scheduling task. Moreover, bulk production consumes by far most time in the scheduling process, which logically offers most room for improvement. The aim of an analytical model is to improve the practice in the future by evaluating results from a mathematical model. In this section, we will answer the following research questions.

5. **How can the overall performance of a scheduler be quantitatively modeled?**
    a. **What drives the trade-off between process and outcome performance of a scheduler?**
    b. **What quantitative model can be defined to model a scheduler's outcome performance?**
    c. **What quantitative model can be defined to model a scheduler's process performance?**
    d. **How to optimize performance of a human scheduler taking into account both outcome and process performance?**

6.1 METHOD

We use the empirical findings from Chapter 5 as input to formulate a reality problem, which is subsequently translated into a conceptual model (see modeling steps in Figure 4) in section 6.2. This conceptual model is analyzed by use of a simulation model in Enterprise Dynamics. Enterprise Dynamics is a discrete event simulation software platform with several market-specific libraries to conform to customer requirements. One of these libraries (Logistics Suite) is suitable for production planning environments. Section 6.3 treats the model for outcome performance whereas section 6.4 focuses on the model for process performance.

6.2 THE TRADE-OFF BETWEEN OUTCOME AND PROCESS PERFORMANCE

In Chapter 5 we have found that one of the major differences between schedulers is the review frequency by which they monitor, adjust, and update the schedule. Where some schedulers chase individual orders and update the plan daily, according to actual demand (close to a make-to-order policy), other schedulers see their task as keeping track of inventory over a specified horizon. The latter group of schedulers thus treats their production schedule as a make-to-stock business in which the plan is based on a demand forecast. From this point on, we define a 'review' as the formal assessment of a schedule with the intention to change it if necessary. The review period is the horizon over which a schedule is fixed, whereas the review frequency defines the number of reviews per month (e.g. for a 28 day month, a review period of 7 days equals a review frequency of 4).

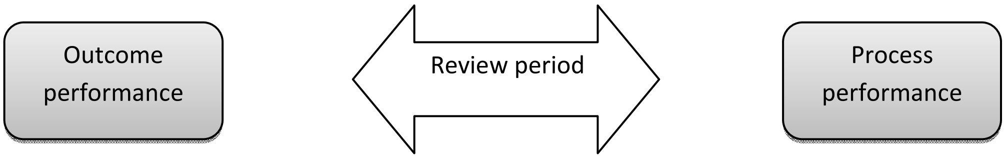


FIGURE 8: THE TRADE-OFF BETWEEN OUTCOME PERFORMANCE AND PROCESS PERFORMANCE OF A HUMAN SCHEDULER

A short review period or high review frequency increases the outcome performance (e.g. high service level to external customers, and low inventory costs). As we have found in Chapter 5, this is mainly valued by Dow employees (planners, CSRs). The opposite is true for BPSC employees, who are responsible for the efficient execution of the scheduling task (i.e. process performance). These managers value a longer review period, a robust plan, and standardized, efficient methods to build and execute the plan. This ongoing discussion at Dow, leads us to the trade-off between process and outcome performance as depicted in Figure 8. "*You cannot have the cake and eat it*", i.e. gaining quality on process performance involves losing quality on outcome performance and vice versa.

In the remainder of this chapter we design models to quantify the effect of the review period on outcome performance and process performance, based on the performance indicators we have found in Chapter 4. In section 6.5 we combine both models and define the overall cost function for the scheduling process, as a function of the chosen review period.

6.3 MODEL FOR OUTCOME PERFORMANCE

In this section we describe the model for outcome performance, based on an example for reactor 107. The input for the other bulk polyol reactors is attached in Appendix D. The product names and all cost related information is confidential and therefore excluded from this thesis. In appendix D the product names are referred to as A to Z. For this example we number the products on reactor 107 with number 1 to 4. The outline of this section consists of a description of the input variables, a model description, the simulation results, a sensitivity analysis for all input variables and a discussion of the results. Overall conclusions will be drawn combined with the simulation output from the process performance model in section 6.5.

In Chapter 4 we have found that the most valued outcome performance indicators are the service levels and inventory targets, in addition to communication quality to stakeholders. These three performance indicators will guide 'good' outcome performance of a human scheduler in our model.

6.3.1 INPUT VARIABLES

The input used for this simulation model is the data which was captured in the empirical part (Chapter 5) of this report, see Appendix D. This input contains the run-rate per product per reactor (i.e. production speed in MT/hour), the optimal run-length per product (MT), and the demand per product per month (MT). The run-rate per product per reactor includes some downtime, waiting time for raw-materials, set-up times, and an overall variance of the systems. Since the variance of this run-rate is not being tracked, a CV equal to 0,5 is assumed. The effect of this assumption is part of the sensitivity analysis. The optimal run-length has been previously calculated by a Dow internal project looking into economic order quantities per product. For this model we assume that this run-length is an optimization of the set-up time (or costs) and the inventory holding costs. This implies that, producing more or less than this quantity is always less (cost) efficient.

To model the benefit of more frequent updating, we analyze the occurrence of demand over time. A shorter review period namely ensures that a higher percentage of demand is already known (i.e. deterministic). The variance in unknown demand (i.e. stochastic demand) therefore decreases if the review frequency increases. According to the planners, approximately 85% of demand is known in case a scheduler looks two weeks ahead. For one month, this average is equal to 60%. For our model we assume that the demand enters the system linearly with 100% known on the second day and 40% known on the 28th day. It should be noted that the average of day 2 to day 14 is 85%, and the average of day 2 to day 28 (1 month) is 60%, See Figure 9.

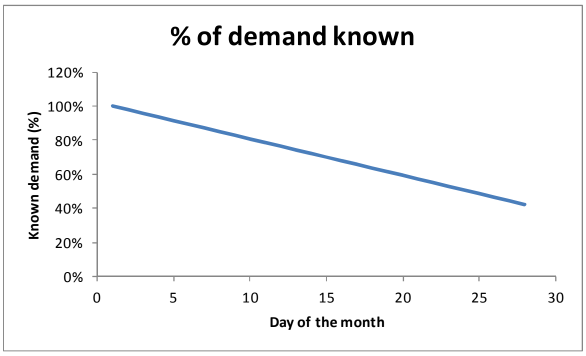
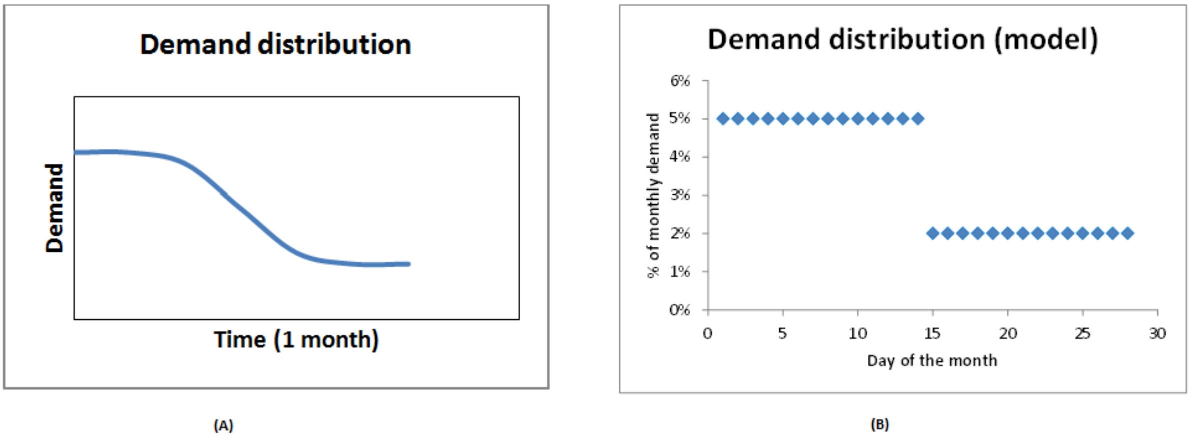


FIGURE 9: PERCENTAGE OF DEMAND KNOWN AS A FUNCTION OF THE REVIEW PERIOD.

Besides this linear order entry, the input data for demand needs some extra attention. The demand data is based on the actual consumption from the inventory tanks, as was tracked in the SAP system. Although we know that system data is not entirely accurate, this is the best available data. We use data over the period May 2014 – November 2014, which represents all data since the implementation of the new SAP system. The variance in demand is also based on the spread in demand per month. Both schedulers and planners highlight the fact that demand is not equally spread through the month, but has a high-low-pattern as depicted in Figure 10. This demand pattern is a result of the payment terms Dow uses to external customers (i.e. customers pay by the end of next month, instead of a fixed number of days after placement of an order, which makes it beneficial to order in the beginning of a month).



(A)

(B)

FIGURE 10: (A) DEMAND PATTERN OF BULK POLYOL DURING THE MONTH, IN A WAY SCHEDULERS DRAW THE PATTERN (B) THE DEMAND PATTERN WE USE IN THE SIMULATION MODEL.

We do not have access to data about daily demand (e.g. requested delivery dates per order), but schedulers argue that the ratio between high and low demand equals approximately 70% in the first two weeks of the month, and 30% in the second two weeks of the month (this rough guess will be part of the sensitivity analyses). As can be seen in Figure 10B, we model demand within the first two weeks, and within the second 2 weeks of the month as a stationary pattern.

Last, we made some assumptions on the distribution of the demand and run-rate. Since both are strictly positive, continuous distributions with no specified relation between mean and variance, we chose to model both with a gamma distribution. For the run-rate we model the average duration per run (in seconds) as a gamma distribution (not the run-rate in metric ton (1 MT = 1.000 ton) per second). A useful property of the gamma distribution for the demand data is the fact that a gamma distribution with shape parameter k and scale parameter θ is the sum of n (for example in the case of n days) individual gamma distributions with shape parameter $\frac{k}{n}$ and scale parameter θ. The mean of this distribution is equal to the shape parameter multiplied by the scale parameter ($k\theta$) and the variance is equal to shape parameter multiplied by the square of the scale parameter ($k\theta^2$). For *n* individual days the input is thus a mean of $\left(\frac{k}{n}\theta\right)$ and variance of $\left(\frac{k}{n}\theta^2\right)$. The input values per reactors are attached in Appendix D.

In the next section we explain how we translate this input to output about the outcome performance (inventory and service level) of the scheduling task.

6.3.2 MODEL DESCRIPTION

The decision variable in our model is the review period for which we analyze the output in terms of a service-level and the average inventory (i.e. the highest ranked performance indicators from Chapter 5). The outline of the model is attached in Appendix G and the variables used for simulation are listed in Table 4. In this simulation model, we run polyol bulk production as a make-to-stock business, based on partly deterministic and partly stochastic future demand. It should be noted that this business can by definition not be modeled entirely as a make-to-order business since the replenishment lead-time is longer than the customer lead time.

TABLE 2: LIST OF VARIABLES FOR OUTCOME PERFORMANCE SIMULATION MODEL

$\boldsymbol{R}$	Review period (days)
$\boldsymbol{d} = (1, \dots, \mathrm{R})$	Day within review period
$\boldsymbol{T} = \frac{28}{R}$	Number of review periods per month
$\boldsymbol{t} = (1, \dots, \mathrm{T})$	Number of the review periods (within a month)
$\boldsymbol{x} = \epsilon\{1, \dots, i\}$	Product type on a reactor with *i* products
$\boldsymbol{RL_x}$	Run-length for product *x* (MT)
$\boldsymbol{Dur_x}$ $\sim gamma(\mu_{Dur,x}, \sigma_{Dur,x})$	Duration of a production run of product *x* (sec)
$\boldsymbol{I_{t,x}}$	Inventory of product *x* at the beginning of review period *t* (MT)
$\boldsymbol{B_{t,x}}$	Backorders of product *x* at the beginning of review period *t* (MT)
$\boldsymbol{S_{t,x}}$	Order up to level of product *x* at the beginning of review period *t*
$\boldsymbol{P_{plan,t,x}}$	Planned production of product *x* at the beginning of review period *t* (runs)
$\boldsymbol{P_{reactor,t,x}} = \epsilon\{0,1\}$	1 if reactor is producing product *x* at the beginning of review period *t*, else 0
$\boldsymbol{D_{known,d,T,x}}$ $\sim gamma(\mu_{known,d,t,x}, \sigma_{known,d,t,x})$	Known demand of product *x* on day d of review period *t* (MT)
$\boldsymbol{D_{unknown,d,T,x}}$ $\sim gamma(\mu_{unknown,d,t,x}, \sigma_{unknown,d,t,x})$	Unknown demand of product *x* on day *d* of review period *t* (MT)
$\boldsymbol{E(D_{unknown,d,t,x})}$ $= \mu_{unknown,d,t,x}$	Expected unknown demand of product *x* on day *d* of review period *t* (MT)

The model consists of a source (DEMAND) which updates the demand quantities per day within the upcoming review period. Appendix H shows an example of one month of demand for product 1 on reactor 107, using a 28 day review period. The columns highlighted in orange are the columns which are refreshed once per review period (in this case, 28 days), based on the gamma distribution specific for the given day. The actual demand of product *x* on day *d* of review period *t* (MT), which is highlighted in green in Table 5, can be calculated as shown in equation [1].

$$\boldsymbol{D_{actual,d,t,x}} = D_{known,d,t,x} + D_{unknown,d,t,x} \tag{1}$$

Figure 11 shows an example of what 2 months of what actual demand at reactor 107 look like. A month in our model consists of 28 days.

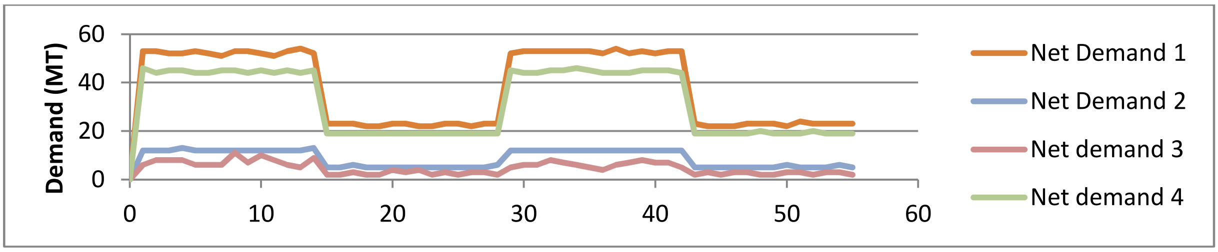


FIGURE 11: DEMAND PATTERN FOR 2 MONTHS ON REACTOR 107 (MT).

The sources DEMAND 1 – DEMAND 4 in the enterprise dynamics model fire the demand quantity per day on every day within a review period. After a refresh of demand to the next period, it starts again with day 1 of the following period. These fired orders are kept in the queues BACKORDERS 1 – BACKORDERS 4. In case there is both inventory (in INVENTORY 1- INVENTORY 4) and a backorder of the same product-type (i.e. an order and inventory), the order is delivered. This means that orders are always delivered from inventory in case there is stock available. The average queue-length of the backorder queue divided by the total order quantity defines our service level (i.e. the percentage of demand that could be delivered at the day it was requested). It should be noted that we do not make a distinction between internal and external orders.

Based on the known demand and the expected value of unknown demand (see Appendix H), the sources for the production plan (PRODUCTION 1 – PRODUCTION 4) fire a production quantity ($Q_{t,x}$) once per review period. The production quantities (in batches) are calculated by equation [2]. The value for product 1 in the example month, is highlighted in yellow in Appendix H. It should be noted that the production quantity is always equal to zero or a multiple of the optimal run-length RL_x per product.

$$\begin{aligned}\boldsymbol{Q_{T,x}} = max\Bigg(0, round\bigg(\frac{1}{RL_x} \\ \cdot \Big(S_{t,x} - I_{t,x} + B_{t,x} - P_{plan,t,x} \cdot RL_x - P_{reactor,t,x} \cdot RL_x + \sum_{d=0}^{R} D_{known,d,t,x} \\ + \sum_{d=0}^{R} E\big(D_{unknown,d,t,x}\big)\Big)\bigg)\Bigg)\end{aligned} \tag{2}$$

The reactor (REACTOR in the simulation model) decides on the sequencing or production orders. For this model, the production sequence is fixed and the products are produced 1 run at a time. Unless there are no production orders waiting for a specific product type, we skip this product type and continue with the next product type. The decision for this type of sequencing is made, because we do not have any specific information about set-up times, which makes it impossible to optimize the sequence. What we do know is that the run-length values have been optimized, in such a way that producing multiple runs of the same product in a row is always less efficient (higher inventory costs) than producing them interspersed by a run of (multiple) (an)other product(s).

We run the model without inventory constraints, even though the actual inventory at Dow is (very) limited. We do this in order to find the optimal balance between process and outcome performance, regardless of the current capacity. In the discussion of the results, we will verify whether the current capacity is sufficient and how this influences the current behavior of a scheduler.

In this last part of the model description, we consider the assignment of products to specific reactors. As can be seen in appendix A, some products can be produced at multiple reactors, with a different run-rate. For the sake of keeping things organized, we pre-assign products to specific reactors. By doing this, we lose the pooling effect of being able to choose where to produce which products. On the other hand, the coefficients of variance in demand are low ($< 0{,}5$), which implies that assigning products to the fastest running reactor, based on average quantities is the better solution. This pre-assignment of products to reactors is a variant of the 'bin packing problem' (Garey & Johnson, 1985). Priorities are to assign as many products to the fastest running reactor as possible, while simultaneously trying to assign the full demand of a reactor grade to one single reactor (minimizing set-up times). For this purpose we use the following heuristic:

1. Assign all products which can only be produced at one reactor to that reactor.
2. Calculate the spare capacity per reactor (as a percentage), based on the time needed to produce the assigned products divided by the total number of hours available.
3. Calculate the capacity consumption per product per reactor (for reactors that can produce a product) in % of the capacity. Start with assigning products to the fastest reactor at which they can be produced. Assign products based on a 'best fit' of this total demand to 90% utilization of the reactor.
4. List the products which are not assigned yet and assign them to a reactor which fits the total demand. For products which are still not assigned, split the demand and spread it over the reactors with spare capacity, in order to end up with an equal utilization over reactors.

The results of this assignment are attached in Appendix D. In case the utilization of a reactor is still above 100%, the run-rates are all increased by an equal multiplier in order to lower the utilization to 90%. The trade-off of 90% is a result queuing theory on the workload in the system with a convex increase in utilization and infinite queues for 100% utilization (Khintchine, 1932). The run-rate is adjusted since the actual run-rate over the past periods was apparently higher, as follows from the consumption data.

6.3.3 ANALYTICAL RESULTS

If we zoom in on our model for reactor 107 with a 28 day review, the only input value we change in order to analyze the effect of inventory on the service level, are the values for $S_{t,x}$. In fact, our model can be seen as a (R, s_t, S_t)-model with a fixed review frequency R. s_t is the re-order quantity, in our case defined as $Q_{t,x}$ per product per review period. S_t, or $S_{t,x}$ in our specific case, is the order-up-to-level. We use a dynamic re-ordering policy, which implies that the level of $S_{t,x}$ can be changed per review period (Wang & Gerchak, 1996). Part of this order-up-to is maintained to mitigate the risk of stock outs due to uncertainties in supply and demand (Beamon (1998); Gupta & Maranas (2003)). Apart from this so called safety stock, the order up to level accounts for the fact that the reactor does not have sufficient capacity to produce the high demand in the first two weeks (70% of demand) within these first 2 weeks. I.e. production needs to be spread over the month, which implies that we need to build up inventory in the second part of the month, to deliver in the first two weeks of the next month. We look into some analytical results on the values of the $S_{t,x}$ levels, with the aim of minimizing the average inventory, while maintaining the service level (Silver, Pyke, & Peterson, 1998).

First of all, slow moving products (i.e. replenishment lead time > 2 weeks, or $\left(\sum_{t=1}^{T} \sum_{d=1}^{R} E\left(D_{actual,d,t,x}\right) < 2 \cdot RL_x\right)$), which are produces less than twice per month, are given a fixed $S_{t,x}$ level through the entire month, which is a safety stock. This safety stock ($SS_{x,t}$) accounts for the variance in demand per lead time (days) and the variance in the lead time:

$$SS_{t,x} \approx Z\sqrt{Avg.\ lead\ time\ \cdot \left(\sigma_{unknown,d,t,x}\right)^2 + E\left(D_{actual,d,t,x}\right) \cdot (st.dev.lead\ time)^2} \qquad [3]$$

Here, Z is the inverse of the normal distribution for the desired service level ($Z = 1{,}96$ for a 95% service level) (Silver, Pyke, & Peterson, 1998) and $E\left(D_{actual,d,t,x}\right)$ the expected value of the demand per day. The average lead time is approximated to be equal to the expected time between production runs $\left(\approx \frac{R \cdot T \cdot RL_x}{\sum_{t=1}^{T}\sum_{d=1}^{R} E\left(D_{actual,dt,x}\right)}\right)$, whereas the standard deviation in this run length is approximated to be 50% of this run length ($CV = 0{,}5$). In real-life, the lead time depends on both the review period and the variance in duration of the other products on the same reactor, but we consider this too much detail for this approximation. The variance in demand is only based on the unknown demand, as can be seen in equation [3].

For fast moving products, the calculation of the $S_{t,x}$ is slightly more complex, since the production capacity in the first two weeks is insufficient to produce the first two weeks of demand and multiple levels for $S_{t,x}$ can be used. The buildup quantities in the second two weeks of the month are calculated as follows: Assume that the slow movers are produced in the first two weeks of the month and consume $\left(\sum_{t=1}^{T}\sum_{d=1}^{R} E\left(D_{actual,dt,x}\right) \cdot \frac{Dur_x}{RL_x}\right)$ seconds of the total capacity (total capacity is 14 days multiplied by 24 hours per day). The remaining capacity is assigned based on proportions of demand of fast moving products, resulting in a lack of production time in the first two weeks. This lack of capacity multiplied (in hours) is multiplier by the proportion of demand of the fast moving products to end up with a buildup quantity in MT $\left(I_{buildup,x}\right)$. An example calculation for reactor 107 is shown in Table 3.

TABLE 3: BUILD UP INVENTORY IN SECOND 2 WEEKS OF THE MONTH FOR FIRST 2 WEEKS OF NEXT MONTH.

	Demand week 1+2 (MT)	Duration (hours)	Proportion	Additional production week 3+4 (hours)	Additional poduction week 3+4 (MT)
Product 1	737	181	52%	61	246
Product 4	623	168	48%	56	208
Capacity needed (hours)		349			
Capacity available (hours)		336			
Capacity for slow movers (hours)		103			
Capacity for fast movers (hours)		233			
Lack of capacity for fast movers (hours)		117			

The values for $S_{t,x}$ are calculated by use of equation [3]. Through exploratory research on the $S_{t,x}$ levels in the simulation model, we have found that these levels should account for the start inventory (safety stock) of period $t + 1$. Table 4 shown an example for one fast moving product with a 7 days review period (i.e. $T = 4$). In this case, period 4 should thus end with the total built up inventory, whereas period 1 should end with 50% of built up inventory left for period 2.

TABLE 4: EXAMPLE CALCULATION OF ST,X LEVELS FOR PRODUCT 1, REACTOR 107.

Product 1		
$S_{1,1}$	$SS_{2,1} + 50\% \cdot I_{build\ up,1}$	$117 + 50\% \cdot 246 = 240$
$S_{2,1}$	$SS_{3,1}$	54
$S_{3,1}$	$SS_{4,1} + 50\% \cdot I_{build\ up,1}$	$54 + 40\% \cdot 246 = 152$
$S_{4,1}$	$SS_{1,1} + I_{build\ up,1}$	$117 + 246 = 363$

In Table 4, we produce 40% of the additional production in week 3 and 60% of additional production in week 4. Logically, we want to build up inventory as late as possible (minimizing the average inventory), thus we divide the lack of production capacity for all fast moving products (in minutes) including the difference in safety stock $\left(\sum_{x=1}^{2}\left(SS_{high} - SS_{low} + I_{build\ up,x}\right)\frac{Dur_x}{RL_x}\right)$ by the spare capacity (minutes/day) in the second part of the month. This provides us with the net number of minutes we need to start building up inventory before the end of the month, which is translated into a ratio per review period. For very high utilization reactors, it is not possible to lower safety stock levels (entirely) during the month, because the capacity is too limited to build the safety stock up again. In this case, the safety stock is kept on high(er) level during the month.

The values in Table 4 do not represent the exact input values needed, since rounding to an integer of full batches requires a threshold of demand plus safety stock. The found values in Table 7 are used as a starting point to explore for optimal values by use of the simulation model. For more frequent reviewing, the number of $S_{t,x}$ levels per product again depends on the expected number of runs per month.

The inventory minimizing pattern discussed in Tables 3 and 4, implies that the average inventory decreases during the first two weeks of the month, and is built up again during the second part of the month. A simplified version of this pattern is depicted in Figure 12. The pattern occurs by use of the dynamic reordering policy which aims at minimize the average inventory while maintaining a fixed service level (Gupta & Maranas, 2003). An interesting observation is the fact that Dow uses an end-of-month inventory target, according to which a scheduler generally lowers inventory in the end of the month. This implies a high number of backorders in the first part of next month.

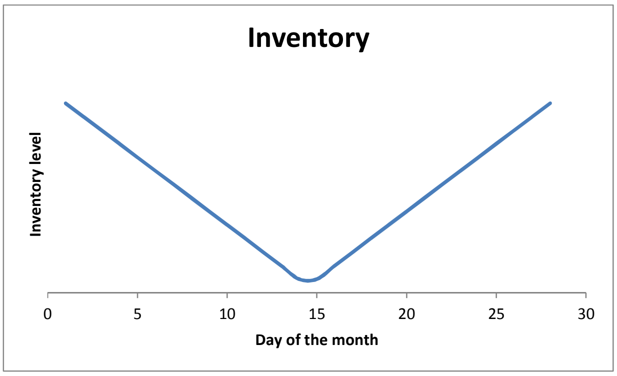


FIGURE 12: INVENTORY PATTERN THROUGH THE MONTH.

6.3.4 SIMULATION RESULTS

We have run the described simulation model over a period of 10 years, excluding the first month as a warm-up period. The review periods which have been observed are 2 days, 4 days, 7 days, 14 days, and 28 days. An example of the inventory fluctuation (28 days review, reactor 107) is depicted in Figure 13. This picture shows the very clear pattern of consuming inventory in the first two weeks and building up inventory in the second two weeks. It should be noted that, in this situation, we only use one $S_{T,x}$ level for the entire month.

Figure 14 shows the same reactor with the same products, but with a review period of 7 days. As a result of lower variance and multiple (four) levels for $S_{T,x}$, we see that the demand pattern can be more accurately followed, resulting in lower average inventory. Both figures have a service level of 95%. We see that the end-of month inventory is the highest inventory level during the month in both cases, as a result of building up inventory for next month. This matches the analytical results in the model description, but contradicts the currently used policy at Dow.

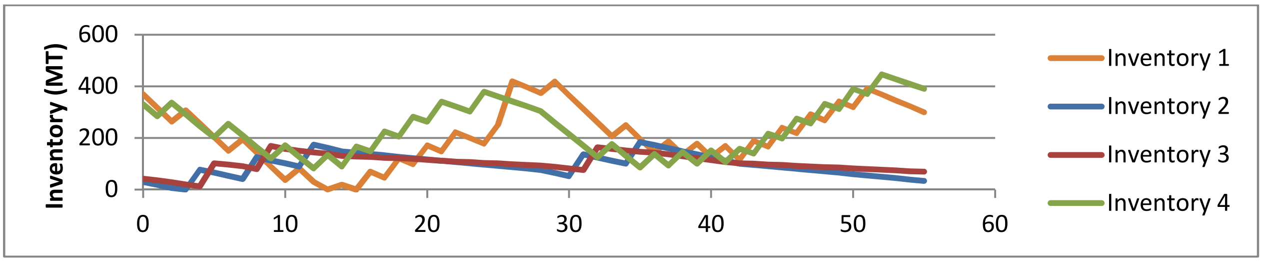


FIGURE 13: INVENTORY OVER 2 MONTHS WITH A REVIEW PERIOD OF 28 DAYS (REACTOR 107, SERVICE LEVEL 95%)

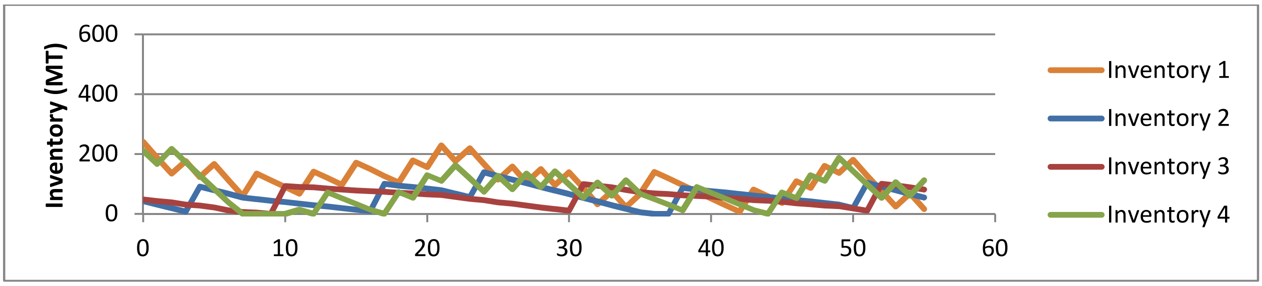


FIGURE 14: INVENTORY OVER 2 MONTHS WITH A REVIEW PERIOD OF 7 DAYS (REACTOR 107, SERVICE LEVEL 95%)

To get an insight in the relation between the service level and the level of $S_{T,x}$, we look into some output of the 28 day review period in more detail. Figure 15 shows the relation between the service level and the average inventory, maximum inventory, and the $S_{T,x}$ level. The yellow dashed line in Figure 15 indicates the inventory capacity for the given product at Dow, while the line in green dots indicates the inventory capacity needed to be able to use this (purely make-to-order) policy. What we thus observe is the fact that the inventory capacity at Dow is too limited to run this 28 day review period with a 95% service level.

Another result we can observe from Figure 15 is the relation between the $S_{T,x}$ level and the average inventory. For the fast moving products (product 1 and product 4) the average inventory is below the level of $S_{T,x}$., while the opposite is true for the slow-moving products (product 2 and product 3). The explanation for this observation is relatively simple. For the fast moving products, the difference between the average demand in the first two weeks, and the average demand in the second two weeks, is relatively high. $S_{T,x}$ is thus primarily the parameters which influences which quantity is produced in advance in the second two weeks of the month. If we look at the slow moving products, these products can generally be produced in the period that the demand occurs. In this case, $S_{T,x}$ accounts for the variance in demand and is primarily a safety stock, which can be lower than the average inventory. Both observations match our analytical findings in the previous section.

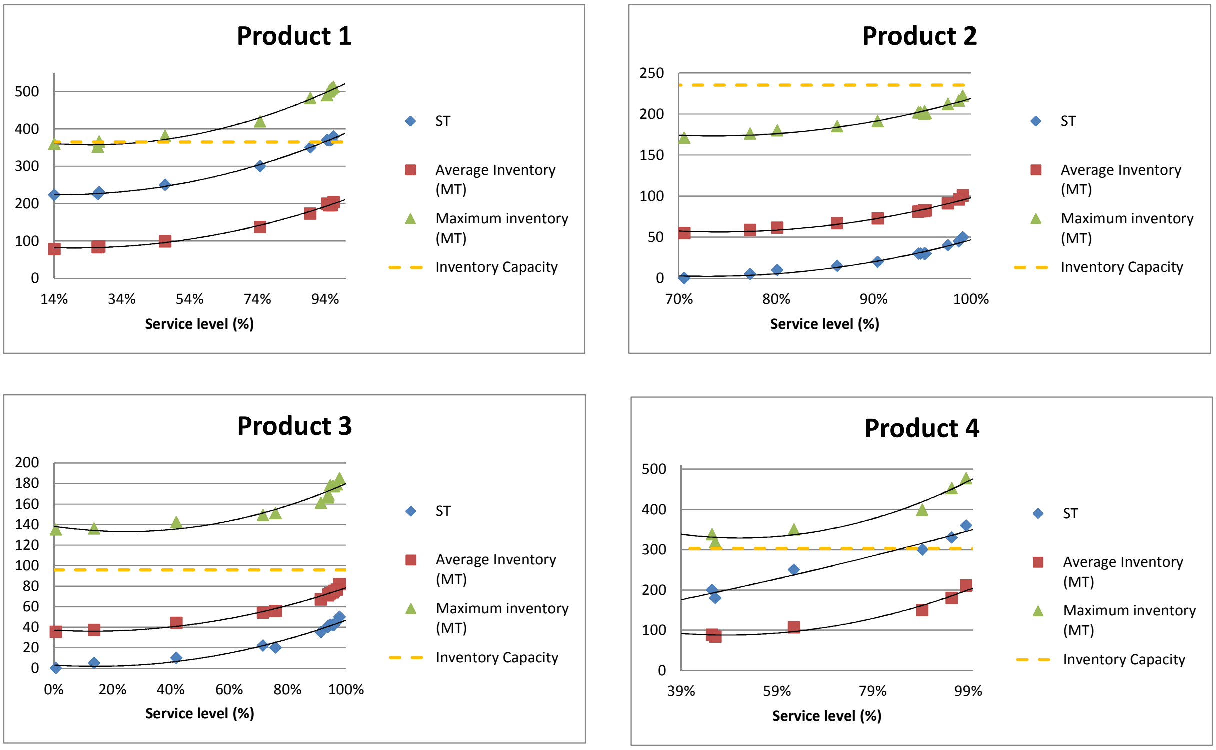


FIGURE 15: AVERAGE INVENTORY AS A FUNCTION OF THE SERVICE LEVEL PER PRODUCT (REACTOR 107, 28 DAYS REVIEW)

Back to the aim of this simulation model: how are the review period, inventory level and safety stock related. Or more specifically: how is the review period of the production schedule related to the average inventory needed to meet a 95% service level? Figure 16 shows the average inventory needed to meet a 95% service level per product, at reactor 107, as a function of the review period. As hypothesized before, the average inventory increases with a longer review period as a result of higher variance in demand and less accurate tracking of the demand pattern. It should be noted that the benefits are lower for shorter review periods (increasing from a 4 day review period to a 2 day review period, hardly changes the inventory). Purely focusing on outcome performance, we can conclude that the higher the review frequency, the better the result, even though the line flattens for higher frequencies.

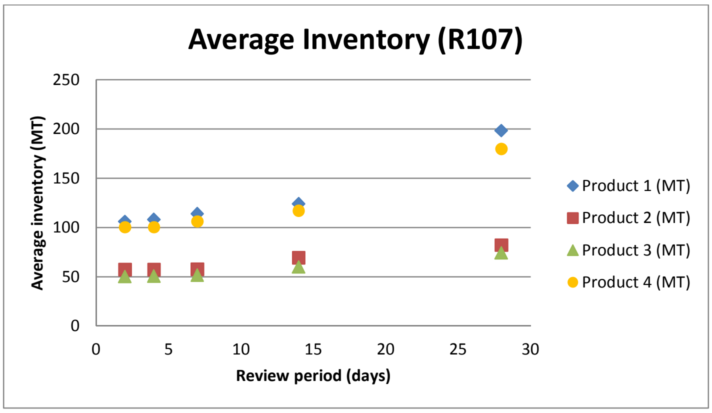


FIGURE 16: THE AVERAGE INVENTORY NEEDED TO MEET 95% SERVICE AS A FUNCTION OF THE REVIEW PERIOD (REACTOR 107).

The remark that we already found in Figure 15, is that the inventory capacity at Dow is very limited. Figure 17 makes this problem even more explicit. The dashed lines show the inventory capacity per product in the same color as the inventory capacity needed to follow a dynamic reordering policy. For product 3 and product 4 our results show that it is impossible to meet an overall service level of 95% given the current inventory capacity, whereas products 1 and 2 only require a minimum review frequency to meet a 95% service level.

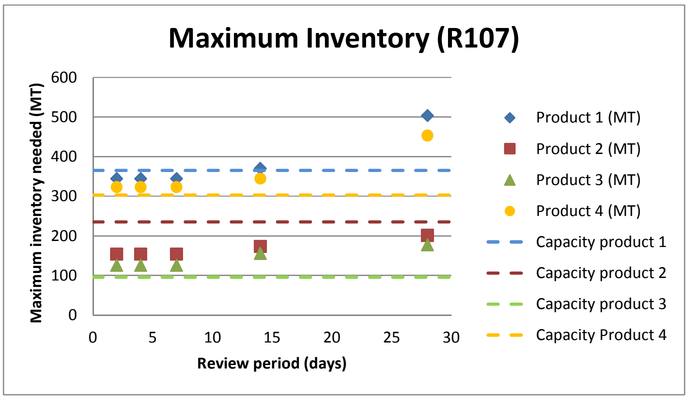


FIGURE 17: MAXIMUM CAPACITY NEEDED AND INVENTORY CAPACITY AVAILABLE AS A FUNCTION OF THE REVIEW PERIOD (REACTOR 107).

The results in Figure 17 bring up the question how this limited inventory affects the current scheduling processes. First of all, Figure 17 matches our earlier finding in Appendix F, which had shown that customers frequently request a delivery date that is not feasible. As we discussed in section 5.2, this increases the number of exceptions on ATP agreements. A more in-depth discussion with schedulers and CSRs on this point confirms that the ATP exceptions are a result of the fact that service levels are low in case the production plan is fixed for any horizon. In order to meet external demand as good as possible, the plan is updated on high frequency.

To get more insights in this short-term updating to increase the service level to external customers, we look into simulation results on the tardiness of backordered products in Figure 18.

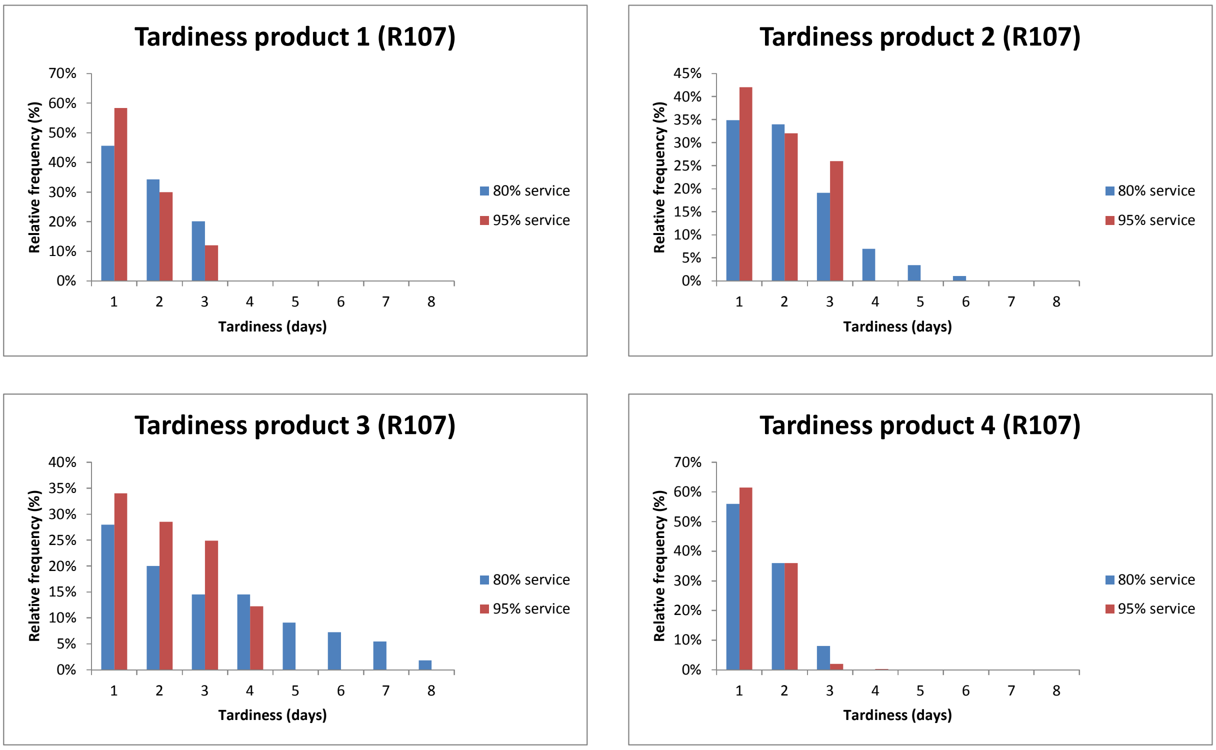


FIGURE 18: TARDINESS OF PRODUCTS ON REACTOR 107.

Figure 18 shows that most backorders are only 1 day late, and the average tardiness is less in case the service level is higher (red bars). The fact that the average tardiness is limited, underlines the opportunity for a scheduler to increase the service level by day-to-day swopping within the production sequence. Moreover, the lead time of packaged polyol products is 14 days, with some slack in drumming process. We can thus conclude that a low service level for internal orders of the drumming terminal is not a problem. The only issue is that this prioritization influences a schedulers' task, which will be part of section 6.4.

The last part of our simulation results considers the end-of-month inventory targets at Dow. In Figure 19 (left), the end of month inventory target is compared to the maximum inventory from our simulation model. As argued before, the inventory is the highest in the end of the month (Figure 12). Our simulation results show that this end of month inventory was for all review periods above the target as given by Dow. This implies that the actual service level at Dow, might be even lower than the results from simulation (i.e. 95% service, given the inventory in Figure 19, cannot be met in case inventory is lowered in the end of the month). The graph on the right hand side of Figure 19 shows that the average inventory from our simulation model, are for all review periods below the inventory target.

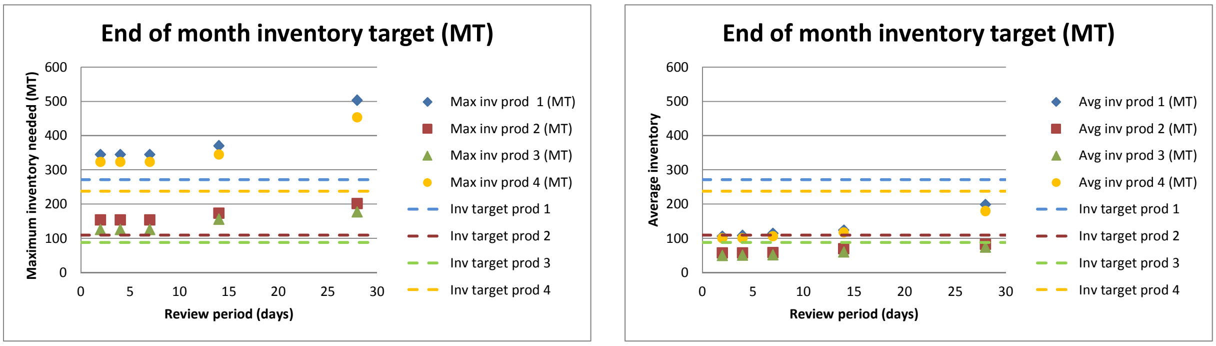


FIGURE 19: END OF MONTH INVENTORY TARGET COMPARED TO AVERAGE AND MAXIMUM INVENTORY AS A RESULT OF DYNAMIC REORDERING.

The upcoming sections will discuss the robustness of the results, as have been found in this simulation model.

6.3.5 SENSITIVITY ANALYSES

In order to verify whether our model is robust, we perform a sensitivity analysis on all input variables in our model. First of all, we look into the variance in case we run the same model, over the same horizon, with the same input, for multiple runs. Results show that for 5 runs of 1 year, the standard deviation in the found service level is 1%, whereas the standard deviation in the average inventory is 2MT.

Our second assumption was on the coefficient of variance in the duration of production per batch. In the simulation results, we assumed a CV equal to 0,5. Changing this coefficient to 0,25, results in an decrease in average inventory for a 95% service level of 3MT. Changing CV to 1 results in an increase in average inventory of 5MT.

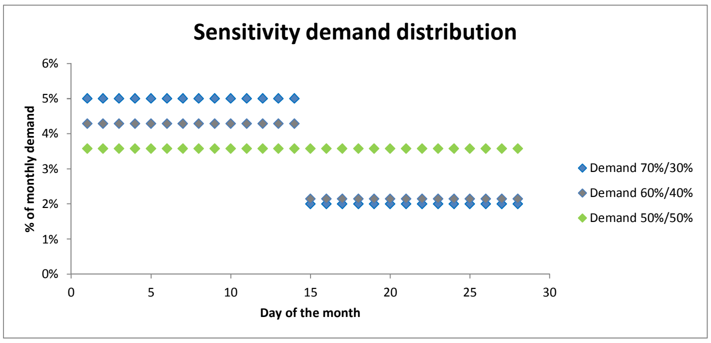


FIGURE 20: SENSITIVITY OF THE DEMAND PATTERN.

Last, we verify how the demand pattern (70% of demand in the first 2 weeks of the month and 30% of demand in the second two weeks of the month) affects our simulation results (see Figure 20). The output from this simulation model is attached in Appendix I, showing a decrease of approximately 10% in average inventory in case the demand pattern follows a 60%/40% pattern. This sensitivity analysis is also part of the sensitivity analysis of the combined outcome and process performance model.

6.3.6 DISCUSSION OF RESULTS

In this section, we discuss the differences between our model and the real-life situation and the level up to which our model covers the situation at Dow.

First of all, this model is based on assumptions on relations and the occurrence of (future) events. More specifically, it overlooks the following details: we doubt the input data used for this model, because we argued before that the currently used workarounds of the SAP systems causes data to be flawed. It might thus be the case that the consumption from tanks does not totally represent the actual demand for bulk polyol. Most likely, this consumption data underestimates the actual demand, since it only includes the actual consumption and no lost sales. Moreover, we based the distributions of demand on only 7 months of data, not taking into account any seasonal effects through the year or future growth in demand. It is very likely that demand will not be stationary over the upcoming few years, as a result of the opening of a new Dow polyol plant in Sadara (Dow joint ventures, 2015).

The second point which could enhance the accuracy of this model, is taking into account an actual variance in run-rates and including set-up times or a changeover matrix. The assumption of simply fixing the production wheel is very efficient for modeling, but lowers the flexibility in production. Logically, it takes time to switch from one product to another product and preferably this is done in an optimal order and frequency. The fact that we fixed the sequence of production underestimates the service level given an average inventory, since it decreases the flexibility of the system, especially in the situation at Dow, where short term swopping of production orders occurs very frequently. On the other hand, we might have overestimated the level of flexibility because we excluded detailed constraints like for example the availability of pipelines during loading of raw materials, which causes a delay in the process. In this model, all these type of constraints are part of the run-rate variability.

Third, there is a difference in the definition of the service level used at Dow, and the service level used in this simulation model. Dow defines service level as the percentage of orders, delivered in time, whereas we defined it as the percentage of production (MT) delivered on time. Although it is a minor difference and rounding values might be the same; our definition slightly underestimates the service level as it is used by Dow. Besides this difference in definitions, schedulers at Dow most likely prioritize external orders over internal orders, which causes our model to underestimate the external service level and overestimate the internal service level.

The last major difference between this simulation model and the real life situation is that we excluded pooling effects between reactors by pre-assigning demand to a specific reactor. Where in real life a scheduler can spread peak demand, this is not an option in the model. Based on this assumption, we slightly underestimated the service level as a function of the average inventory. The contrary is true for constraints on simultaneous production of different products on different reactors. In this model we excluded these constraints by pre-assigning products to reactors. By assuming we can produce every product on a random moment in time, we overestimated the flexibility of the system.

Besides these remarks, the principles behind this model and the idea behind it (analyzing inventory as a function of the review period) is generalizable to other business, other products, and even other organizations. Our aim was to design a robust model for the given data, which is the model we presented. Even though the results might not be 100% accurate, it gives multiple interesting insights in the current situation at Dow and how outcome performance and the review period are related.

6.3.7 CONCLUSIONS REGARDING THE MODEL FOR OUTCOME PERFORMANCE

- The review period influences the level of outcome performance in such a way that the average inventory needed to meet a fixed service level, is lower for a shorter review period
  - A shorter review period is beneficial because less demand uncertainty needs to be covered
  - A shorter review period is beneficial because the demand pattern through the month can be followed more accurately. The impact of this pattern depends on the number of production runs per month
  - The decrease in average inventory as a result of a higher review frequency flattens for higher review frequencies and is limited to a certain level

- The current inventory capacity at Dow is too limited (for some products) to run the business as a make-to-stock business with a 95% overall service level
- (Low) end-of-month inventory targets contradict the dynamic reordering policy in which average inventory is minimized for a given service level
- The combination of limited inventory, the asymmetric demand pattern, and the end-of-month inventory target causes the service level, based on a make-to-stock policy to be low. This results in a high number of ATP exceptions and consequently in a high review frequency

6.4 MODEL FOR PROCESS PERFORMANCE

Given the output of the simulation model for outcome performance, we analyze the flipside of the coin; i.e. process performance. Aim of this model is similar to the aim of the previous model, but now we analyze performance indicators for process performance as indicated in section 5.1. In this model we consider the time a scheduler spends in the informational role, the total time needed for the scheduling task and responsiveness in answering questions. The outline of this chapter follows is similar to the previous section: we discuss the input variables, describe the model, analyze the sensitivity for input variables, and discuss the results. Section 6.5 will subsequently combines the model for outcome performance with the model for process performance into an overall cost function.

Before describing the model in detail, we emphasize that this model focuses on the scheduling task, regardless of how good or bad a scheduler executes his or her task in the current situation. This section does not give a judgment about the current performance of individual schedulers, but we limit our focus to how the review period influences the definition of the scheduling task.

6.4.1 INPUT VARIABLES

Input variables for this model are based on a previous time study at the same scheduling department at Dow, BPSC. This time study was executed by Larco, Fransoo, and Wiers (2012). Object of analysis was the same group of scheduling functions, even though some schedulers have been replaced by new employees. We assume that the scheduling task has been executed in the same way during the past two years. Schedulers confirm that they execute the scheduling task in a way their predecessor told them to.

Larco, et.al. (2012) emphasized that scheduling activities occur in time and as such time should be understood as one of the most important resources of a scheduler. Besides that, the scheduler activities encompass more than just an actual decisional role (scheduling and rescheduling), but also the informational, monitoring and transactional roles must be fulfilled. Observations in this paper have given us insights in the amount of time invested in specific roles: 28,5% decisional role, 11,7% monitoring role, 47,1% informational role and 12,8% transactional role (Table 4 in Appendix J).

Other useful information from Larco, et. al.'s studies are the following: the average review period of a scheduler was 1,8 (working) days (Table 7 in Appendix J). Larco et. al. tracked the average duration of a task per role and have shown that there is a difference in endogenous and exogenous triggers to interrupt or finish a specific task. Also, we have data about the average response time (responsiveness) of a scheduler on external requests of information (Tables 3 and 6 in Appendix J).

6.4.2 MODEL DESCRIPTION

Larco, Fransoo and Wiers (2012) already highlighted time as the main resource of a scheduler, coupled by the complex, non-linear use of time (i.e. time spent in different functions, not necessarily in a sequential way). The workflow of a scheduler is highly fragmented, tasks have dependencies among each other and they are often fragmented, due to interruptions by others, and self-interrupted. In order to get a better grip on priorities, responsiveness, the relations between different tasks, and the distribution of time across different roles, we did some additional observations.

One result of our observations is that the decisional, monitoring, and transactional tasks occur mostly periodically (once per review period). It should be noted that the reviewing process contains multiple decisional tasks, multiple monitoring tasks, and multiple transactional tasks. Changing the plan asks for a fixed sequence of steps (e.g. check inventory, check SAP system, update scheduler sheet, etc.).

We know that schedulers work full-time (40 hours per week), and the time invested in the decisional role plus monitoring role plus transactional role (28,5% + 11,7% + 12,8%) is a fixed number of tasks, occurring once per 1,8 days. The paper by Larco et. al. shows that these tasks have a typical duration of 7 minutes per tasks with a coefficient of variation (CV) equal to 1 (Table 6 in Appendix J). This equals 59 tasks (decisional + monitoring + transactional) per review period. Reviewing for example 50% less frequently decreases the workload in these roles by 50%. In our Enterprise Dynamics Simulation model (Appendix K), these tasks are fired at the beginning of every review period (SOURCE DECISIONAL ROLE) and the duration is modeled as a gamma distribution with a mean and variance equal to 7 minutes (CV = 1). It should be noted that the review period is translated to working days, so reviewing twice per month (14 days run-time at the plant) is modeled as a review period of 10 working days.

Tasks of a totally different nature are tasks in the informational role. This type of tasks arrives at random moments throughout the day. Generally, these tasks are external interruptions (whereas the tasks in the decisional, monitoring and transactional role are endogenously triggered) for a scheduler, and a scheduler gives a higher priority to this type of task (e.g. answering an e-mail of phone-call before continuing for example their transactional work). This behavior is also reflected in the ranking of performance indicators; all schedulers mentioned that providing information to stakeholders was (one of) their highest priorities. Tasks in the informational role have a typical duration of 5 minutes, also with a coefficient of variation equal to 1. In our model (Appendix K), we modeled these tasks as Poisson arrivals. The scheduler (SCHEDULER TASK) is in fact modeled as a M/G/1-queue with priorities (Khintchine, 1932). The informational role is assumed to be totally exogenously triggered and has a higher priority than the periodically occurring tasks (transactional, monitoring and decisional). To make sure that the scheduler does not create an infinite queue of tasks, we assume a utilization of 90%.

The last observation we did is that the number of tasks in the informational role can be seen as a multiplier of the number of tasks in the decisional role. The more frequently a scheduler updates the plan, the more questions he or she receives per review period. This dependency is graphically shown in Figure 21, where the red line in the left graph represents the number of decisional, monitoring and transactional tasks per review period. As can be seen, this number is independent of the review frequency. The blue line, indicating the informational role, shows that the number of exogenous interruptions (informational tasks) increases with the review frequency. The graph on the right hand side shows the work load per review period, taking into account the average duration of 7 minutes for a decisional task and 5 minutes for a task in the informational role. Note that we implicitly assume that the informational role can be reduced to zero in case the review frequency is very low, whereas it goes to an infinite workload for infinite frequent reviewing.

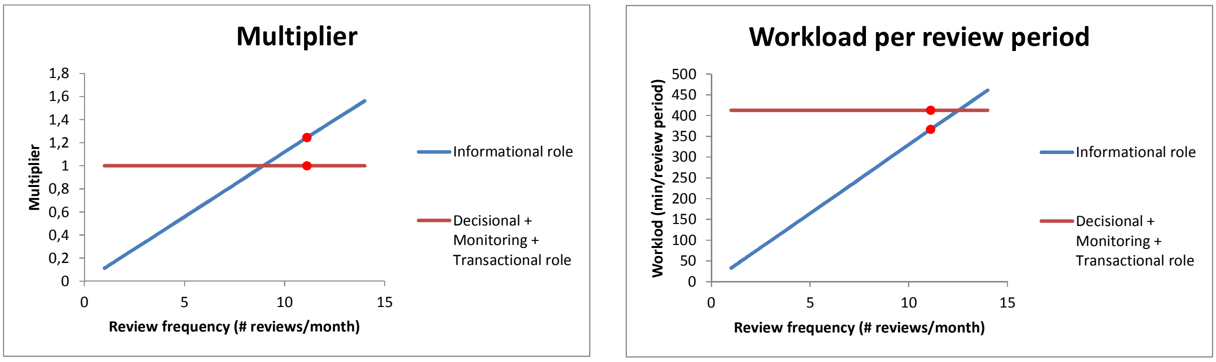


FIGURE 21: THE RELATION BETWEEN THE DECISIONAL, MONITORING, TRANSACTIONAL AND INFORMATIONAL ROLE OF A SCHEDULER.

We use the situation as found by Larco et. al. as a starting point. The input parameters are listed in Table 5 and highlighted with a red dot in Figure 21. The red dot in right graph shows the current situation where 47,1% of time is spent in the informational role.

TABLE 5: NUMBER OF SCHEDULING TASKS PER ROLE FOR A REVIEW PERIOD OF 1,8 WORKING DAYS.

Decisional + transactional + monitoring	
Review period (working days)	1,8
# tasks per review period	59
# tasks per month	656
Average duration (min)	7
Average duration (sec)	420
CV	1
Stdev duration (sec)	420

Informational	
Multiplier	1,24
# tasks per review period	73
# tasks per month	816
Interarrival-time (sec)	706
Average duration (min)	5
Average duration (sec)	300
CV	1
Stdev duration (sec)	300

The results, robustness, and accuracy of this model will be discussed in the upcoming sections.

6.4.3 SIMULATION RESULTS

Before we look into the actual simulation results on the relation between the review period and the total time needed to execute the scheduling task, we verify the initial model based on output of the research by Larco, Fransoo, and Wiers (2012). The findings that can be most easily be verified is the response time of a scheduler. As said, we modeled external requests in the informational role, with a higher priority than the tasks in the decisional, monitoring, or transactional role. The results that we have found on the average response time of a scheduler, are depicted in Figure 22. The left picture shows the actual time measurements by Larco, Fransoo, and Wiers, while the right picture shows data from the simulation model with the same input values.

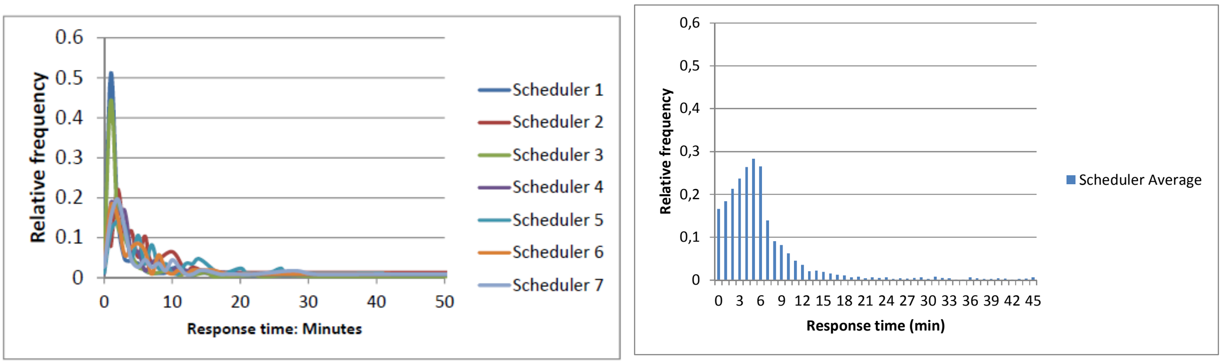


FIGURE 22: AVERAGE RESPONSE TIME OF A SCHEDULER (LEFT IS MEASUREMENT BY LARCO, FRANSOO, WIERS, RIGHT IS SIMULATION RESULT).

Table 9 shows three formal measurements to compare the model and observation results. These results show that the model matches previous observations accurately. It should be noted that the response time depends on the utilization of a server, i.e. the total workload divided by the total time a scheduler has available in this situation. Further results in this chapter will only consider the total workload needed to execute the scheduling task.

TABLE 6: COMPARISON OF MODEL AND PAPER BY LARCO, FRANSOO AND WIERS (2012).

Measure	**Paper Larco, Fransoo, Wiers (2012)**									**Model**
	Scheduler 1	Scheduler 2	Scheduler 3	Scheduler 4	Scheduler 5	Scheduler 6	Scheduler 7	**Average**	**Stdev**	
Median	2	4	3	3	5	6	7	4,3	1,8	5
>30 min	4,8%	10,4%	4,4%	9,3%	3,5%	4,8%	6,2%	6,2%	2,6%	7%
> 60 min	4,8%	7,8%	2,0%	7,5%	3,5%	4,8%	3,6%	4,9%	2,1%	3%

Changing the review frequency (or review period) in our process performance simulation model (Appendix K), provides the results on the relation between workload and review period as shown in Figure 23. The picture on the left, in which the total workload per month is shown as a function of the review period, gives clear insights in the fact that the decisional role increases linearly, while the informational role is convex. This implies that, for shorter review periods, less time needs to be spent in the informational role (see also Figure 21). The graph on the right hand side gives insights in the workload as a function of the review period. The x-axis is the same as used in the model for process performance, which allow us to combine both models later on.

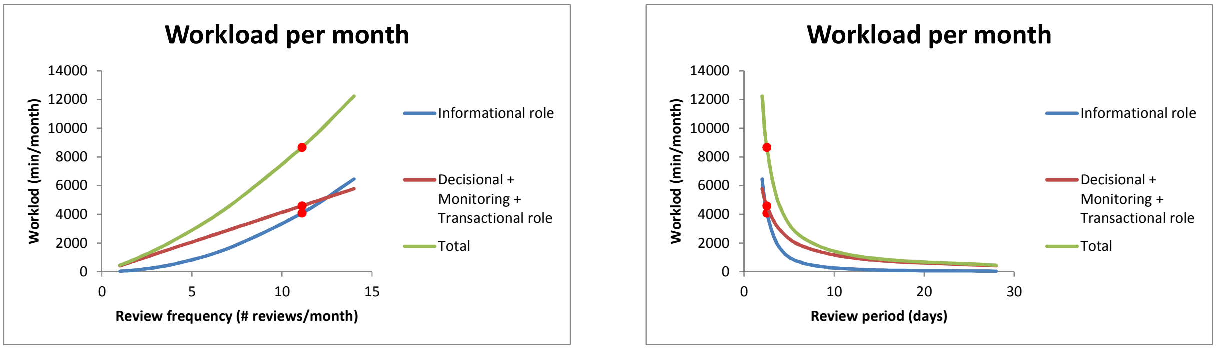


FIGURE 23: WORKLOAD AS A FUNCTION OF THE REVIEW FREQUENCY (LEFT) AND REVIEW PERIOD (RIGHT).

What this model for process performance shows is the opposite conclusion of the conclusion from the outcome performance model, namely: the longer the review period, the better. Also, this line flattens in the end, but in this case for a long review period. Besides this, we observe that the average current review frequency at Dow is very high, which is a result of the very frequent ATP exceptions, as we have argued in section 6.3. This policy causes thus a very high workload for a scheduler.

6.4.4 SENSITIVITY ANALYSES

The model above is based on a lot of assumptions, mainly on the relation between the decisional, monitoring and transactional role on one hand, and the informational role on the other hand. This relation is therefore the main focus of this sensitivity analysis. From this point on, we refer to the current workload as 1 FTE and to all other situations as a percentage of this full time equivalent.

The four variations on that will be checked for sensitivity are shown in Figures 24 to 27 and listed in Table 7. The left graph in Figure 24, Figure 25, and Figure 26 shows the relation between the review frequency and the number of tasks per review period. The right graph in these pictures shows the total workload as a function of the review period. It should be noted that the x-axis have thus opposite meanings.

In Figure 24 we analyze the impact of a decreasing decisional role. In case schedules are adjusted instead of totally renewed, this might decrease the number of steps needed if the schedule is updated more frequently.

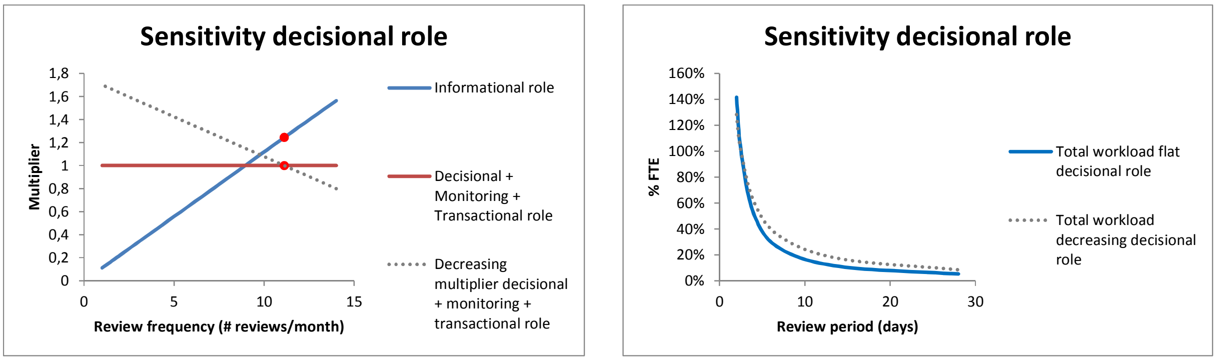


FIGURE 24: SENSITIVITY OF THE DECISIONAL ROLE IN THE PROCESS PERFORMANCE MODEL.

In Figure 25 we analyze the sensitivity of the informational multiplier, and more specifically the situation in which the informational role does not increase in workload in case the review frequency is increased. This model thus assumes a fixed number of questions per review.

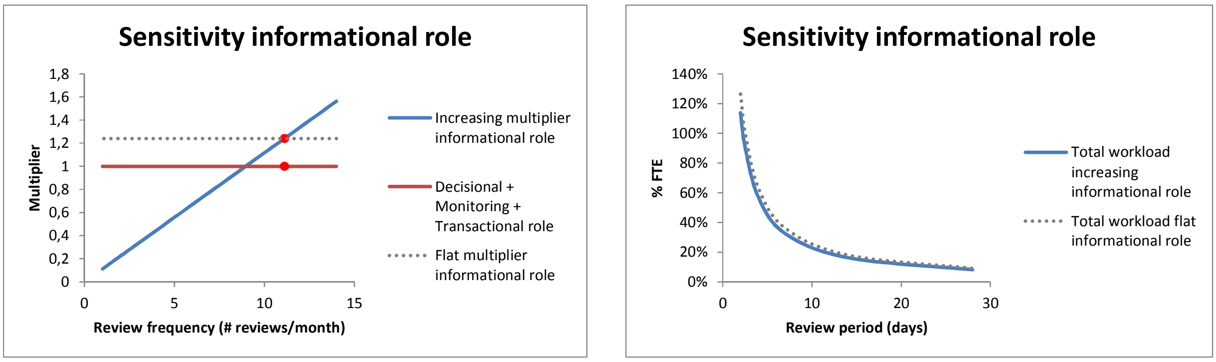


FIGURE 25: SENSITIVITY OF THE INFORMATIONAL ROLE IN THE PROCESS PERFORMANCE MODEL.

In Figure 26 we analyze the effect of decreasing the multiplier, for example by better support of the informational role. This situation does also occur in case the informational role is not totally exogenously triggered, but a scheduler can decide when to execute an informational task.

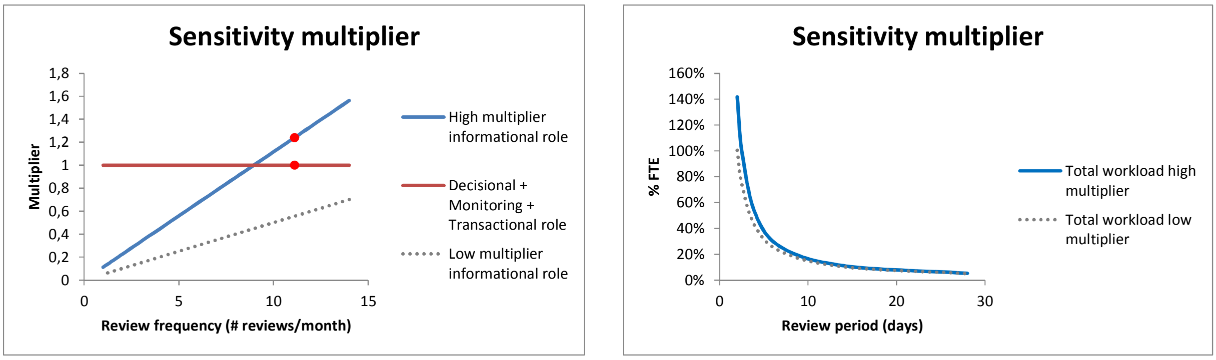


FIGURE 26: SENSITIVITY OF DECREASING THE INFORMATIONAL MULTIPLIER IN THE PROCESS PERFORMANCE MODEL.

Last, we analyze in Figure 27 what the effect is of a decrease in the overall number of tasks. In this situation we have decreased the number of decisional tasks per review period from 59 to 39. This also decreases the amount of time spend in the informational role.

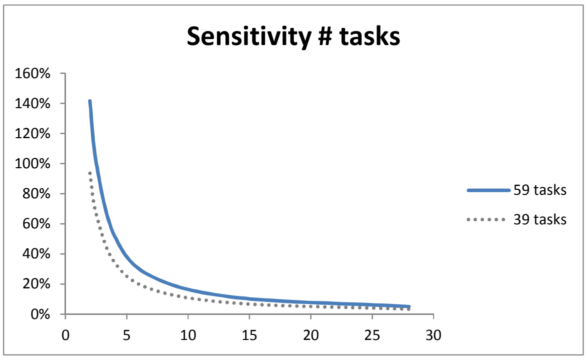


FIGURE 27: SENSITIVITY OF THE NUMBER OF TASKS IN THE PROCESS PERFORMANCE MODEL.

The overall conclusions that can be drawn from Figures 24 to 27 and Table 7 is that the process performance model is very robust for changes in the dependency between the decisional role and the informational role. Moreover, we can conclude that, for high review frequencies, better support of specific tasks does not outweigh the effect of lowering the review frequency.

TABLE 7: SENSITIVITY OF THE PROCESS PERFORMANCE MODEL.

Decisional role		Informational role		Multiplier		# tasks	
Review period (days)	Delta workload	Review period (days)	Delta workload	Review period (days)	Delta workload	Review period (days)	Delta workload
2	-13%	2	13%	2	-41%	2	-48%
4	10%	4	6%	4	-10%	4	-18%
7	9%	7	4%	7	-3%	7	-9%
14	6%	14	2%	14	-1%	14	-4%
28	3%	28	1%	28	0%	28	-2%

6.4.5 DISCUSSION OF RESULTS

Again, this model provides interesting insights on the current situation at Dow, even though it is not a 100% accurate representation of the real-life situation. The major issue is the fact that we model a human decision maker as a machine (M/G/1 queue), which is a way of thinking most behavioral scientist reject. By doing this, we overlook factors such as work-pressure, stress (the longer the queue of tasks, the higher the stress level for an employee), learning curves, and personal differences. It is hard to guess for which data points this results in an under or overestimation of the output, but what we do know is that job performance follows an inverted u-shape with the workload (Anderson, 1967), i.e., a scheduler with a challenging workload, will most likely perform best. By implementing a specific review period as the standard way of working, one should consider the effect on a scheduler's task, which will also be part of section 7.

The next disadvantage of this way of modeling is that we implicitly assumed that a scheduler spends all of his/her time scheduling. In the real-life situation, schedulers also spend time in going to meetings, helping others, etc. This implies that, especially for the long review periods, the total workload is underestimated. Also, we overlooked crisis situations like a total breakdown of the plant. This model is thus only accurate for the relatively standard day-to-day behavior of a scheduler.

The last point which is not included in this model is the amount of workarounds around the (SAP) system. We assume a fixed amount of time invested in the decisional, transactional, and monitoring role. The SAP system has been developed to optimize scheduling decisions, based on strict agreements on a lead-time, and other terms and conditions. In the actual situation we see that schedulers do not find the SAP system useful for high frequency reviewing, because they need to take into account a totally different (more detailed) set of constraints. If we translate this to the time spent in different roles, it might thus be the case that the time invested in for example transactional role, also increases as a result of more workarounds at a high review frequency. This implies an even steeper increase in workload for high review frequencies, but since we have shown that the model is not very sensitive, this is most likely a minor overestimation.

Besides the limitations of our model as discussed above, this model has given a new angle on the way schedulers work. Especially the informational role as a multiplier of the other roles explains finding on schedulers' behavior and predicts future behavior more accurately.

6.4.6 CONCLUSIONS REGARDING THE MODEL FOR PROCESS PERFORMANCE

- The review period influences the level of process performance in such a way that the total time needed is lower for a longer review period
    - A longer review period is beneficial because the total workload is lower
    - A longer review period is beneficial because a scheduler spends relatively less time in the informational role
    - The relative benefit of a increasing the review period decreases for longer review periods

- The current way of working at Dow (i.e. frequent ATP exceptions), forces schedulers to review very frequently, which results in a high workload
- For high review frequencies, it is more efficient to decrease the review frequency, compared to improving support for (one of the) scheduling roles

6.5 VALUE CASE FOR THE OVERALL PERFORMANCE MODEL

The previous two sections have shown that, the hypothesis that outcome and process performance are a trade-off, can be confirmed. The aim of this section is to combine both models to quantify and optimize the behavior of a human scheduler. First, we summarize our findings from Chapters 5 and 6 schematically in Figure 28.

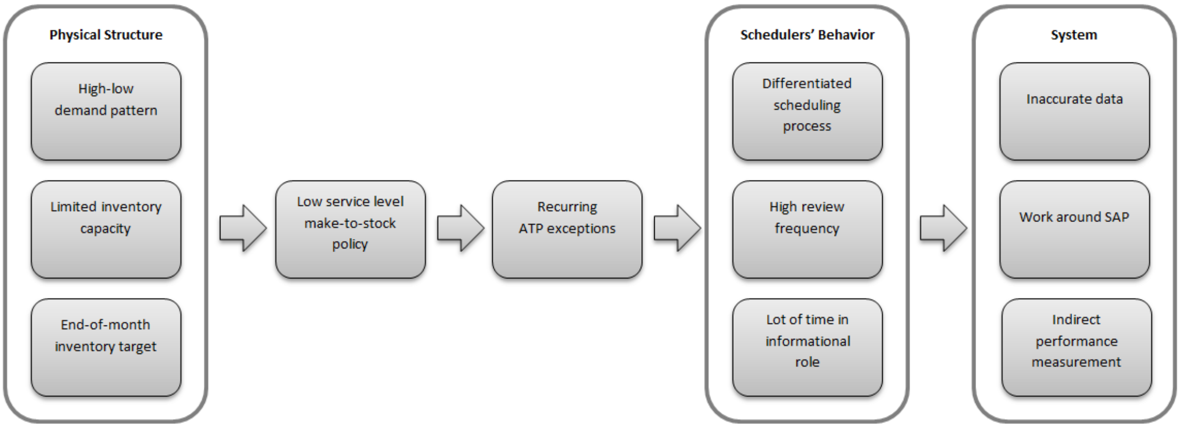


FIGURE 28: SUMMARY OF THE FINDINGS ON THE SCHEDULING PROCESSES WITHIN DOW, BPSC.

We follow this picture step-by-step, starting on the right hand side. The starting point of this research was the observation that the SAP system is not used in the way it is supposed to, and schedulers use a differentiated scheduling process. The system-block on the right hand side of this picture shows that working around the system also interacts with data inaccuracy and indirect performance measurement. Looking for root causes of this behavior, we have found that (one block to the left Figure 28) schedulers update their schedule very frequently, their day-to-day plan is exception driven, and they spend a lot of time in the informational role, and solve problems in a self-invented way. This '*schedulers' behavior*' block is also what makes back-up of absent schedulers complicated, and the learning path towards becoming a (good) scheduler very long. The main driver for this scheduling behavior (again 1 block further to the left), are the frequently occurring ATP exceptions. These exceptions are in turn a result of the fact that service levels are very low in case the business is scheduled as a make-to-stock business. Because these make-to-stock service levels are low, CSRs and schedulers try to increase the (external) service by daily updates in the schedule. And last, the block on the left hand side shows that the low service level is driven by a combination of the seasonal demand pattern trough a month, the limited inventory capacity and the end-of-month inventory reporting. In the remainder of this section we look into the question how Figure 28 can be changed and whether it is worth changing.

The models in sections 6.3 and 6.4 have quantified the trade-off between outcome performance and process performance of a human scheduler. The results indicate that the best solution for process performance is exactly the opposite of the best result for outcome performance. The most interesting conclusions can logically be drawn from a combined model for outcome and process performance. The best indicator to compare outcome and process performance is based on the total costs of the process. Even though this model is a cost optimization, all costs have been excluded from this report, as it is confidential information. All costs are scaled to a percentage of expected current costs.

Since schedulers are responsible for multiple reactors, we assume that the time spent on a reactor is equal to the percentage of reactor grades assigned to this reactor. For example: scheduler 3 is responsible for 3 reactors and 4 out of 10 reactor grades are assigned to reactor 107. We assume thus that $\frac{4}{10} = 40\%$ of his/her time is invested in scheduling reactor 107. For process performance we use the costs of a full-time equivalent (FTE), while we base the inventory holding costs on a fixed percentage over the value of a product. This approximation of the total costs (inventory + workforce) per year, as a function of the review period on reactor 107 is depicted in Figure 29. The red dot indicates the current review period (1,8 working days) at Dow.

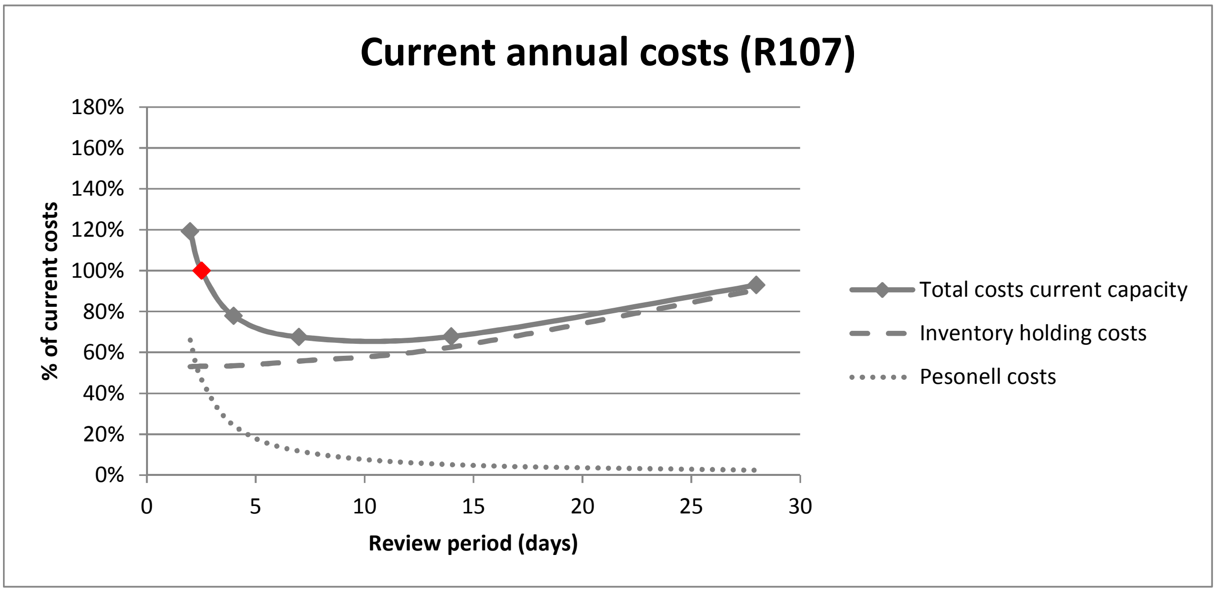


FIGURE 29: TOTAL COSTS (INVENTORY + SALARIES) FOR REACTOR 107 AS A FUNCTION OF THE REVIEW PERIOD.

As can be seen in Figure 19, the ideal (most cost efficient) review period for reactor 107, based on both inventory holding costs and wages is equal to 7 days. This indicates that the current review period at Dow is (far) too short to be efficient.

The bottleneck in changing the current situation to a review period is 7 days, is the high current number of exceptions on ATP agreements. These exceptions are driven by the fact that the inventory is too limited to meet a reasonable service level while running the business on a make-to-stock basis. To verify whether it is worth increasing the inventory capacity, we consider the option of hiring additional storage containers for a fixed payment per day. A container has a volume of 24MT. The number of additional containers needed per product on reactor 4 is listed in Table 8. The table on the right hand side refers to the product names as have been used in Appendix D.

TABLE 8: ADDITIONAL INVENTORY NEEDED TO MEET A 95% SERVICE LEVEL AT REACTOR 107.

Additional inventory (containers) R107				
Review period (days)	Product 1	Product 2	Product 3	Product 4
2	0	0	2	1
4	0	0	2	1
7	0	0	2	1
14	1	0	3	2
28	6	0	4	7

Additional inventory (containers) R107				
Review period (days)	Product N	Product O	Product P	Product Q
2	0	0	2	1
4	0	0	2	1
7	0	0	2	1
14	1	0	3	2
28	6	0	4	7

If we include the costs of capacity increase in the overall cost function, this leads to a result as shown in Figure 30. The conclusion that can be drawn from this graph is that, the overall saving of increasing capacity for products 3 and 4 (or P and Q), minimizing short term ATP exceptions, and thereby changing the review period to 7 days (green dot in Figure 30), is approximated to be equal to 22% of total costs.

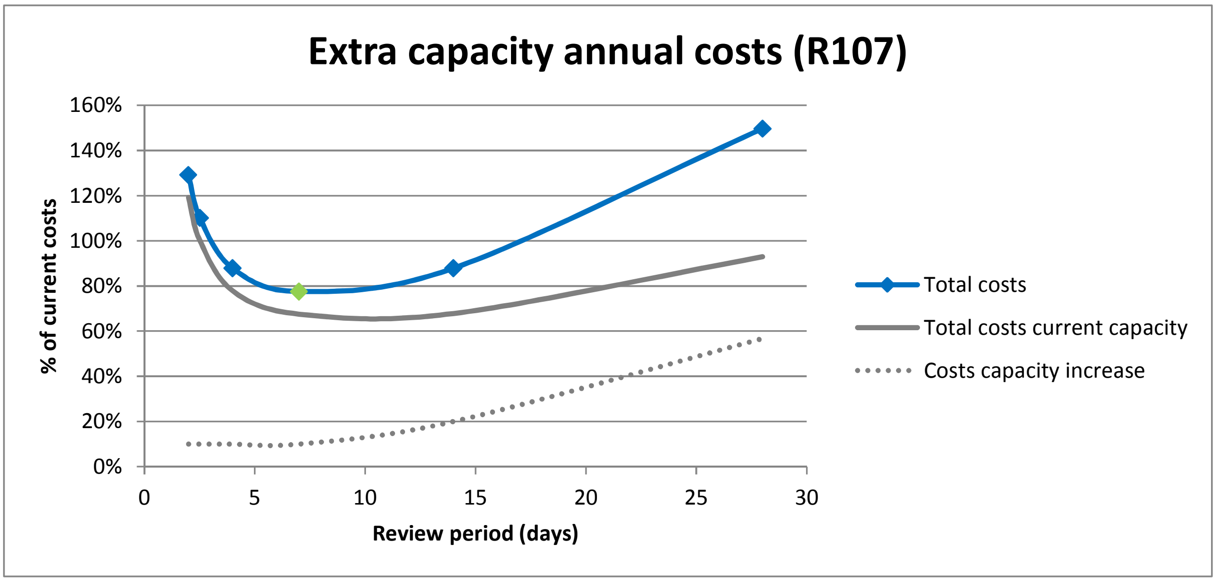


FIGURE 30: THE OVERALL COST FUNCTION INCLUDING EXTRA CAPACITY FOR REACTOR 107.

The output for all other reactors is attached in Appendix L (we only considered reactors with more than 1 assigned product, since the reactors with 1 product are all sold out and can thus produce this product at maximum speed, and do not need any (re-)scheduling). For reactors 103, 104, 105, 107, 110, and the CPP reactor, the investment of extra capacity outweighs the savings of a lower review period (to 7 days or 14 days, the latter for reactors 101 and 110). For reactor 101 the inventory capacity is already sufficient. The overall saving of this combined performance model is 26% of the current total costs of the scheduling function for these reactors. This saving is a result of around 50% decrease in the workforce needed for scheduling.

For the other reactors (i.e. 111, 113, 114 and 115) Dow copes with bottleneck products, which have an inventory capacity that is too limited to cover this difference in additional storage containers. Because of products I, V, X, AA, BB, DD, GG, and HH, which have a lack of capacity of more than 150 MT or 50% of the needed capacity, the additional investment is too high. Note that the inventory capacity for product AA (470 MT) is even too limited to fit one production run of this product (491 MT), which implies that the product can only be produced at the time it is loaded by a customer.

For these bottleneck reactors, the number of ATP exceptions is expected to be the highest, giving schedulers 1 and 4 a very challenging job. If we look back at the discussion about whether or not schedulers should adjust their schedule using a very high frequency, these were also the schedulers highlighting the importance of a very short review period (in addition to scheduler 2, who is mainly responsible for drumming). These statements can better be understood taking into account the constraints on a scheduler's inventory capacity. Observations on the current way of working confirm that these two schedulers spend most time in the informational role (quoting their colleagues: "*they are always on the phone*"), which confirms the findings of our model.

6.5.1 SENSITIVITY ANALYSES

In order to check the robustness of this combined model, we use the sensitivity analysis from both separate models. For the outcome performance model, we analyzed sensitivity as a result of changing the demand pattern from 70%/30% to 60%/40%. If we include these changes (Appendix I) in the overall cost function, this leads to the result in Figure 31, where we also included a 50%/50% pattern.

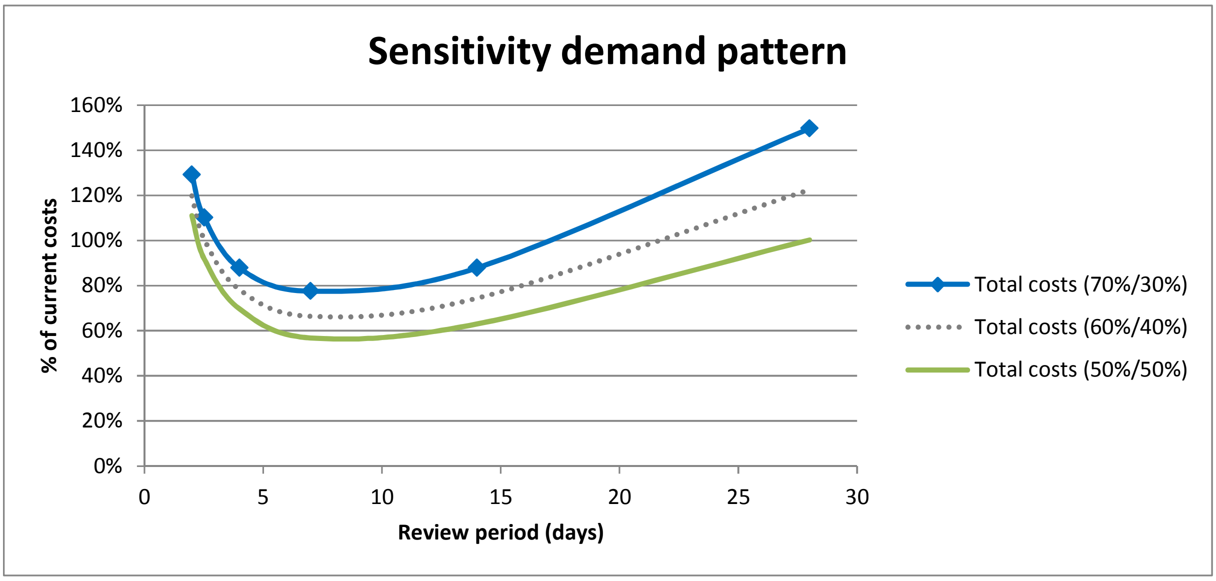


FIGURE 31: SENSITIVITY OF THE OVERALL COST FUNCTION FOR CHANGES IN THE DEMAND PATTERN.

As we see in Figure 31, changing the demand pattern from 70%/30% to 60%/40% saves approximately 10% in overall costs. The ideal situation, i.e. a 7 days review period, remains the same. The results show that the needed capacity increase in this situation includes only 1 container for product 3 (instead of 2 containers for product 3 and 1 container for product 4, see Table 8). If we manage to flatten out the demand pattern to 50%/%0%, e.g. by changing the payment terms, this would save another 10%, or approximately 20% compared to the current 70%/30% situation. It should be noted that we still need 1 additional container for product 3, even if the demand pattern is flat. This highlights the fact that that only a flat demand pattern is not enough to meet a high service level on all reactors, while scheduling production on a purely make-to-stock basis.

For the process performance model we have shown that the model was very robust for changes in the dependencies between the decisional and the informational role. As a reference, the overall cost functions for these changes are attached in Appendix M, which shows that the overall cost function is hardy affected by the mutual relations between tasks and the number of tasks. The conclusion that we draw from this part of the sensitivity analysis is that lowering the review frequency is by far more efficient than looking for better support in the current scheduling process, in terms over overall (cost) efficiency.

6.5.2 DISCUSSION OF RESULTS

Taking into account the limitations of the separate models for outcome and process performance, we did not make any rigorous new assumptions on the combined model. The major issue if we consider the real-life situation is the fact that this model promises improvement, but leaves the organizational changes needed to make this happen implicit. This redesigned situation is the topic of Chapter 7.

6.5.3 CONCLUSIONS REGARDING THE OVERALL PERFORMANCE MODEL

- Outcome performance and process performance of a human scheduler are a trade-off that can be quantitatively modeled as a function of the review frequency, leading to overall efficiency maximization
- Choosing the right review frequency is associated with substantial costs savings in the overall scheduling function
- Lowering the review frequency is more efficient than looking for better support in the current scheduling process at Dow, in terms over overall (cost) efficiency

- The current review frequency at Dow is (much) higher than optimal. This review frequency is driven by the too limited storage capacity which causes frequent ATP exceptions

- Increasing storage capacity, which results in less ATP exceptions and consequently a longer review period, saves approximately 26% in overall costs for reactors 101, 102, 103, 104, 105, 110 and the CPP reactor
- For reactors 111, 113, 114, and 115, Dow copes with several bottleneck products with a storage capacity that lacks more than 150 MT (or 50%) of storage capacity to run the business on a purely make-to-stock basis. This lack of capacity is too expensive to cover in additional storage containers

- The inventory constraints confirm previous observations of the human schedulers. Schedulers with a tighter inventory constraint spend relatively more time in their informational role and update the schedule more frequently

- Another way to save costs in operations is by flattening the seasonal demand pattern trough a month (Figure 10). If the demand pattern is distributed evenly through the month, this saves a rough estimate of 20% in overall costs. The amount of additional storage capacity also depends on the demand pattern, albeit that in case of a flat demand pattern, still additional inventory is needed to meet a 95% service level by use of a make-to-stock policy

7 PROCESS REDESIGN

In the previous section we have shown that the a model considering both process and outcome performance of the scheduling function has huge potential to improve the cost efficiency of this business function. We have shown how the current processes at Dow are driven (Figure 28), and why this situation is not optimal (Figure 30). As we mentioned already in the discussion of section 6.5, the thesis has, up to this point, only looked into the potential for improvement, but did not take into account the organizational changes need to get to this improved situation. Therefore, the aim of this Chapter is to take a step back and answer the following research questions:

4. **How can the current situation be redesigned in order to increase the overall performance of a scheduler?**
    a. **How can the optimal solution, found in the previous research questions, be implemented at Dow, BPSC?**
    b. **How does the redesigned situation contribute to standardization of processes and IT support?**

7.1 IMPLEMENTATION PLAN OF THE PROFIT MAXIMIZING REVIEW FREQUENCY

For this implementation plan, we once again follow the cause-and-effect analysis as shown in Figure 28. What we have shown in section 6.5 is that, for most reactors, the investment of additional inventory capacity is covered within the high increase in cost efficiency. In order to get to this point, we start from the left side of Figure 28. The first step on the (long) road to standardization is to change one or (preferably) multiple parts of the physical structure of the scheduling problem. The first possible improvement is to flatten out the demand pattern (by reconsidering the payment terms), the second solution is increasing the inventory capacity by renting additional storage containers, and the third improvement direction is to track inventory based on the month average, instead of an end-of-month inventory target. As a result of these mutually related changes in the physical structure, the service level for both internal and external order can be increased, while production is scheduled on a purely make-to-stock basis (using a dynamic reordering policy of the demand pattern is not flat).

As soon as this service level is high, the collaboration between scheduler and CSR can be changed. If the service level is high, the number of ATP exceptions can be minimized. As a result, a CSR can function as a gate keeper for external orders, allowing orders with a feasible delivery date according to the system, and rejecting orders which cannot be delivered on time (at most 5%). This change in responsibilities, allows the scheduler to change his/her behavior in multiple ways. First of all, he/she needs less time in the informational role, since the most frequent occurring stream of information can be minimized. Second the review frequency can be lowered to the optimal frequencies as have been found in Chapter 6. And third, opportunities are enabled to consolidate the scheduling process amongst schedulers. The expectation is that the total workforce for the scheduling function can be decreased by 50%.

The benefits of the aimed changes in the schedulers' behavior, lead to a number of benefits in the system (last block in Figure 28). First of all, the schedulers' task is brought closer to what the SAP system is designed for: supporting the decisional role for scheduling on a make-to-stock basis. As a result, the number of excels sheets around the SAP system can be minimized, resulting in more accurate data and opportunities to measure direct performance indicators.

Above, we describes the ideal situation and do not take the reactors with bottleneck products (lack of capacity >150MT or 50% of needed capacity) into consideration. For these products and reactors, the opportunities to change something in the physical structure of the scheduling problem (e.g. increasing capacity) should be explored in future research. In the current situation it is more cost-efficient to keep the (high) review frequency as it is and try to keep the (external) service level as high as possible by making frequent changes in the schedule. For these schedulers it would be interesting to look into other ways to support their tasks by treating ATP exceptions as a schedulers' primary role instead of treating it as an exception. In case Dow does not increase the inventory capacity for the other reactors, the same is through for all other schedulers.

7.2 STANDARDIZATION IN PROCESSES AND IT SUPPORT

In this section we look into the benefits for standardization and the IT structure if Dow manages to implement the aimed structure from the previous section. More specifically, we look into how the new structure affects: the schedulers' knowledge, skills and behavior, the ability and use of IT, the information reliability and correctness, the planning structure and the scheduling complexity and uncertainty (Crawford & Wiers, 2001).

7.2.1 SCHEDULER'S KNOWLEDGE, SKILLS AND BEHAVIOR

One of the reasons for this research is the fact that schedulers currently need a lot of experience to execute their task on a reasonable level. The redesigned situation changes the role of a scheduler in such a way that the task can be more standardized and less exception driven, which decreases the need for experienced schedulers. As a result of lowering the amount of time in the informational role is lowered, schedulers need fewer skills to prioritize endogenous and exogenous tasks. Moreover, back-up of a scheduler with a similar task is made easier and it increases opportunities to transfer schedulers across businesses. The most important change is that the same job can be executed with less FTE in scheduling and a shorter training period.

7.2.2 ABILITY AND USE OF IT

The ability and use of IT was also one of the main drivers for writing this paper. One of our first observations was the mismatch between what the SAP ECC systems is designed for (i.e. standard processes, decisional role, routine task) and what the schedulers' main priority is now (i.e. re-scheduling, exception management, informational role). By reviewing less often and minimizing the number of (ATP) exceptions, there will be more overlap between the system's design and the schedulers focus. In the 'new' situation, SAP can be used to optimize schedules, and communicate the schedule to stakeholders.

7.2.3 INFORMATION AVAILABILITY, RELIABILITY AND CORRECTNESS

If we look at the struggles and limitations related to the project, the major concern is accuracy of data. Besides that, it is the bottleneck in defining and especially using direct performance indicators for the scheduling task. Logically, schedulers fear to be judged on inaccurate data. The root cause of inaccurate or missing data in the current SAP system is the huge number of workarounds and the use of secondary systems (e.g. excel, e-mail, or even pen and paper). A better match between the schedulers' task, procedures, and agreements, as has been discussed in the previous 2 sections, would enhance the information availability, reliability and correctness.

7.2.4 PLANNING STRUCTURE

The planning structure, as currently used, is attached in Appendix B, in which also the discussion about make-to-stock or make-to-order can be found. In this thesis we concluded that inventory capacity, given the demand pattern, is too limited to meet a 95% service level by use of a make-to-stock policy, whereas an increase in inventory capacity enables opportunities to optimize the planning structure. Another observation in the current structure is the mismatch between performance indicators that are ranked as most important by Dow and BPSC respectively, which results in a vague description of business requirements, processes, and scheduling responsibilities. The 'new' situation enables opportunities to develop the planning structure (especially the relation between CSR and scheduler and between Dow and BPSC) in such a way that it contributes to balancing process and outcome performance.

7.2.5 SCHEDULING COMPLEXITY AND UNCERTAINTY

This section has become a repetition of facts, but also the current scheduling complexity and uncertainty is highly driven by the frequently mentioned vague agreements, ATP exceptions, and workarounds. Stricter observations of processes, and agreements lowers the scheduling complexity and uncertainty.

8 DISCUSSION AND LIMITATIONS

Before summarizing the conclusions of the chapters above, we once more discuss the limitations of this (way of doing) research. The specific limitations of the simulation models have already been treated in those chapters, so in this chapter we will have a broader perspective on the positioning of this research.

First of all, this paper is a case study on schedulers' behavior. In order to verify the generalizability of the results, more research in different scheduling situations, different companies, and different people is needed. The simulation model for outcome performance is case-specific for batch industry, but can easily be adjusted to other types of scheduling situations (e.g. continuous processes, flow production). The model for process performance is probably more generalizable to other situations, but the most rigorous assumption is the multiplier direct relation between the decisional and informational role. This assumption should be verified within different scheduling contexts (especially situations with sufficient capacity), before conclusions about the generalizability of this model can be drawn.

The second limitation is the fact that our model, even though it is robust for the data used, is founded in relatively poor data. As we discussed before, we mainly doubt the data on demand and on the run-rates of different products. Moreover, demand patterns are likely to change as a result of the opening of Dow's Sadara plant.

The last limitation of this research is the fact that we have zoomed in on one part of the production process, while in real-life, all processes are related. In this case, we build a model for bulk production, not taking into account that (for example) better spread in bulk production (by reviewing more often) also has benefits for the PO and EO plant, which in that case have a more stationary demand. The same is true on the other side of the bulk production, where side logistics and the drumming terminal are also related to what the bulk reactor does.

9 CONCLUSIONS AND RECOMMENDATIONS

In this last chapter, we give a recap of how this research contributes to scientific knowledge and improvement at Dow, BPSC, Terneuzen. Besides that, we summarize the answers to research questions and list al recommendations for Dow and for future research.

9.1 SCIENTIFIC CONTRIBUTION

In this section we look into implications of our findings for a broader perspective than the Dow scheduling department. Besides that, we define how this thesis gives a scientific contribution to the knowledge in the field of behavioral operations in planning and scheduling, resulting from our goals in Chapter 3.

First of all, we managed to define case specific performance indicators, and more important, we managed to get a grip on the mutual relationship between performance indicators. Where a lot of research has been done on an optimization of outcome performance, the knowledge on process performance still lags behind (Fransoo, Wäfler, & Wilson, 2011). Most previous studies have only mentioned the fact that more research is needed into the process by which schedulers are generated, whereas we have contributed to the knowledge in this field by explicitly defining the trade-off between outcome and process performance, resulting from the review period of a human scheduler. This trade-off is not only applicable for this specific scheduling situation, but can be extended and used within any scheduling environment.

Besides the contribution in explicit definition of the trade-off between process and outcome performance, we quantified the impact of the review frequency on both process and outcome performance by use of a simulation model. This model allows us to optimize the review period given the physical structure of the scheduling problem. Previous studies have looked into responsiveness and better support of the scheduling task (Davis, 1989) (Larco, Wiers, & Fransoo, 2013) (Cegarra & Wezel, 2012), but did not quantify the impact of process performance on the overall (cost) efficiency of the scheduling business function. The structure of this model can also be used in different contexts, bringing together theory and practice, and increase scheduling performance in the real-life scheduling situation. Moreover, the conclusions from this model consist of profound recommendations for the scheduling function in general. Two examples are the following: 1. choosing the appropriate review frequency results in substantial cost savings on the overall scheduling function; 2. Decreasing the review frequency is the more efficient in terms of overall performance than better support in (one of the) current scheduling tasks.

This thesis takes a relatively new perspective in using mathematical models to predict behavioral processes. Behavioral science mostly limits research methods to qualitative methods and laboratory studies (Katok (2011); Wezel, Cegarra, & Hoc (2011)), aiming at fully mapping the decision making process in the mind of human(s) (schedulers). This thesis shows the benefit of using research methods like simulation modeling in a behavioral context, to predict future behavior.

Besides our primary model for the trade-off between process and outcome performance of a human scheduler, simulation results have also given insights in the effect of financial and accounting agreements on operational efficiency. More specifically, we have quantified the impact of end-of-month inventory reporting in case of an opposite demand pattern. Additionally we have quantified the impact of end-of-next-month payment terms on a demand imbalance in operations. For both types of accounting agreements our model has given an indication of the decrease in cost efficiency of the scheduling function. This problem is a broadly recognized problem within a boarder context of production environments, and further investigation of this topic has potential to increase scheduling efficiency a lot more.

Our process performance model contributes to scientific knowledge by a new angle on the relation between the decisional role of a human scheduler and his/her informational role. Where previous studies have indicated the informational role as one of the most time consuming scheduling functions, the relation between these scheduling roles had not been defined before (Larco, Fransoo, & Wiers (2012); Larco, Wiers, & Fransoo (2013); Snoo (2011); Snoo, Wezel, & Jorna (2011)).

9.2 ANSWERS TO RESEARCH QUESTIONS

In addition to the scientific contribution above, we also contribute to the overall efficiency of the scheduling function at Dow, BPSC. In this section we provide a summary of findings and conclusions per research question and how this contributes to increasing performance at Dow.

1. **How can scheduling performance at Dow, BPSC be defined?**

Scheduling performance at Dow, BPSC can be defined as a combination of outcome performance (i.e. meeting delivery dates and lowering inventory) and process performance (i.e. information quality and responsiveness). Different stakeholders have different opinions on the optimal balance between the two types of performance, which results in the fact that the preferred way of working of a scheduler is not unambiguously defined. Dow values outcome performance associated with frequent updating of a schedule, while BPSC values process performance and a steady plan. Currently, schedulers spend a lot of time in their informational role, which is also reflected in the performance indicators they rank most important.

2. **What are the drivers for a differentiated scheduling process?**
    a. **Which sub-tasks can be determined based on organizational drivers for differentiated scheduling processes?**
    b. **What is the role of a scheduler per defined scheduling (sub-)task?**

Four scheduling tasks can be determined within the scope of this research: 1. PO/EO, 2. Raw materials, 3. Bulk, 4, Drumming/Formulations/blends. The responsibilities per task are listed in Chapter 5.2. Currently, most schedulers have a number of sub-tasks. Besides these differentiation based on organization drivers, the differentiated scheduling process for bulk production is also driven by a lack of clarity in the definition of a schedulers' task and the management structure of logics systems (push/pull, inventory policy, acceptance of rush orders etc.), lack of clarity in business requirements (level of flexibility, service level, etc.), and different opinions on what a scheduler's responsibilities are and what schedulers like within their job (e.g. puzzle solving). These ambiguities also drive a high variability and high number of (ATP) exceptions in a scheduler's daily job. The most fundamental difference between (bulk) schedulers is the way in which they treat ATP exceptions, and the frequency by which review their schedule. The fact that schedulers work in self-made processes and work exception-driven, does not match the functionalities of the SAP system.

3. **How can the overall performance of a scheduler be quantitatively modeled?**
    a. **What drives the trade-off between process and outcome performance of a scheduler?**
    b. **What quantitative model can be defined to model a scheduler's outcome performance?**
    c. **What quantitative model can be defined to model a scheduler's process performance?**
    d. **How can the behavior of a human scheduler be optimized taking into account both outcome and process performance?**

The review period a scheduler uses for updating and monitoring his/her production plan, drives the trade-off between outcome and process performance of a scheduler. A more frequent review period lowers the average inventory needed to meet a pre-defined service level (high outcome performance). The flipside of the coin is that a less frequent period decreases the workload of updating and adjusting schedules (high process performance). Choosing the right review frequency is associated with substantial cost savings in the scheduling function, see an example in Figure 32.

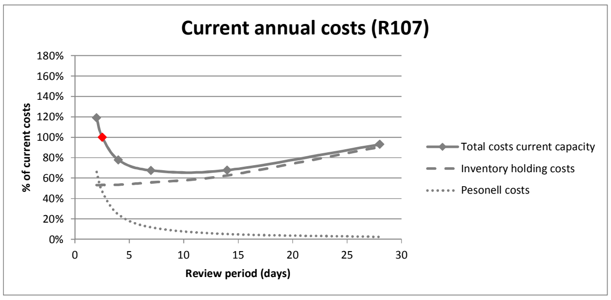


FIGURE 32: POTENTIAL COST SAVING AS A RESULT OF CHOOSING THE RIGHT REVIEW FREQUENCY.

Lowering the review frequency at Dow has to cope with a couple of difficulties. Output of the simulation models, and empirical investigation have shown that the current work processes at Dow are a result of the cause and effect diagram in Figure 33. From our outcome performance model it follows that currently used end-of-month inventory targets contradict the dynamic reordering policy in which average inventory is minimized for a given service level.

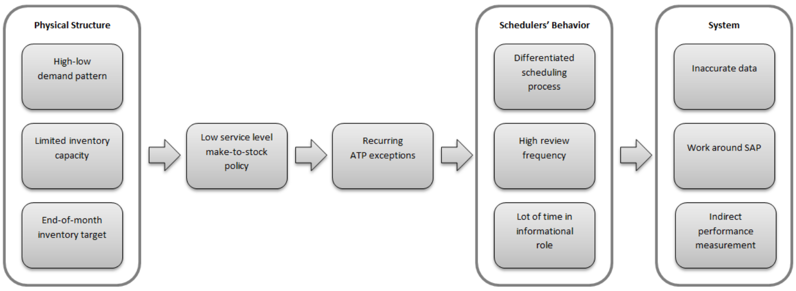


FIGURE 33: ROOT CAUSES FOR THE DIFFERENTIATED SCHEDULING PROCESS AT DOW.

We have analyzed for which reactors a capacity increase in hired storage containers is worth the investment, and shown that the expected cost saving for reactors 101, 103, 104, 105, 110, and the CPP reactor is equal to 26% in case the review frequency is lowered. An example of this a cost function including capacity increase is shown in the picture below. For reactors 111, 113, 114, and 115, the lack of inventory capacity is too much to cover in additional containers.

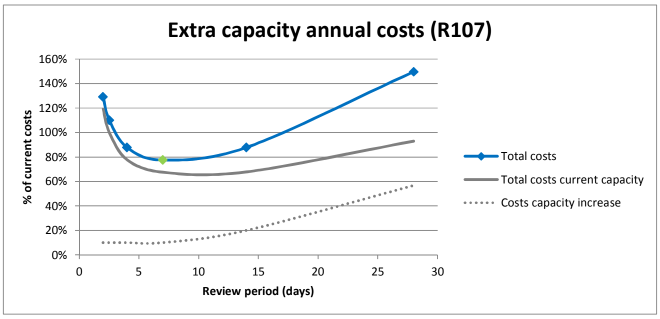


FIGURE 34: THE OVERALL COST FUNCTION INCLUDING ADDITIONAL REACTOR CAPACITY. 100% INDICATES THE CURRENT COST.

Another way to save costs in operations is by flattening the seasonal effect in demand pattern through a month as a result of the payment terms. If demand is spread evenly across the month, this saves a rough estimate of 20% in overall costs. The amount of additional storage capacity also depends on the demand pattern, albeit that in case of a flat demand pattern, still additional inventory is needed to meet a 95% service level by use of a make-to-stock policy.

For high review frequencies (like the current situation at Dow), it is more efficient to decrease the review frequency, compared to improving the support in (one of the) scheduling roles.

4. **How can the current situation be redesigned in order to increase the overall performance of a scheduler?**
    a. **How can the optimal solution, found in the previous research questions, be implemented at Dow, BPSC?**
    b. **How does the redesigned situation contribute to standardization of processes and IT support?**

To implement the redesigned scheduling process, given the optimal situation found in the answer to research question 3, Figure 33 is followed from left to right. The block on the right hand side of this figure shows that the final result is that scheduling can be standardized and the SAP system can be used. This has benefits for, performance measurement, data accuracy, ease of backing-up colleagues, shortening learning path towards becoming a scheduler, and opportunities to transfer schedulers across business.

9.3 RECOMMENDATIONS FOR THE BPSC, DOW CHEMICAL COMPANY, TERNEUZEN

Based on the analyses in the previous chapters and the conclusions above, we list the resulting recommendations for Dow.

1. **Acknowledge the trade-off between process and outcome performance for the scheduling function**

Considering the combined model of both types of performance indicators has the potential to substantially increase cost efficiency of the scheduling function. Acknowledging the trade-off includes aligning performance indicators across business functions (i.e. Dow and BPSC), which creates clarity on business requirements, the structure of logistic systems, and the task of a scheduler.

2. **Increase storage capacity for bulk polyol**

The lack of storage capacity is the current driver of the high number of ATP exceptions, leading to a far from optimal situation in the review frequency. For reactors 101, 103, 104, 105, 110, and the CPP reactor, the cost of hiring additional storage containers is covered in the expected costs savings for the scheduling process. For reactors 113, 114 and 115 (products I, V, X, AA, BB, DD, GG, and HH) the inventory capacity is too limited to cover the lack of capacity in storage containers. For these products, the opportunities to increase storage capacity should be part of further investigation.

3. **Reconsider the end-of-next-month payment terms, and monitor average inventory instead of end-of-month inventory**

The current seasonal pattern in demand during the month is a result of the end-of-next-month payment terms. A flat demand pattern saves a rough estimate of 20% in operations as a result of lower inventory. Whether this outweighs the benefits in accounting, should be part of further investigation. The end-of-month inventory target forces a production pattern, opposite to the pattern (a dynamic re-ordering policy) that minimizes average inventory for a fixed service level.

4. **Increase the service level for bulk polyol, while using a make-to-stock policy, and observing ATP agreements more strictly**

This recommendation is a follow-up on the realization of recommendations 2 and 3. Under the assumption that the inventory capacity is sufficient for the demand pattern, the service level (both for internal and external orders) should be increased. This reduces the need for ATP exceptions, which currently drive a high review frequency and high inefficiency in the scheduling process. Scheduling on a make to stock basis, means minimizing the number of ATP exceptions, and consequently lowering the amount of time a scheduler needs to spend in the informational role.

5. **Decrease the review frequency for scheduling**

This recommendation is a follow-up on the realization of recommendation 4. In case schedulers can rely on a dynamic reordering make-to-stock policy, the review frequency for scheduling should be lowered to 7 days (for reactors 103, 104, 105, and the CPP reactor) or 14 days (for reactors 101 and 110). This increases the cost efficiency of the scheduling process by an expected 26%, as a result a decrease in workforce needed for execution of the scheduling function of approximately 50%. As a result of this decreased review frequency, the scheduling process can be consolidated across schedulers and SAP can support the standardized role.

6. **If the inventory capacity is not increased, then consider ATP exceptions as the main responsibility of a scheduler instead of treating it as an exception**

If the decision is made not to increase inventory capacity, the review frequency cannot be lowered, since the ATP exceptions continue to occur on a frequent basis. Otherwise, the service level to external customers will be too low. In this case, the ATP exceptions should be considered one of the main responsibilities of a scheduler and DSSs and work process should be designed for support of this task. The design of this process should be object of further investigation, and scheduling cannot be consolidated across businesses.

9.4 RECOMMENDATIONS FOR FUTURE RESEARCH

In this section we list the recommendations for future research.

1. **Analyze the trade-off between process and outcome performance**

This thesis had made the trade-off between outcome and process performance very explicit. For future research on outcome or process performance, researchers should take into account that both are related. The combination of both performance indicators is a promising direction to increase performance of the process by which schedules are created. Interesting directions for future research would be to investigate whether other drivers for the trade-off can be defined, and how this trade-off occurs in other scheduling environments.

2. **Investigate time as one of the most important resources of a human scheduler**

In this thesis we have looked into the relation between different scheduling roles, from the perspective of workload. More research is needed to analyze the mutual relations between scheduling tasks and how schedulers use their time. The review frequency is most likely not the only driver for the ratio between different scheduling tasks, and future research should investigate other contextual factors influencing the usage of time within the process of schedule creation.

3. **Consider other scheduling roles (not only the decisional role) of a scheduler in the development and analysis of Develop Decision Support Systems for scheduling**

As shown in multiple different environments, the main objective of a scheduler is not to build a production plan, but to fulfill multiple different roles. Currently, decision support systems are mainly designed to support the decisional role of a scheduler. Great progress can be made in process performance, in case DSSs would support the informational role too.

4. **Quantify the cost of accounting agreements (e.g. end-of-month reporting) in operations**

In this thesis, we quantified the impact of accounting agreements on the demand- and production- pattern, and resulting efficiency in operations. This problem is recognized in a broad range of production environments and future research should quantify the effects of these generally used agreements across businesses.

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11 VARIABLES

$\boldsymbol{R}$	Review period (days)
$\boldsymbol{d} = (1, \dots, \mathrm{R})$	Day within review period
$\boldsymbol{T} = \frac{28}{R}$	Number of review periods per month
$\boldsymbol{t} = (1, \dots, \mathrm{T})$	Number of the review periods (within a month)
$\boldsymbol{x} = \epsilon\{1, \dots, i\}$	Product type on a reactor with *i* products
$\boldsymbol{RL_x}$	Run-length for product *x* (MT)
$\boldsymbol{Dur_x} \sim gamma(\mu_{Dur,x}, \sigma_{Dur,x})$	Duration of a production run of product *x* (sec)
$\boldsymbol{I_{t,\mathrm{x}}}$	Inventory of product *x* at the beginning of review period *t* (MT)
$\boldsymbol{B_{t,\mathrm{x}}}$	Backorders of product *x* at the beginning of review period *t* (MT)
$\boldsymbol{S_{t,x}}$	Order up to level of product *x* at the beginning of review period *t*
$\boldsymbol{P_{plan,t,\mathrm{x}}}$	Planned production of product *x* at the beginning of review period *t* (runs)
$\boldsymbol{P_{reactor,t,x}} = \epsilon\{0,1\}$	1 if reactor is producing product *x* at the beginning of review period *t*, else 0
$\boldsymbol{D_{known,d,T,x}} \sim gamma(\mu_{known,d,t,x}, \sigma_{known,d,t,x})$	Known demand of product *x* on day d of review period *t* (MT)
$\boldsymbol{D_{unknown,d,T,x}} \sim gamma(\mu_{unknown,d,t,x}, \sigma_{unknown,d,t,x})$	Unknown demand of product *x* on day *d* of review period *t* (MT)
$\boldsymbol{E}(\boldsymbol{D_{unknown,d,t,x}}) = \mu_{unknown,d,t,x}$	Expected unknown demand of product *x* on day *d* of review period *t*(MT)
$SS_{t,x}$	Safety stock of product *x* in review period *t* (MT).
$I_{buildup,x}$	Quantity of product *x* that needs to be built up in the second part of the month in order to meet demand in the first part of the month.

12 DEFINITIONS AND ABBREVIATIONS

Aggregate plan	Plan for the production process over a 1 to 5 years horizon, to give an idea to management as to what quantity of materials and other resources are to be procured and when, so that the total cost of operations of the organization is kept to the minimum over that period.
Arrival rate	Number of customers or orders arriving per unit of time (e.g. MT/day)
Backorder	An order (quantity) which cannot be delivered on the requested or confirmed delivery date
Batch production	A technique used in manufacturing, in which the object in question is created stage by stage over a series of workstations, and different batches of products are made. In the polyol specific case, a reactor produces one batch of a fixed amount at once.
BPSC	Business Process Service Center
CSR	Customer Sales Representative
CV	Coefficient of variance (standard deviation/mean)
Decisional role	One of the four scheduling roles as defined by Jackson et. al. (2004). The decisional role includes scheduling and re-scheduling activities for a given horizion.
Demand	Quantity of a product requested by a customer
Demand forecast	An estimate of the quantity of a product that customers will purchase
Deterministic process	Data without randomness in the development of future states of the system
Dow	The Dow Chemical Company
Empirical research	A way of gaining knowledge by means of direct and indirect observation or experience
Enterprise Dynamics	A discrete event simulation software platform developed by INCONTROL Simulation Solutions
EO	Ethylene Oxyde; a raw material for Polyol production
Finishing train	When the polyol manufacturing reaction is complete, the polyol products are separated from byproducts and water by means of precipitation and distillation on a finishing train
FTE	Full-time equivalent; a unit that indicates the workload of an employed person

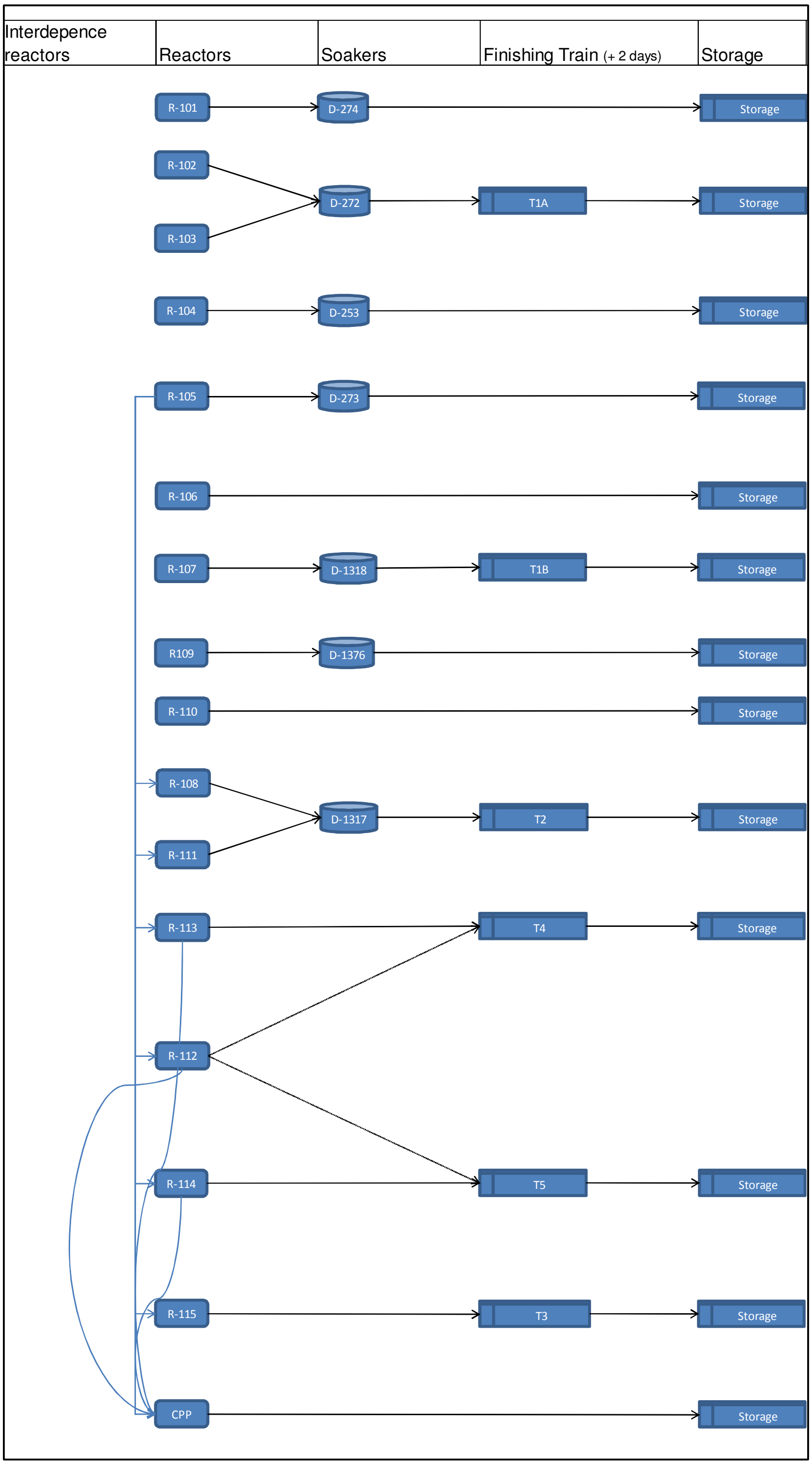
Gamma distribution	A two-parameter family of continuous probability distributions with shape parameters k and scale parameter theta
GMID	Unique code per product (bulk/packaged good) within Dow
IBC	Intermediate Bulk Container
Informational role	One of the four scheduling roles as defined by Jackson et. al. (2004). The informational role includes providing and collecting information from external parties.
Initiators	Product to initiate the reacting between EO/PO and other raw materials for polyol production in a reactor
Inter arrival time	The time between consecutive events
Job production	Producing custom work, such as a one-off product for a specific customer or a small batch of work in quantities usually less than those of mass-market products
Lead time	The latency between the initiation and execution of a process
Make to order	A production approach where products are not built until a confirmed order for produts is received
Make to stock	A build-ahead production approach in which production plans may be based upon sales forecast and/or historical demand
Monitoring role	One of the four scheduling roles as defined by Jackson et. al. (2004). The monitoring role complements the decsional role and consists of monitoring stocks, demand fluctuations, new customer orders and the execution of production orders so that the scheduler may asses the need for re-scheduling.
MT	Metric Ton (1.000 ton = 1.000.000 kg)
Outcome performance	Performance measure for scheduling related to the quality of a schedule (e.g. service level, inventory costs). (Snoo, Wezel, & Jorna, 2011)
OTC2e	Service level measure based on requested delivery date
OTC6i	Service level measure based on confirmed delivery date
Planning	Planning and scheduler refer to the (manufacturing) management process by which resources are assigned to processes in time. At Dow, planning considers the 3 months to 1 year horizon.
PO	Propylene Oxyde; a raw material for polyol production
Poisson process	A stochastic process that counts the number of events and the time points at which these events occur in a given time interval
Polyol	An alcohol containing multiple hydroxyl groups

Process performance	Performance measure for scheduling related to the efficiency of the planning or scheduling process (e.g. speed of schedule adaption, responsiveness) (Snoo, Wezel, & Jorna, 2011)
Queuing theory	The mathematical study of waiting lines or queues. In queuing theory a model is constructed so that queue lengths and waiting times can be predicted
Reactor	In a reactor, an initiator reacts with PO/EO, or other raw materials to produce polyol
Reactor grade	A specific bulk polyol products (GMID)
Replenishment lead time	The total period of time that elapses from the moment it is determined that a product should be reordered until the product is available. For sequenced batch production it is the period time from the start of the first production run of a specific product until the start of the second run of the same product.
Response time	Response time is the total amount of time it takes to respond to a request for service
Review	The formal assessment of a schedule with the intention to change it if necessary
Review frequency	The number of reviews per unit of time
Review period	The time between two consecutive reviews
Run rate	The amount of product that can be produced per unit of time (e.g. MT/hour)
Safety stock	A term used by logisticians to describe a level of extra stock that is maintained to mitigate risk of stock outs due to uncertainties in supply and demand
SAP ECC	Enterprise Resource Planning software which incorporates the key business functions of an organization
Scheduling	Planning and scheduler refer to the (manufacturing) management process in which resources are assigned to processes in time. At Dow, scheduling considers the day to day release of production orders.
Service level	The amount of product, or the number of orders that can be delivered at the requested (or confirmed) delivery date (e.g. orders/day or MT/day)
Simulation modeling	the process of creating and analyzing a digital prototype of a physical model to predict its performance in the real world
Standard deviation	A measure used to quantify the amount of variation or dispersion of a set of data values (square-root of variance)
Stochastic process	A collection of random variables representing the evolution of some system of random values over time
Tardiness	The amount of time a order is delivered late
Ton	A non-SI metric unit of mass equal to 1000 kilograms

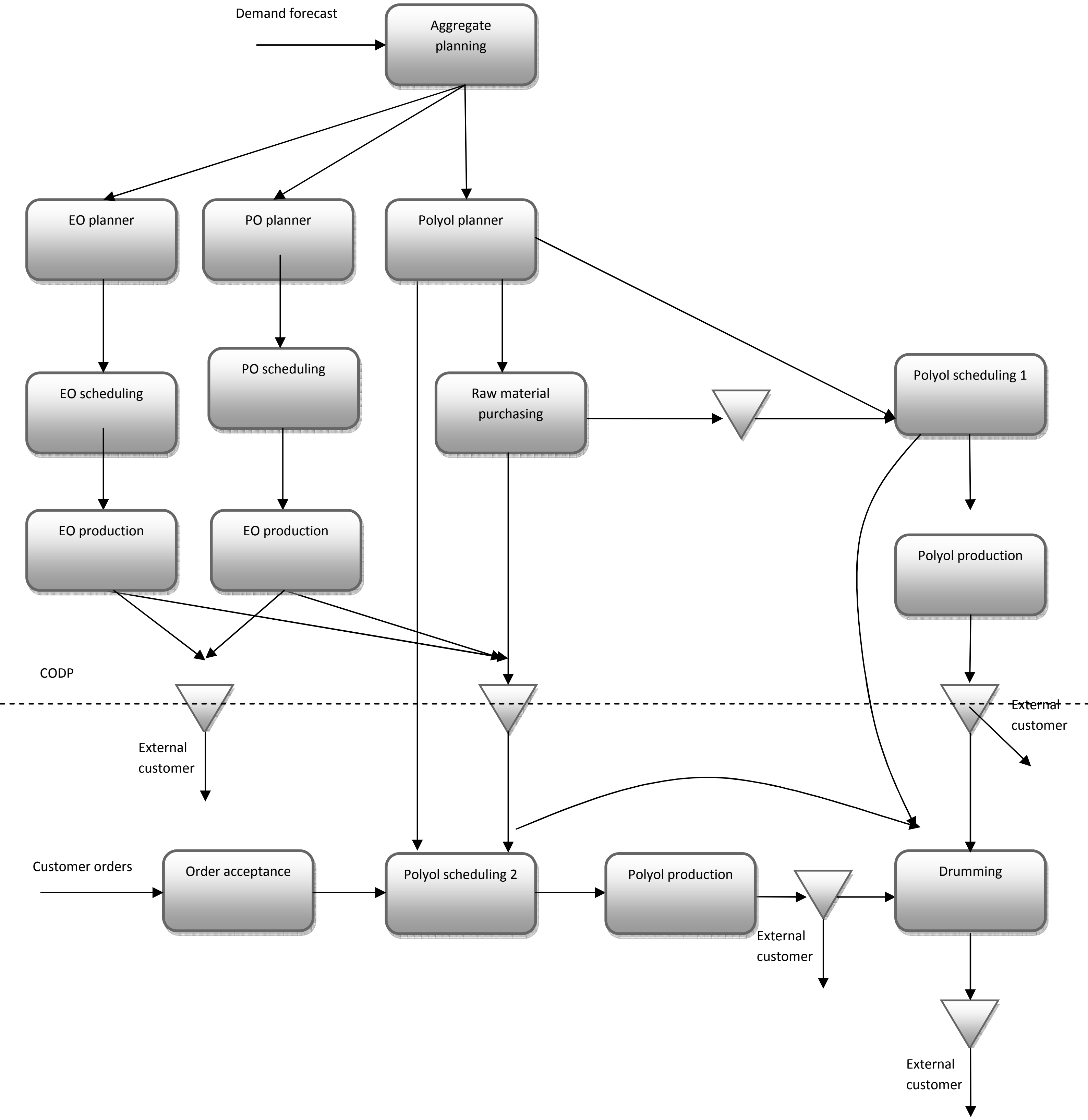
Transactional role	One of the four scheduling roles as defined by Jackson et. al. (2004). The transactional role infovoles the follow-up of prescribed procedures of the firm, such as creating a delivery note.
TU/e	Eindhoven University of Technology
Variance	The square of the standard deviation, which is a measure to quantify the amount of variation or dispersion of a set of data values

13 APPENDICES

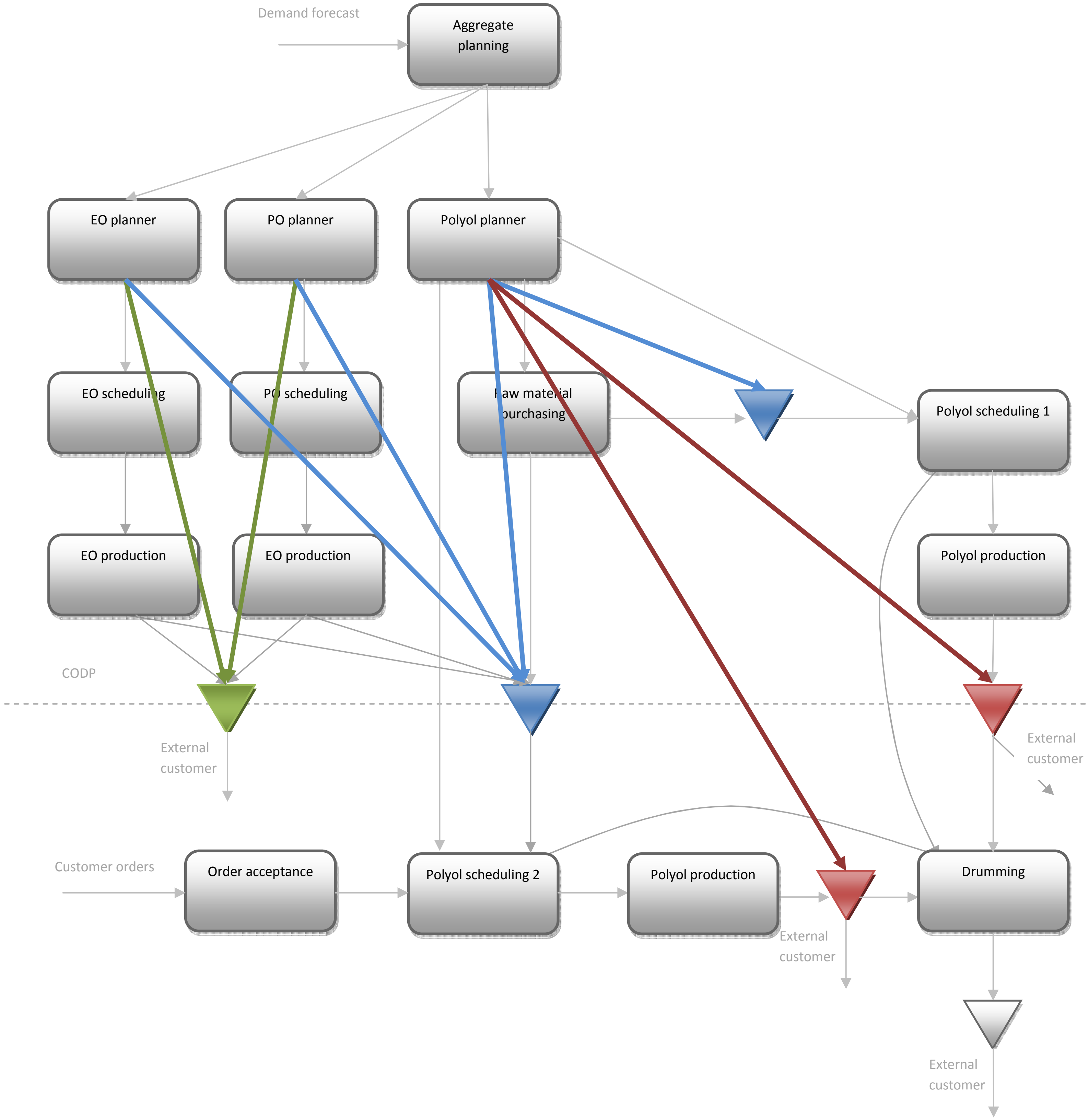
APPENDIX A: REACTOR AND TRAIN OVERVIEW POLYOL, BPSC TERNEUZEN



APPENDIX B: POLYOL SCHEDULING, BPSC TERNEUZEN



APPENDIX C: INVENTORY TARGETS



APPENDIX D: DATA BULK PRODUCTION PER SCHEDULER

The tables below show the input data for the simulation model for outcome performance. Per scheduler, the reactors are listed. The demand is translated to 28 days (based on the number of days in the data period May 2014 to November 2014).

Scheduler 1

Reactor	Product	Demand per month (MT)	Demand standard deviation (MT)	CV	Run rate (MT/hour)	Run-length (MT)	Inventory capacity (MT)	Inventory target (MT)	% assigned	Correction factor run rate (%)	Assigned demand per month (MT)	Assigned inventory capacity (MT)	Assigned inventory target (MT)	K	Theta
		Average (May 2014-November 2014) SAP consumption	SAP consumption		Planners workbook	Planners workbook	Master database Tank Overview	Average (May 2014-November 2014) Planners workbook	Heuristic chapter 6	* heuristic chapter 6					
104	A	2676	191	0,1	2,8	33	302	231	50%	12%	1.208	151	115	89	14
	B	591	64	0,1	2,3	99	173	125	0%						
	C	138	24	0,2	0,7	29	75	97	100%		125	75	97	30	4
	D	160	23	0,1	1,8	29	68	120	100%		145	68	120	44	3
105	A	2676	191	0,1	3,3	33	302	231	50%	17%	604	151	115	20	30
	E	118	39	0,3	0,7	30		66	100%		106		66	8	14
	B	591	64	0,1	2,8	99	173	125	100%		534	173	125	69	8
	C	138	24	0,2	1,7	29	75	97	0%						
	D	160	23	0,1	2,2	29	68	120	0%						
108	A	2676	191	0,1	3,6	33	302	231	0%						
112	A	2676	191	0,1	5,4	73	73	231	0%						
	F	1700	572	0,3	6,1	73	790	454	0%						
	G	21983	6533	0,3	7,4	74	5004	322	30%		312	1.501	97		
	H	346	166	0,5	6,3	7	480	322	0%						
113	F	1700	572	0,3	20,5	450	790	454	100%	80%	1.536	790	454	8	193
	H	346	166	0,5	19,6	300	480	322	100%		312	480	322	4	80
	G	21983	6533	0,3	20,6	675	5004	3574	70%		9.729	3.503	2.502	10	1941
	I	1777	662	0,4	20,6	450	460	429	100%		1.605	460	429	7	246
114	G	21983	6533	0,3	18,0	158			0%						

Scheduler 2

Reactor	Product	Demand per month (MT)	Demand standard deviation (MT)	CV	Run rate (MT/hour)	Run-length (MT)	Inventory capacity (MT)	Inventory target (MT)	% assigned	Correction factor run rate (%)	Assigned demand per month (MT)	Assigned inventory capacity (MT)	Assigned inventory target (MT)	K	Theta
		Average (May 2014-November 2014) SAP consumption	SAP consumption		Planners workbook	Planners workbook	Master database Tank Overview	Average (May 2014-November 2014) Planners workbook	Heuristic chapter 6	* heuristic chapter 6					
CPP	J	3649	644	0,2	7,03	248	1579	1819	100%	20%	3296	1579	1819	297	11
	K	148	26	0,2	2,23	132	159	144	100%		134	159	144	12	11
	L	1267	300	0,2	5,32	213	800	666	100%		1144	800	666	315	4

Scheduler 3

Reactor	Product	Demand per month (MT)	Demand standard deviation (MT)	CV	Run rate (MT/hour)	Run-length (MT)	Inventory capacity (MT)	Inventory target (MT)	% assigned	Correction factor run rate (%)	Assigned demand per month (MT)	Assigned inventory capacity (MT)	Assigned inventory target (MT)	K	Theta
		Average (May 2014-November 2014) SAP consumption	SAP consumption		Planners workbook	Planners workbook	Master database Tank Overview	Average (May 2014-November 2014) Planners workbook	Heuristic chapter 6	* heuristic chapter 6					
106	M	301	99	0,3	1	66	238		100%						
107	N	1052	283	0,3	4,1	96	365	271	100%	0%	1052	365	271	14	76
	O	245	195	0,8	3,7	96	235	109	100%		245	235	109	2	154
	P	134	22	0,2	3,7	96	96	88	100%		133	96	88	36	4
	Q	890	378	0,4	3,7	96	303	238	100%		889	303	238	6	161
110	R	71	39	0,6	0	50	135	52	100%	0%	64	135	52	3	22
	S	99	60	0,6	0,9	50	89	58	100%		89	89	58	2	37
	T	31	20	0,7	0,7	50			100%		28			2	13
	U	107	80	0,7	0,7	50			100%		97			2	60

Scheduler 4

Reactor	Product	Demand per month (MT)	Demand standard deviation (MT)	CV	Run rate (MT/hour)	Run-length (MT)	Inventory capacity (MT)	Inventory target (MT)	% assigned	Correction factor run rate (%)	Assigned demand per month (MT)	Assigned inventory capacity (MT)	Assigned inventory target (MT)	K	Theta
112	V	1285	700	0,5	3,0	75,9	790	418	0%						
	W	2043	943	0,5	3,1	76	790	501	0%						
	X	806	195	0,2	2,3	76,4	470	0	0%						
	Y	520	224	0,4	3,6	76,4	770	364	0%						
114	Y	520	224	0,4	8,0	480	770	364	100%	10%	469	770	364	5	97
	V	1285	700	0,5	11,1	480	790	418	100%		1161	790	418	3	381
	W	2043	943	0,5	11,0	480	790	501	100%		1845	790	501	4	435
	X	806	195	0,2	9,3	480	470		100%		728	470		16	47
	Z	2869	1251	0,4	6,6	480	470	327	0%						
	AA	543	124	0,2	9,3	480	470		100%		491	470		17	28
	BB	990	455	0,5	5,3	480	485	372	0%			485	372		
	CC	2017	458	0,2	8,9	320	630	560	100%		1822	630	560	18	104
115	Z	2869	1251	0,4	8,1	320	1300	686	100%	20%	2592	1300	686	5	545
	BB	990	455	0,5	7,6	495	485	372	100%		894	485	372	4	210
	DD	2134	1173	0,5	7,9	495	470	492	100%		1927	470	492	3	645
	CC	2017	458	0,2	7,9	495	630	560	0%						
	FF	584	126	0,2	6,8	320	470	212	100%		526	470	212	20	27

Scheduler 5

Reactor	Product	Demand per month (MT)	Demand standard deviation (MT)	CV	Run rate (MT/hour)	Run-length (MT)	Inventory capacity (MT)	Inventory target (MT)	% assigned	Correction factor run rate (%)	Assigned demand per month (MT)	Assigned inventory capacity (MT)	Assigned inventory target (MT)	K	Theta
108	GG	2177	835	0,4	3,7	420		636	0%						
	HH	2650	942	0,4	2,8	420		18	80%						
	II	1334	964	0,7	3,2	420			0%						
111	II	1334	964	0,7	5,3	420	770		100%	10%	1205	770		2	697
	GG	2177	835	0,4	5,8	420	770	636	100%		1966	770	636	6	320
	HH	2650	942	0,4	4,6	420	770	18	20%		96	154	4	0	1673
109	JJ	3827	1441	0,4	5,3	47			100%						
101	KK	594	254	0,4	1,7	60	324		100%	0%	537	324		5	108
	LL	727	234	0,3	1,2	105	321	172	50%		164	161	86	1	151
102	LL	727	234	0,3	1,3	105	321	172	0%						
	MM	1288	467	0,4	1,3	105	490	240	65%			319	156		
103	LL	727	234	0,3	1,3	105	321	172	50%	0%	164	161	86	1	151
	MM	1288	467	0,4	1,2	105	490	240	35%		142	172	84	0	484

APPENDIX E: DEMAND PACKED GOODS CPP

In the table below, the monthly demand for CPP packed goods is listed. For the sake of confidentiality, the product names have been deleted. As can be seen, the order quantities are generally lower than the quantities ordered for bulk (appendix D), while the coefficient of variance is generally higher.

Demand (MT)	Standard deviation Demand (MT)	CV
571200	234720	0,4
72415	57409	0,8
85155	46178	0,5
78015	50678	0,6
282080	204252	0,7
1436917	316374	0,2
12600	9896	0,8
8820	9662	1,1
21700	17503	0,8
2660	6516	2,4
95200	69874	0,7
29540	29581	1,0
28560	29579	1,0
78400	60728	0,8
78400	95430	1,2
566440	256310	0,5
109200	170253	1,6
107800	128211	1,2
1430897	401518	0,3
290537	193599	0,7
266600	361562	1,4
259720	356426	1,4
11760	14176	1,2
11760	14176	1,2
2800	6859	2,4
3080	3999	1,3
3	4	1,7
4	5	1,2
2	3	1,5
3	8	2,4
3	4	1,7

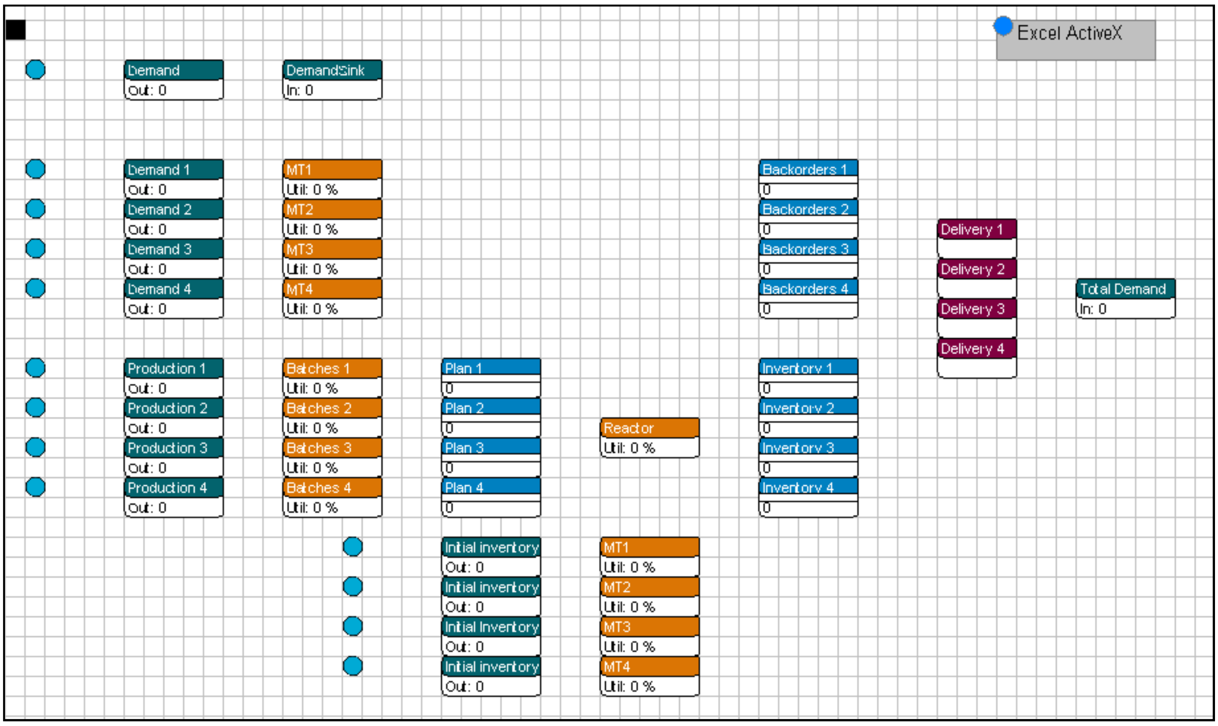
Appendix F: Service levels Polyol bulk

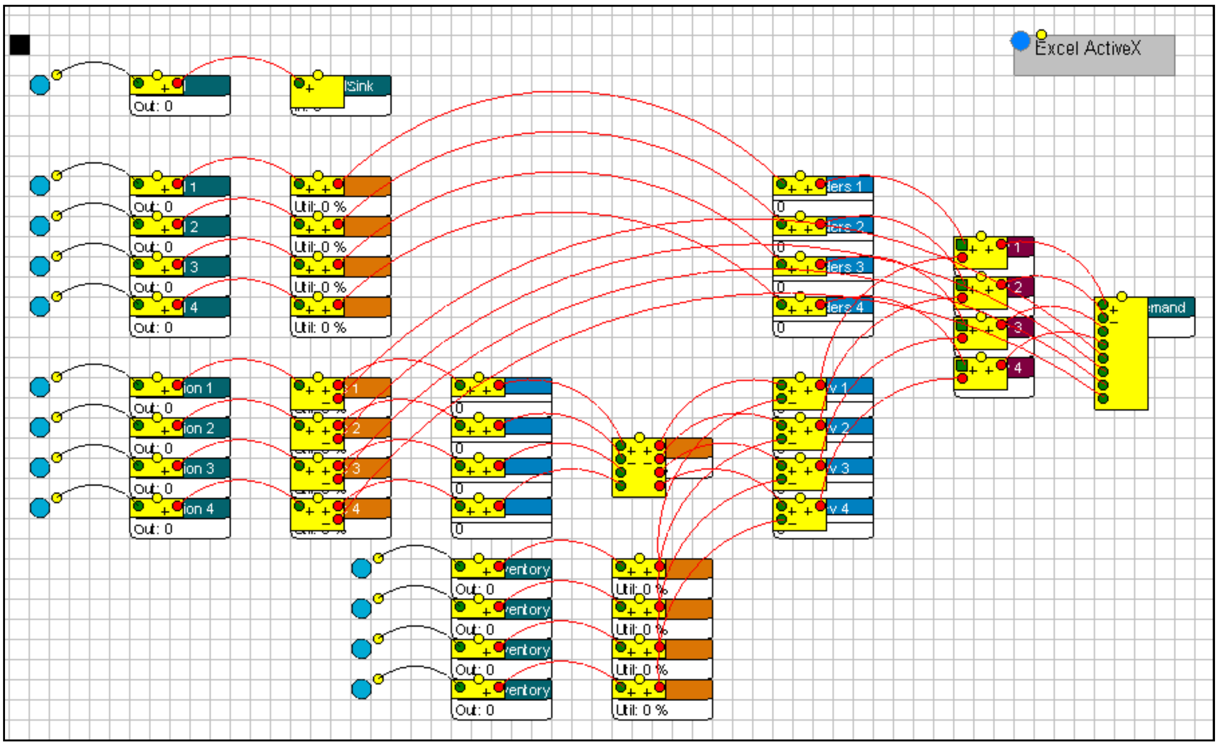
The product names are confidential and therefore deleted. OTC2e reports the difference between requested delivery date and actual delivery date, whereas OTC6i reports the difference between confirmed delivery date and actual delivery date. This data represents an average over the months May-November 2014. Column 1 and 2 represent data for all orders (both internal and external), and column 3 only focuses on external orders. The Dow employee responsible for service level reporting doubts the accuracy of reporting on internal orders (e.g. all orders might be reported at the beginning or the end of a week).

The average service level considering both bulk and packed goods for poyol is 93% over the same period.

Service levels bulk								
OTC2e All bulk	Averge	Stdev	OTC6i All bulk	Averge	Stdev	OTC6i bulk External trade only	Averge	Stdev
58%	57,7 %	23,2 %	74%	74,2 %	22,8 %	77 %	87,0 %	18,2 %
42%			49%			100 %		
68%			81%			100 %		
44%			58%			86 %		
68%			88%			94 %		
79%			93%			92 %		
69%			87%			100 %		
33%			52%			80 %		
52%			77%			0 %		
73%			89%			90 %		
50%			85%			85 %		
64%			84%			91 %		
34%			61%			100 %		
53%			67%			76 %		
83%			92%			75 %		
76%			87%			83 %		
26%			41%			92 %		
7%			19%			95 %		
44%			79%			92 %		
75%			100%			74 %		
70%			87%			85 %		
71%			86%			85 %		
43%			56%			97 %		
62%			76%			100 %		
100%			100%			100 %		
72%			89%			100 %		
33%			100%			79 %		
25%			32%			97 %		
99%			100%			80 %		
25%			25%			100 %		
50%			59%			79 %		
100%			100%			100 %		

APPENDIX G: ENTERPRISE DYNAMICS MODEL FOR OUTCOME PERFORMANCE (R107)



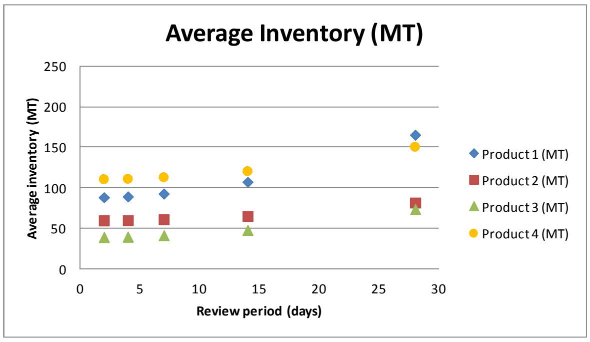


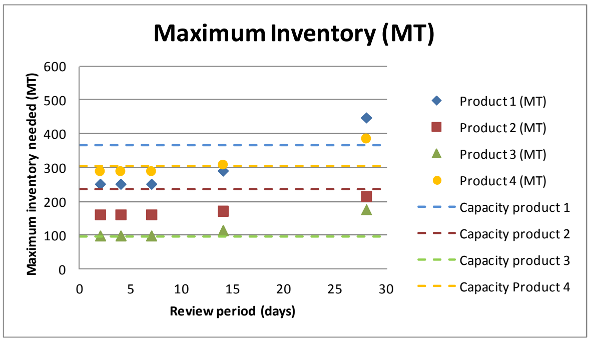
APPENDIX H: MODEL DEMAND

The table below shows an overview of the demand as is used in the outcome performance model for product 1 on reactor 107. The first column indicates the day of the month, the second column indicates the percentage of demand that is expected to occur on this day (see also Figure 10). The third column shows the percentage of orders that is known in advance on a specific day in the future (see Figure 9). The columns for mean known, variance known, mean unknown, and variance unknown are based on the gamma distribution for monthly demand with parameters k and theta as indicated in the second row of the table. Mean known on day 10 equals for example: $5\% \cdot 81 \cdot k \cdot \theta$. The data in columns known demand and unknown demand are drawn from a gamma distribution with mean and variance as indicated in the adjacent two columns. The column total demand (green) adds the two orange columns, whereas the right column (expected demand) adds the known demand to the expected unknown demand. The number of batches for production is calculated based on the known demand and expected value of unknown demand as is highlighted in the bottom line of the table.

						Product 1					
k	13,82			Theta	76,1602						
Day	% of orders on this day	% of orders known	Mean Known	Variance Known	Known demand	Mean Unknown	Variance Unknown	Unknown demand	Total demand	Expected unknown demand	Expected total demand
1	5%	100%	52,611763	4006,9226	51,31963	0	0,00		51,31963424	0	51,319634
2	5%	98%	51,484368	3921,0599	51,17127	1,12739493	85,86	1,24720337	52,41847219	1,13	52,298664
3	5%	96%	50,356973	3835,1973	50,08797	2,25478985	171,73	2,4026243	52,49059691	2,25	52,342762
4	5%	94%	49,229578	3749,3347	48,97614	3,38218478	257,59	3,65394126	52,63008517	3,38	52,358329
5	5%	91%	48,102184	3663,4721	48,30364	4,50957971	343,45	4,40576357	52,70940597	4,51	52,813222
6	5%	89%	46,974789	3577,6094	47,07172	5,63697464	429,31	5,90727923	52,97899682	5,64	52,708692
7	5%	87%	45,847394	3491,7468	44,70984	6,76436956	515,18	6,7737858	51,48362155	6,76	51,474205
8	5%	85%	44,719999	3405,8842	43,87678	7,89176449	601,04	8,34519777	52,22198009	7,89	51,768547
9	5%	83%	43,592604	3320,0216	44,01039	9,01915942	686,90	9,56768213	53,57807005	9,02	53,029547
10	5%	81%	42,465209	3234,1589	42,46649	10,1465543	772,76	10,1400867	52,60657299	10,15	52,613041
11	5%	79%	41,337814	3148,2963	41,68425	11,2739493	858,63	11,3165765	53,00082806	11,27	52,958201
12	5%	76%	40,210419	3062,4337	40,24812	12,4013442	944,49	11,9964372	52,24455478	12,40	52,649462
13	5%	74%	39,083024	2976,571	38,19303	13,5287391	1.030,35	13,2861883	51,47922303	13,53	51,721774
14	5%	72%	37,955629	2890,7084	38,12642	14,6561341	1.116,21	14,6193605	52,74577927	14,66	52,782553
15	2%	70%	15,783529	1202,0768	16,04216	6,76436956	515,18	6,80768921	22,84984421	6,76	22,806525
16	2%	68%	15,30036	1165,2785	15,53489	7,24753882	551,97	7,0931234	22,62801511	7,25	22,782431
17	2%	66%	14,81719	1128,4802	14,67392	7,73070807	588,77	7,82214104	22,49605925	7,73	22,404626
18	2%	64%	14,334021	1091,682	14,53144	8,21387733	625,57	8,22927703	22,76072115	8,21	22,745321
19	2%	61%	13,850852	1054,8837	14,04133	8,69704658	662,37	8,17064279	22,21197051	8,70	22,738374
20	2%	59%	13,367683	1018,0854	12,98365	9,18021584	699,17	9,19729227	22,18093742	9,18	22,16
21	2%	57%	12,884513	981,28716	12,7863	9,66338509	735,97	9,6159047	22,40220318	9,66	22,449684
22	2%	55%	12,401344	944,48889	11,97221	10,1465543	772,76	10,0428878	22,01509313	10,15	22,11876
23	2%	53%	11,918175	907,69062	11,86071	10,6297236	809,56	10,1704567	22,03116363	10,63	22,490431
24	2%	51%	11,435006	870,89235	12,37961	11,1128929	846,36	10,9528215	23,33243475	11,11	23,492506
25	2%	49%	10,951836	834,09409	11,23739	11,5960621	883,16	11,5377387	22,77512947	11,60	22,833453
26	2%	46%	10,468667	797,29582	10,67145	12,0792314	919,96	12,5967737	23,26822625	12,08	22,750684
27	2%	44%	9,9854979	760,49755	10,43889	12,5624006	956,75	12,4044452	22,84333342	12,56	23,001289
28	2%	42%	9,5023287	723,69928	9,971054	13,0455699	993,55	12,8707914	22,84184535	13,05	23,016624
											1050,6332
Total # batches											**11**

APPENDIX I: OUTCOME PERFORMANCE FOR 60%/40% DEMAND PATTERN





APPENDIX J: DATA FROM LARCO, FRANSOO, WIERS (2012) ON PROCESS PERFORMANCE

All figures in this appendix are from the paper: "The schedulers' usage of time – A case-study at BPSC, Dow Chemical, Terneuzen", by Larco, Fransoo, and Wiers (2012). Firgure 3, Table 3 and the text field below it, show data about responsiveness of a scheduler. Table 4 provides data about how much time schedulers spend in the different roles. Table 6 shows the mean durations of specific tasks and Table 7 shows review frequencies per scheduler.

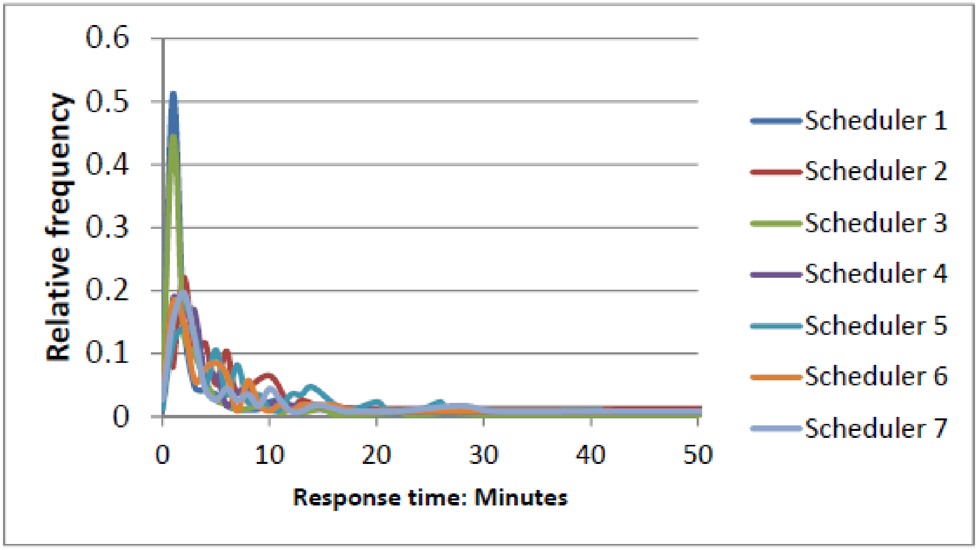
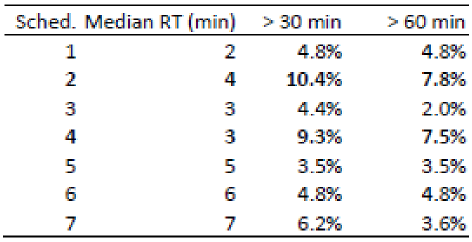


Figure 3: Response times distribution across schedulers



Sched.	Median RT (min)	> 30 min	> 60 min
1	2	4.8%	4.8%
2	4	10.4%	7.8%
3	3	4.4%	2.0%
4	3	9.3%	7.5%
5	5	3.5%	3.5%
6	6	4.8%	4.8%
7	7	6.2%	3.6%

Table 3: Diversity in the scheduling environment

Implications for performance metrics:

These results prompt a discussion of how to understand and operationalize "responsiveness" as a metric. Instead of measuring the mean or median of the time taken to reply a request, cut-off values of what is reasonable (on average) may be set. Then the "responsiveness" metric may be established as the percentages that exceed the cut-off values. It may be argued that not all requests are of equal importance, however as a metric to be analyzed in an aggregate manner, setting a unique cut-off point may suffice.

Scheduler	Decisional	Informational	Monitoring	Transactional
1	33.6%	53.8%	6.1%	6.5%
2	41.2%	36.5%	11.5%	10.8%
3	20.2%	52.9%	12.7%	14.3%
4	43.9%	34.8%	15.0%	6.3%
5	15.4%	57.7%	8.4%	18.6%
6	28.0%	43.6%	5.1%	23.3%
7	24.0%	63.9%	6.0%	6.0%
Total	**28.5%**	**47.1%**	**11.7%**	**12.8%**

Table 4: Time usage across schedulers supporting different roles (idle time excluded)-Idle times are excluded.

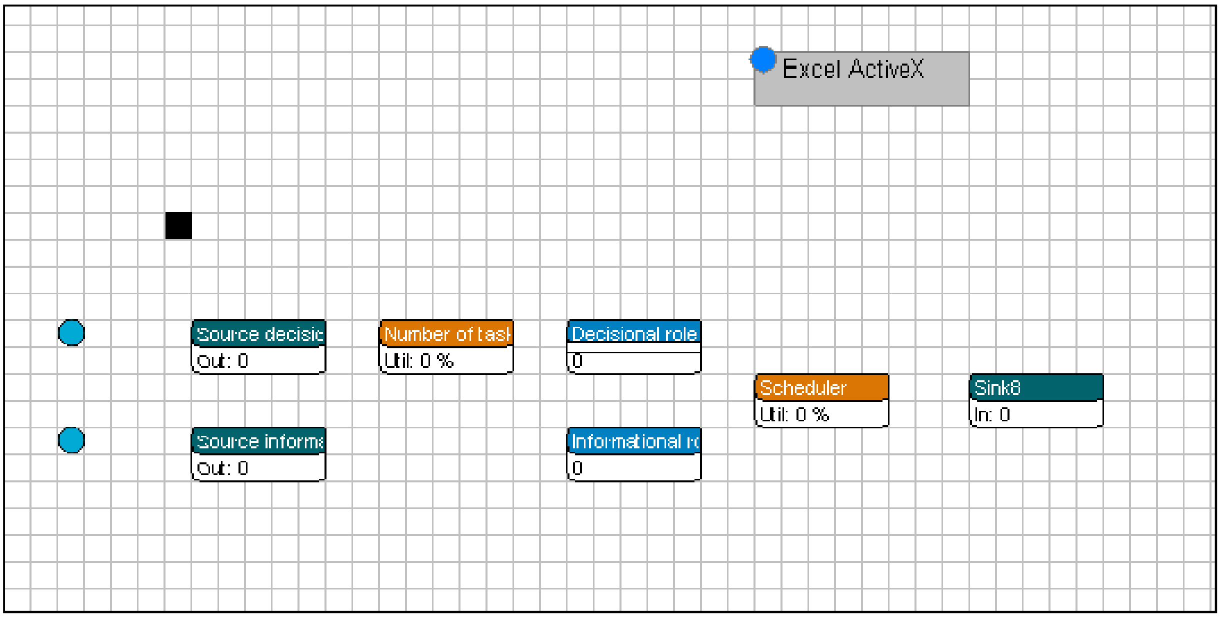
	Decisional		Monitoring			Informational		Transactional	
Scheduler	Scheduling	Re-scheduling	Stock movements & demand	Production execution	Raw materials	Information User	Information Disseminator	Updating product base	Creating delivery notes
1	6.67	5.93	4.40	2.50	10.00	1.46	4.98	N.A.	3.50
2	8.10	6.86	N.A.	3.00	11.50	3.42	5.72	N.A.	20.00
3	8.10	6.86	4.39	N.A.	3.73	2.65	3.65	5.92	2.00
4	4.50	4.95	5.80	4.89	N.A.	4.07	4.03	N.A.	4.82
5	N.A.	5.49	3.75	8.00	3.00	5.75	7.21	N.A.	6.33
6	N.A.	8.07	N.A.	4.50	7.50	3.26	5.86	2.67	N.A.
7	N.A.	7.68	5.50	9.00	5.75	5.46	8.29	0.00	N.A.

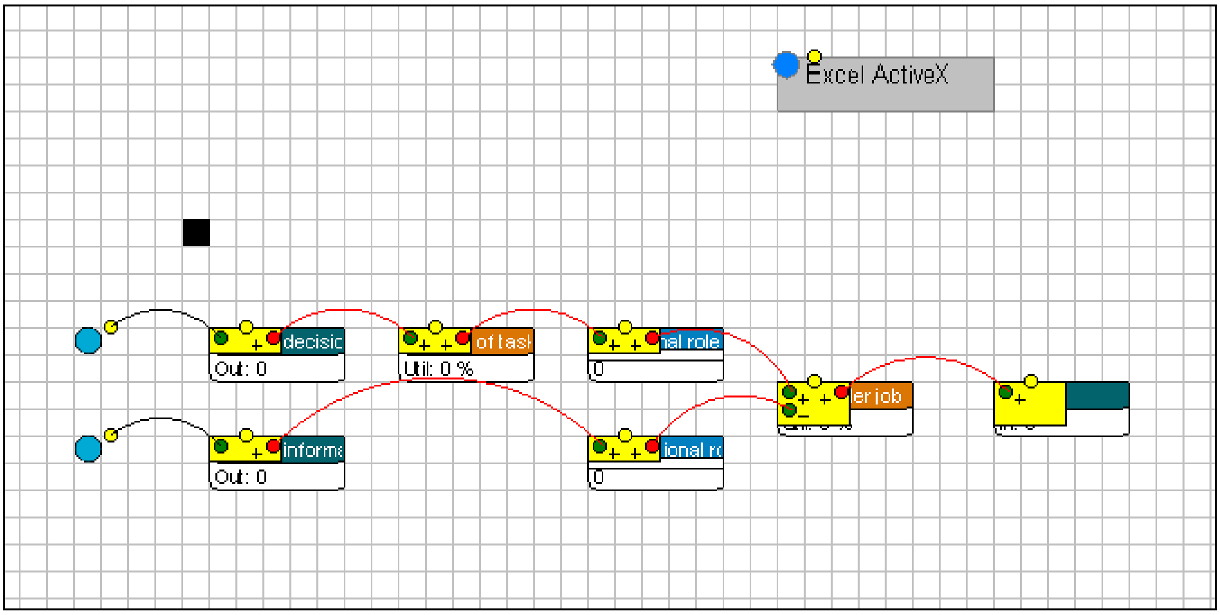
Table 6: Mean processing times (60% of all durations have coefficients of variations > 1)

On average, what is the frequency in which you monitor the stock balances of SKU's in SAP at your OWN initiative (i.e. not requested or motivated by customer service representative)?					
Only reactively	Once per week	2-4 X week	Daily	2x per day	>2x times per day
0%	5%	16%	63%	11%	5%
On average, what is the frequency in which you monitor the status of production orders execution at your OWN initiative?					
Only reactively	Once per week	2-4 X week	Daily	2x per day	>2x times per day
13%	7%	0%	53%	20%	7%

Table 7: Frequencies of monitoring activities

APPENDIX K: ENTERPRISE DYNAMICS MODEL FOR PROCESS PERFORMANCE

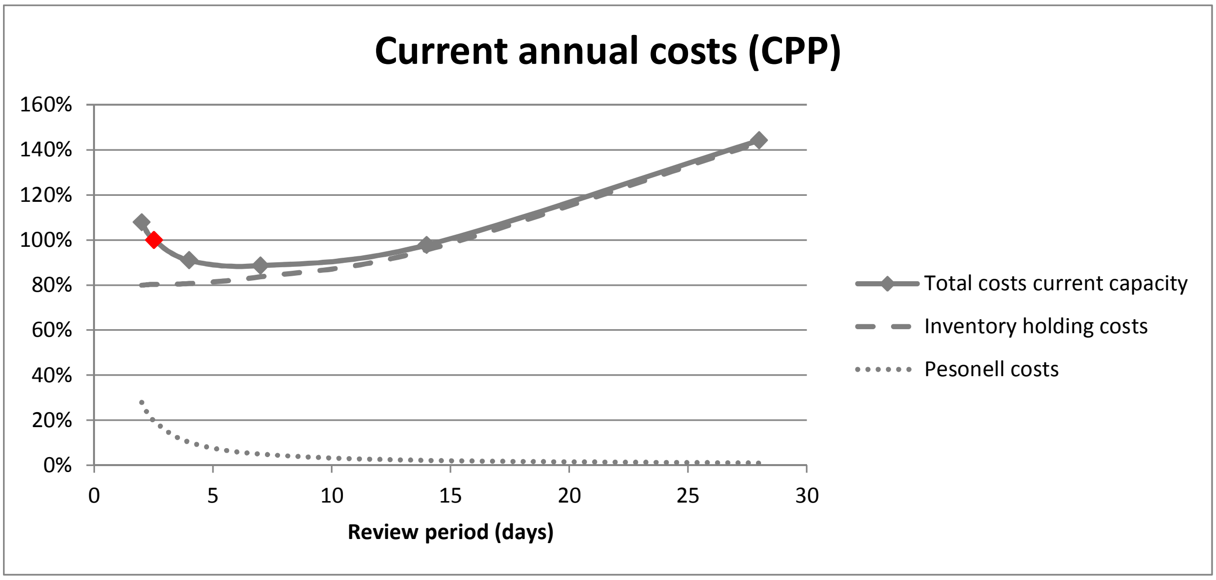


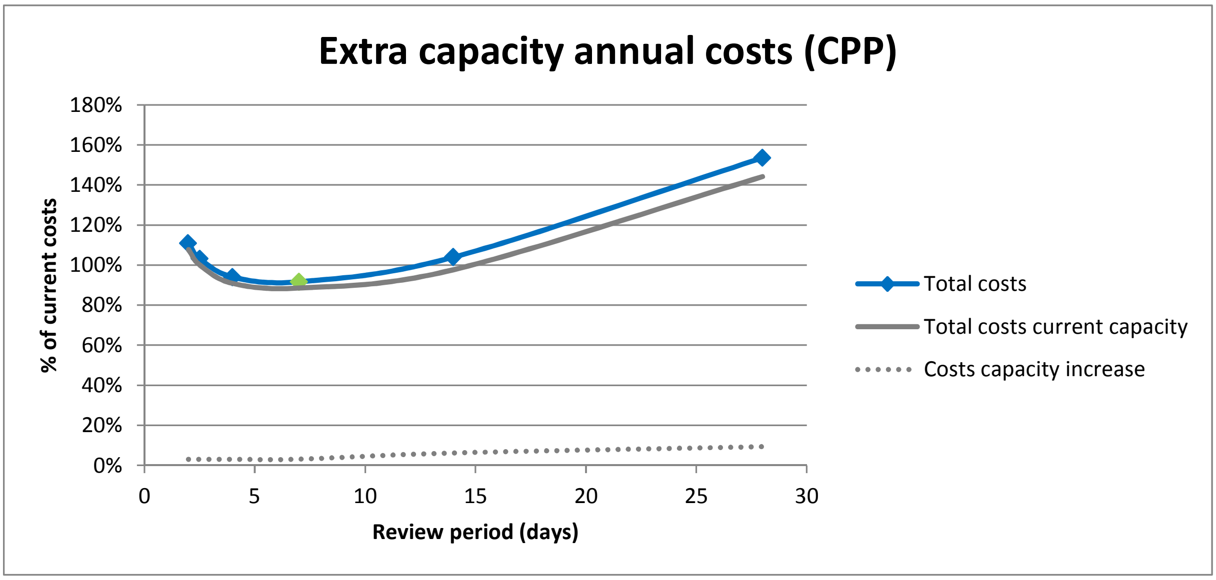


APPENDIX L: REACTOR OUTPUT

REACTOR CPP

The optimal review frequency for the CPP reactor is 7 days, with an expected gain of 8% in (cost) efficiency. The scheduler responsible for the CPP reactor, is also responsible for scheduling of drumming. According to this employee 80% of time is invested in drumming, while 20% of time is invested in scheduling of bulk. Thus 20% FTE is assigned to this reactor.

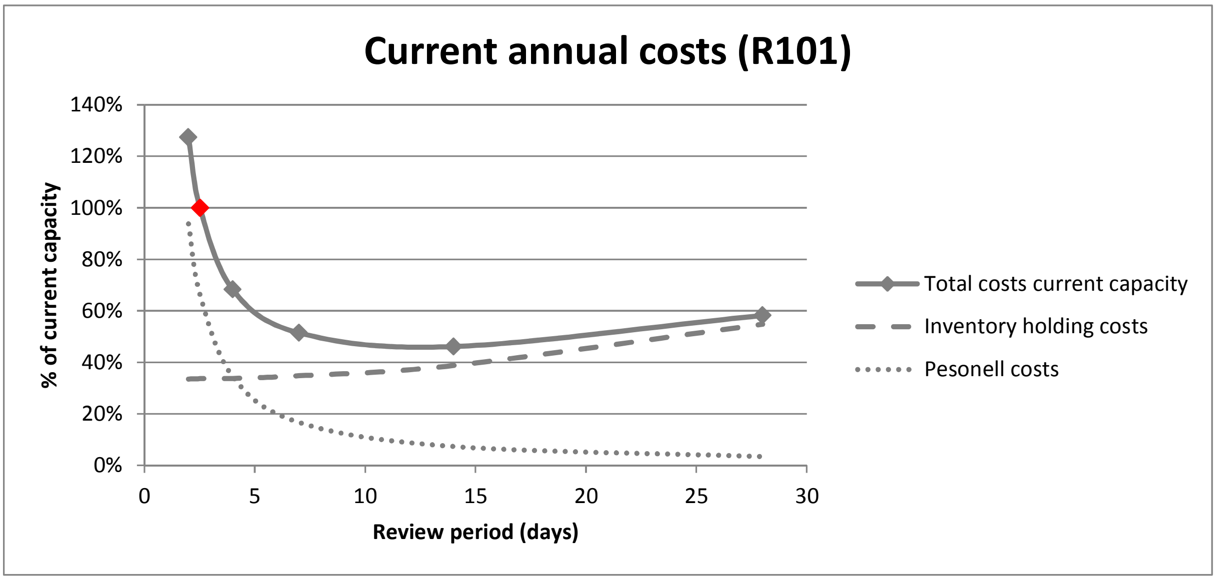


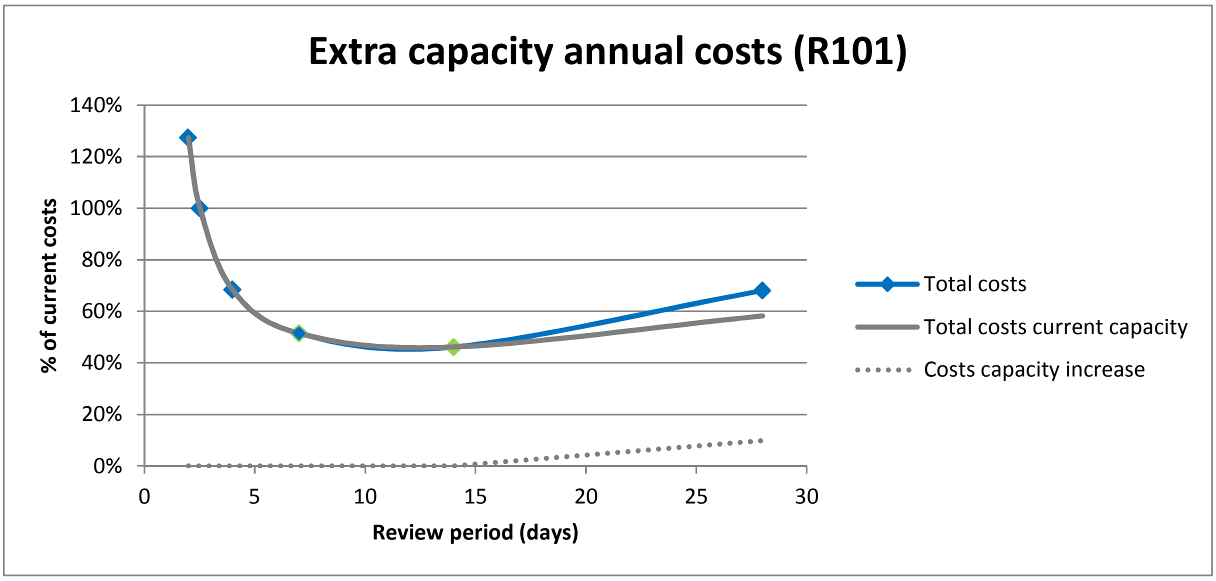


Additional inventory (containers) CPP			
Review period (days)	Product J	Product K	Product L
2	0	1	0
4	0	1	0
7	0	1	0
14	0	2	0
28	0	3	0

REACTOR 101

The optimal review frequency for reactor 101 is 14 days, with an expected gain of 49% in (cost) efficiency

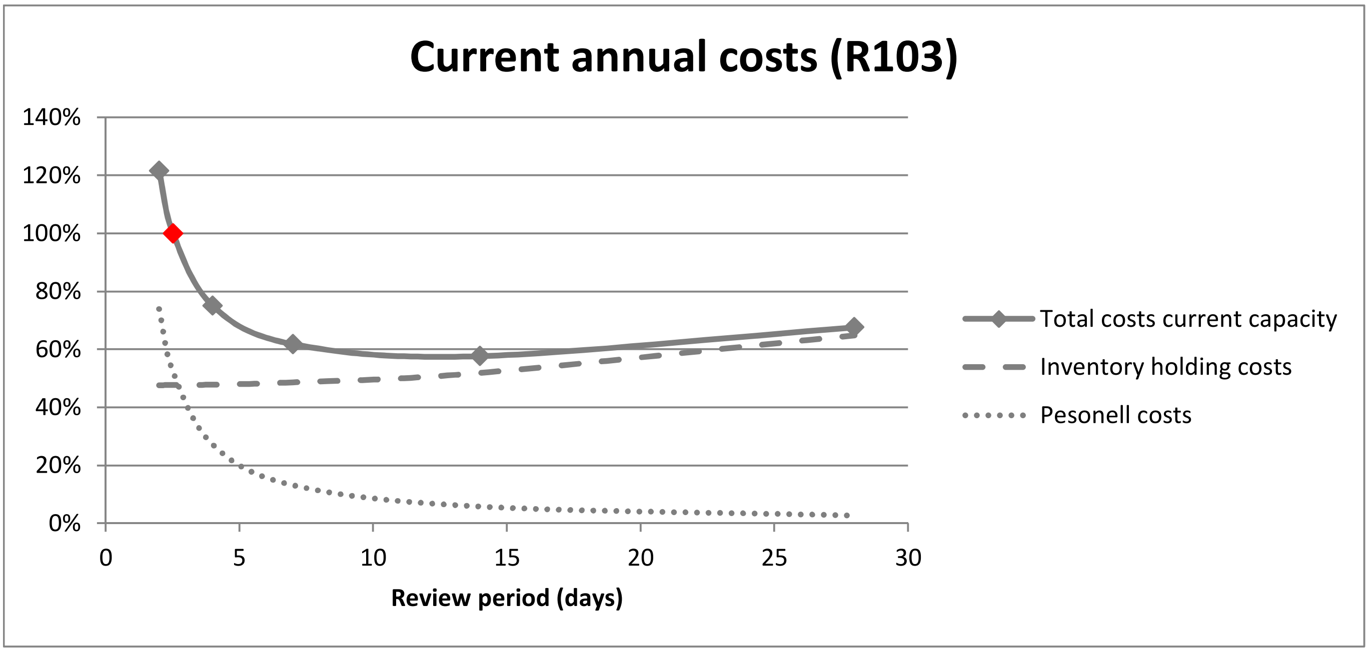


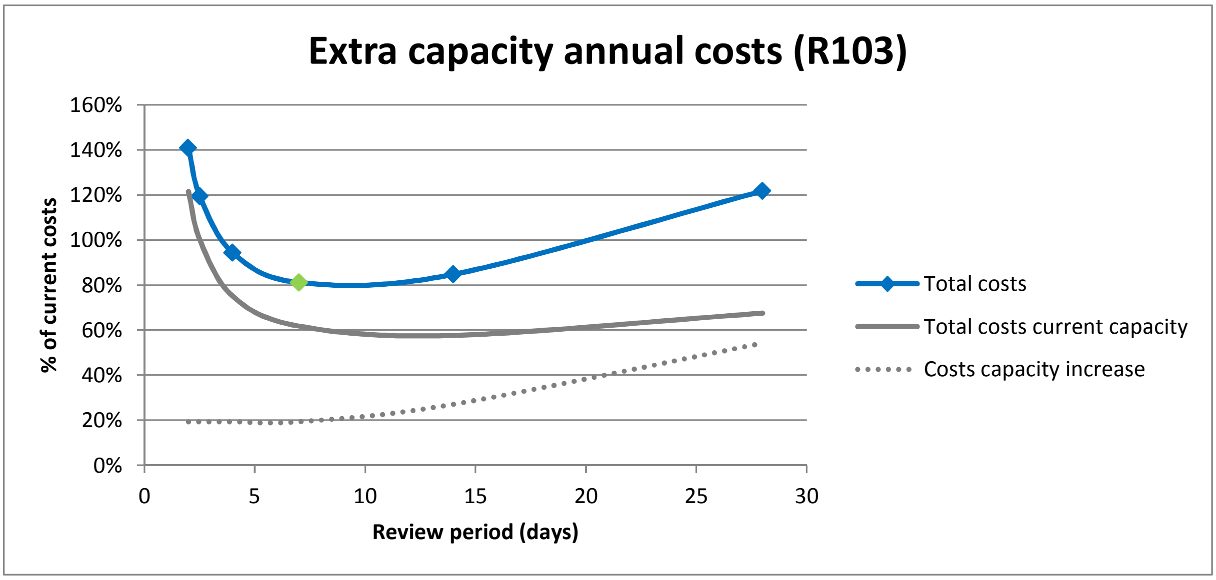


Additional inventory (containers) R101		
Review period (days)	Product KK	Product LL
2	0	0
4	0	0
7	0	0
14	0	0
28	0	2

REACTOR 103

The optimal review frequency for reactor 103 is 7 days, with an expected gain of 19% in (cost) efficiency

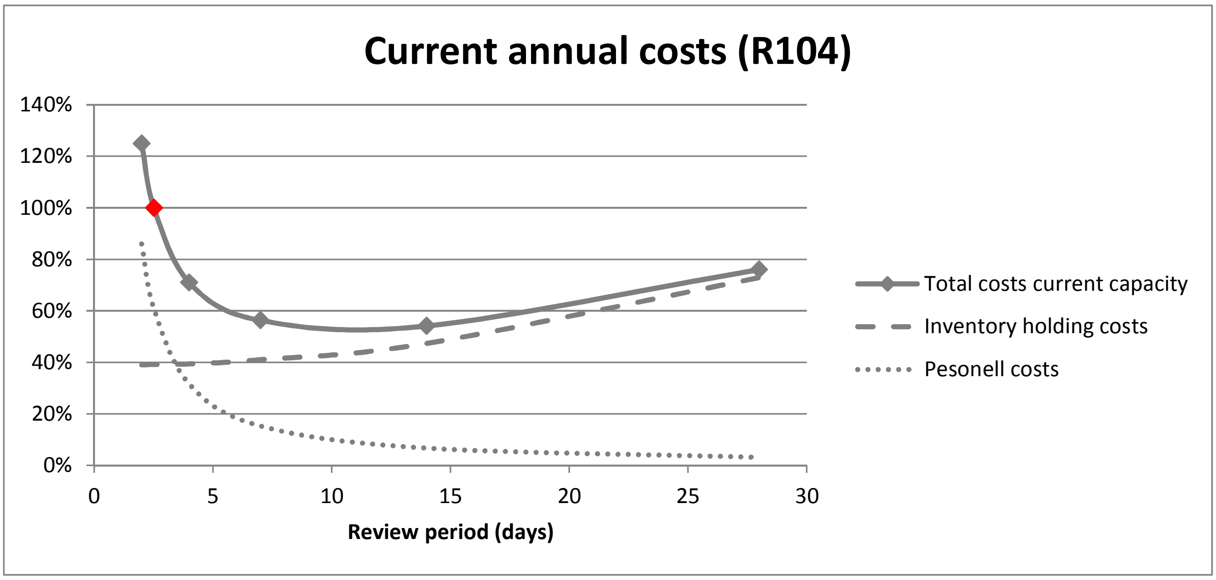


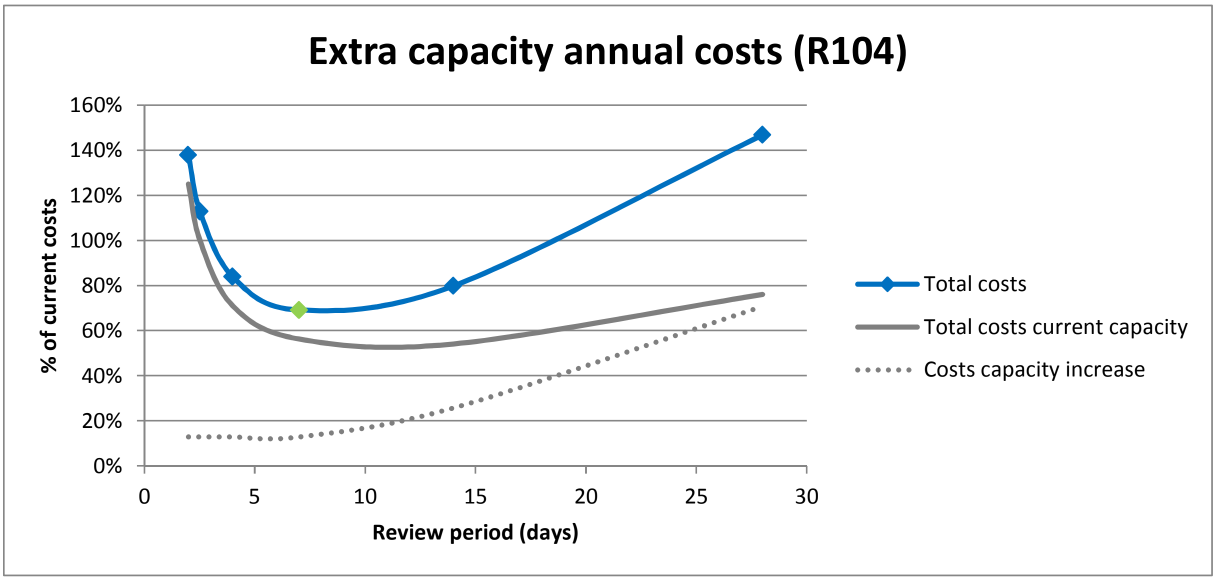


Additional inventory (containers) R103		
Review period (days)	Product LL	Product MM
2	0	5
4	0	5
7	0	5
14	1	6
28	5	9

REACTOR 104

The optimal review frequency for reactor 104 is 7 days, with an expected gain of 31% in (cost) efficiency.

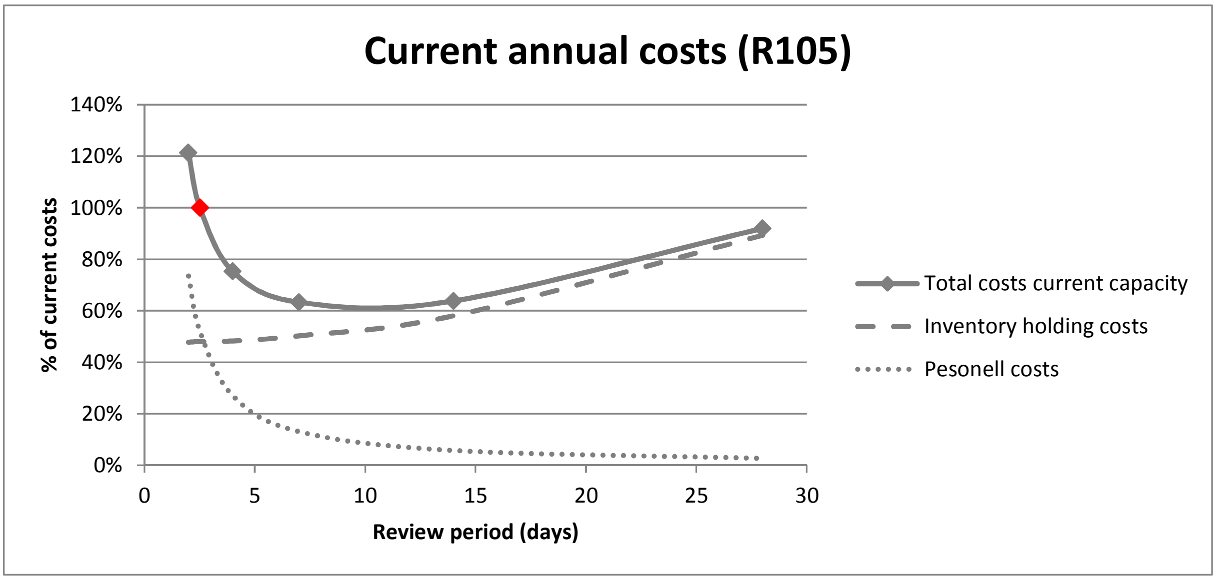


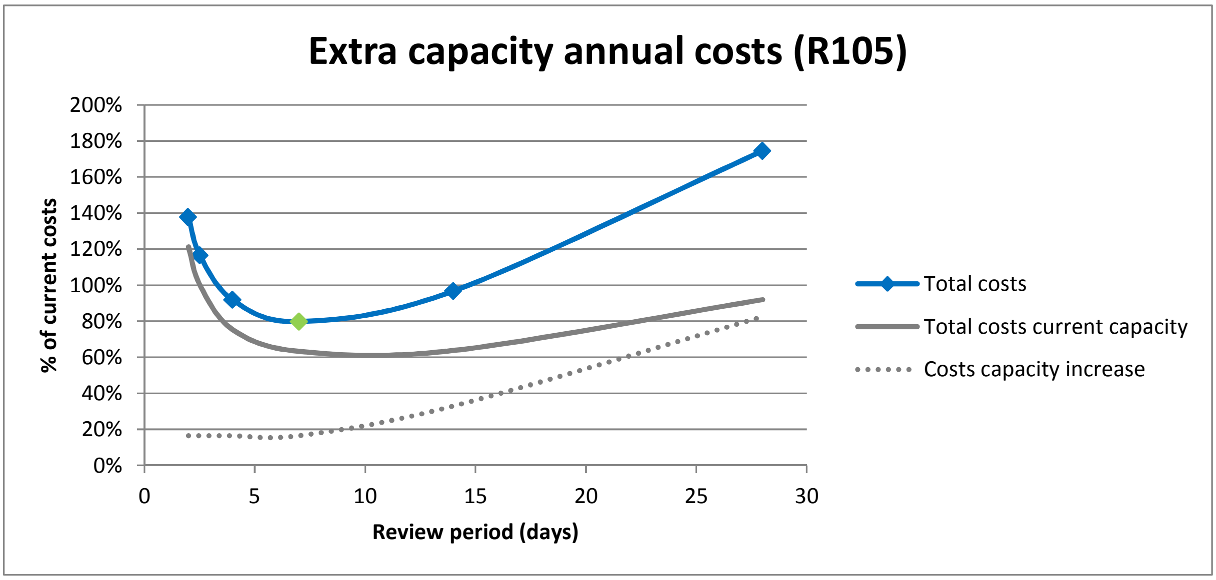


Additional inventory (containers) R104			
Review period (days)	Product A	Product C	Product D
2	2	0	0
4	2	0	0
7	2	0	0
14	4	0	0
28	9	1	1

Reactor 105

The optimal review frequency for reactor 110 is 7 days, with an expected gain of 20% in (cost) efficiency. The inventory constraint for product E is unknown, but according to the scheduler not a constraint. We assume that capacity increase is not necessary for these products.

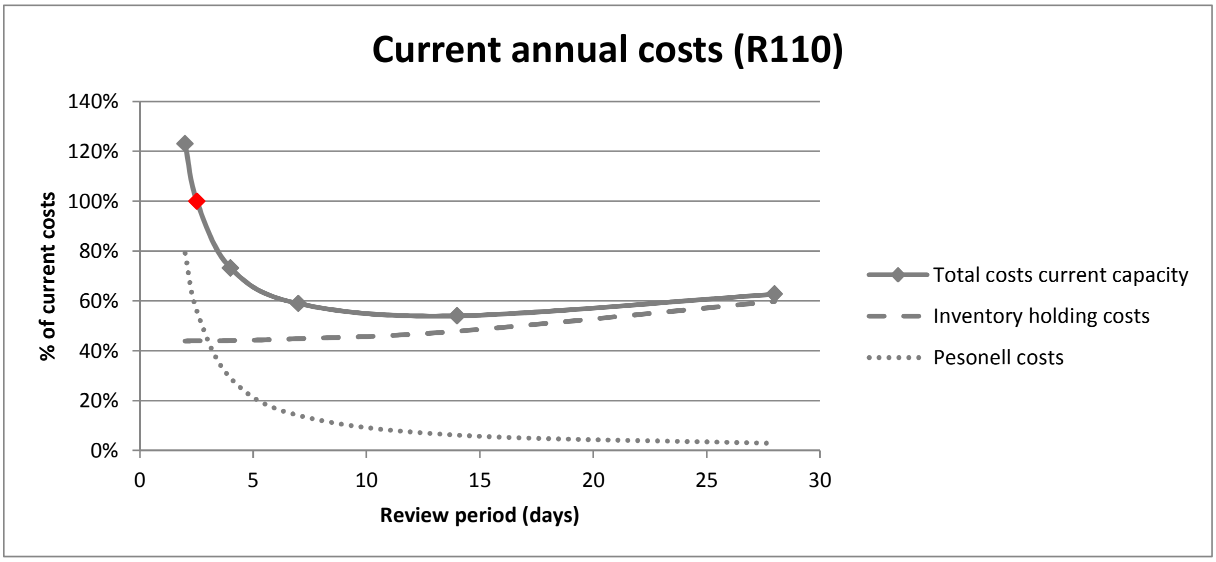


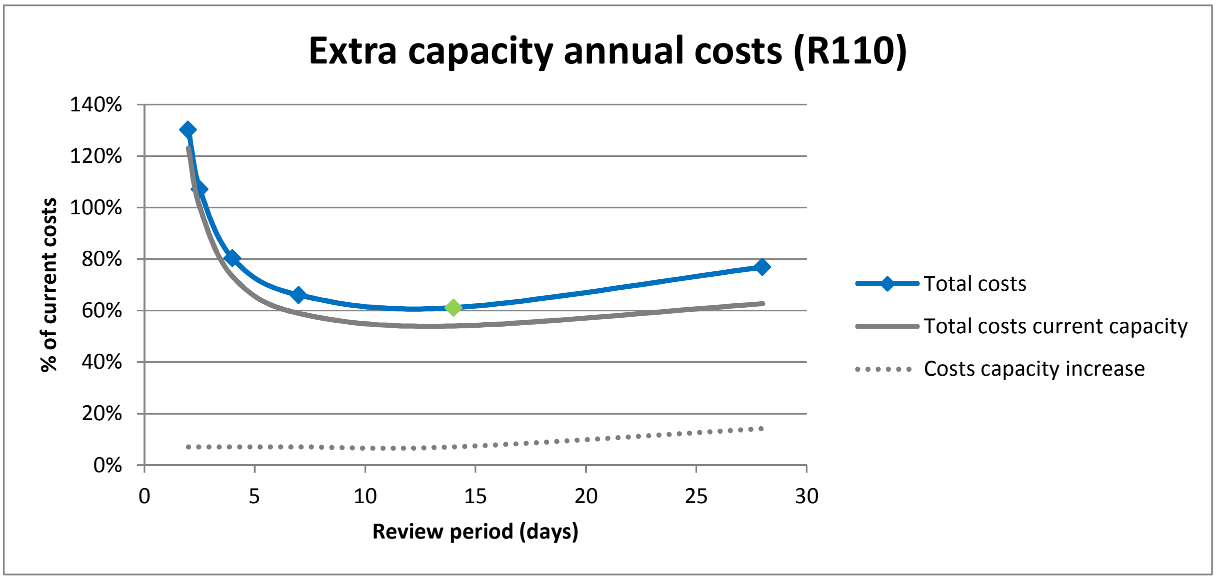


Additional inventory (containers) R105			
Review period (days)	Product A	Product E	Product B
2	3		0
4	3		0
7	3		0
14	5		1
28	10		5

REACTOR 110

The optimal review frequency for reactor 110 is 14 days, with an expected gain of 34% in (costs) efficiency. The inventory constraint for products T and U is unknown, but according to the scheduler not a constraint. We assume that capacity increase is not necessary for these products.

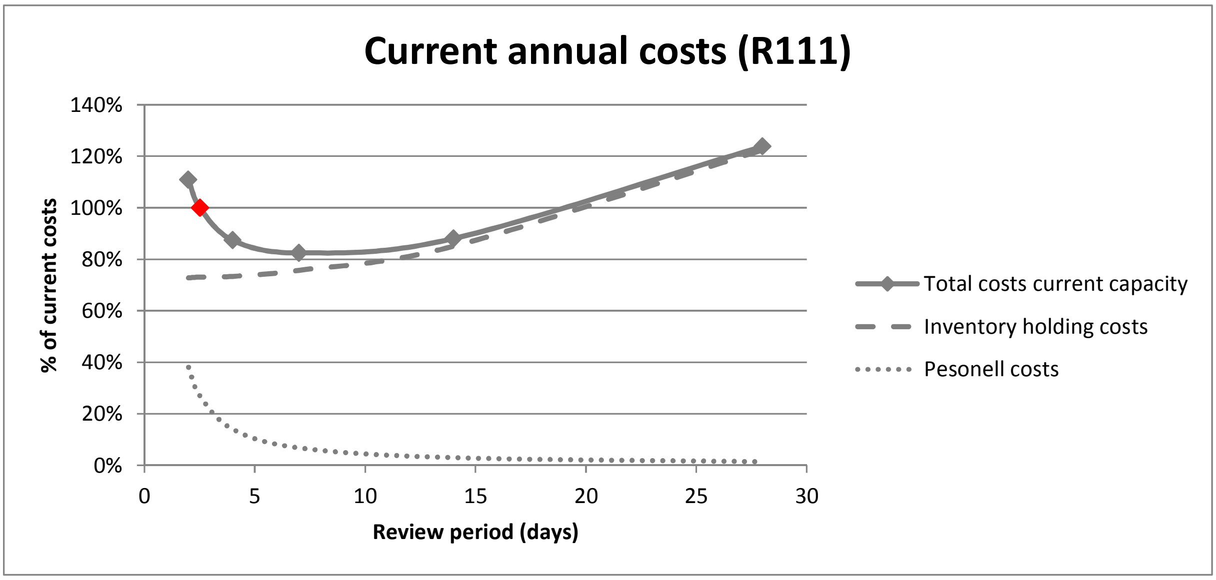


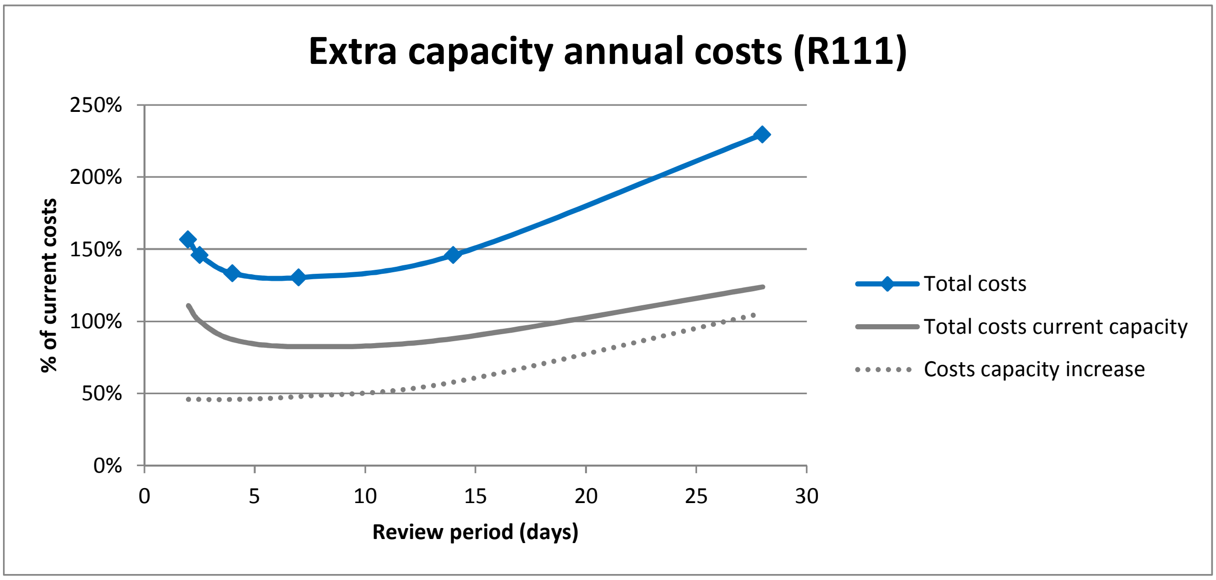


Additional inventory (containers) R110				
Review period (days)	Product R	Product S	Product T	Product U
2	0	2		
4	0	2		
7	0	2		
14	0	2		
28	0	4		

REACTOR 111

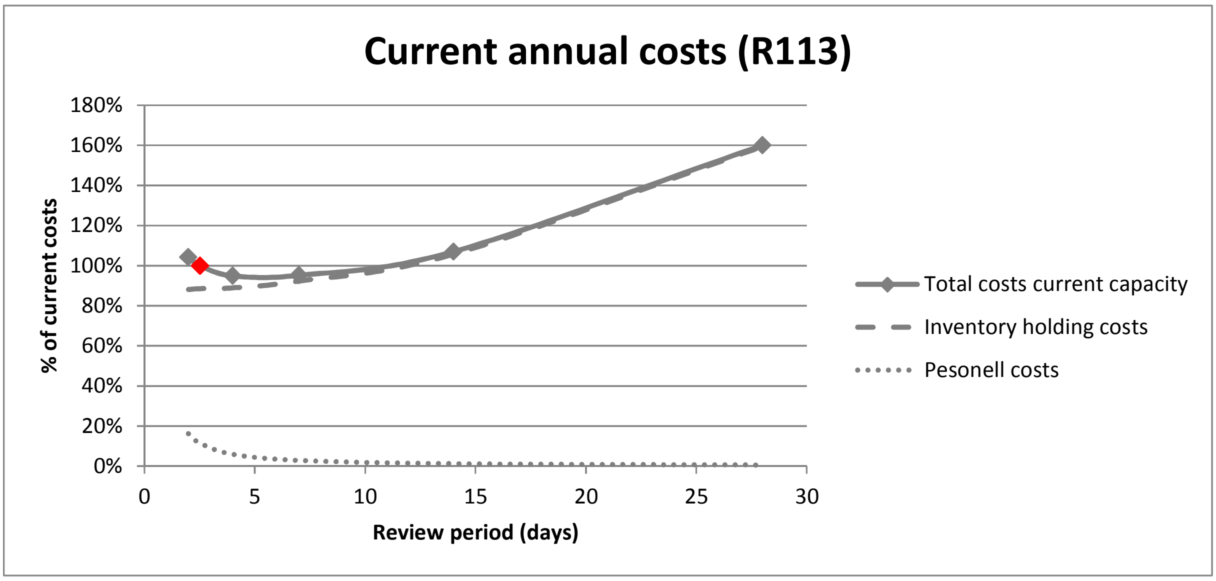
The costs of capacity increase in containers does not outweigh the saving of less frequent reviewing for reactor 111.

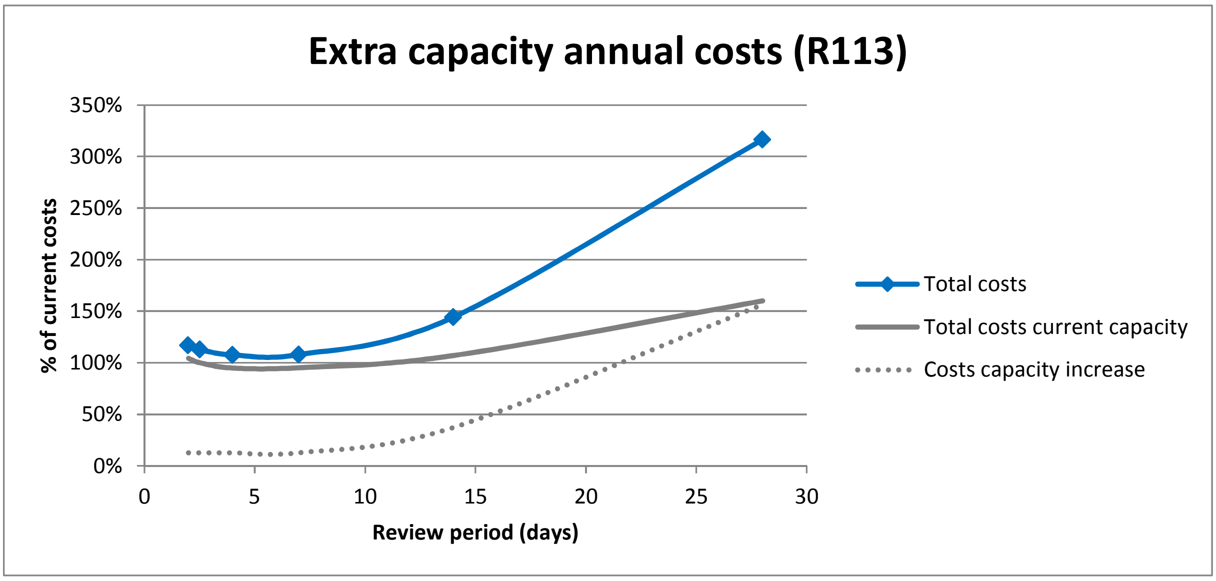




Additional inventory (containers) R111			
Review period (days)	Product II	Product GG	Product HH
2	0	18	5
4	0	18	5
7	0	19	5
14	0	22	7
28	3	36	14

REACTOR 113

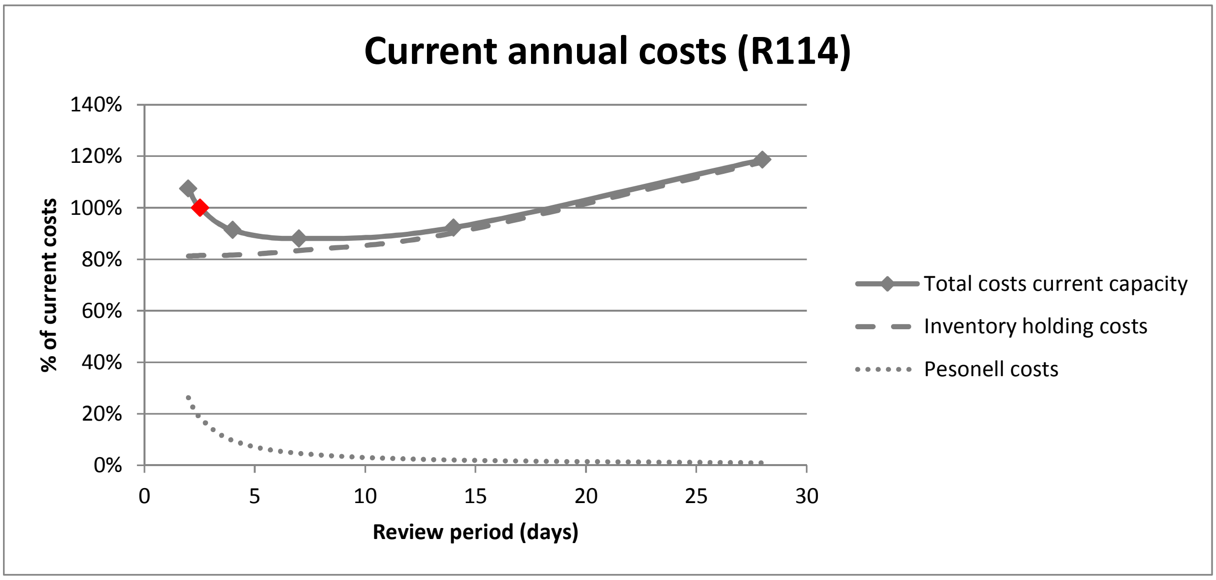


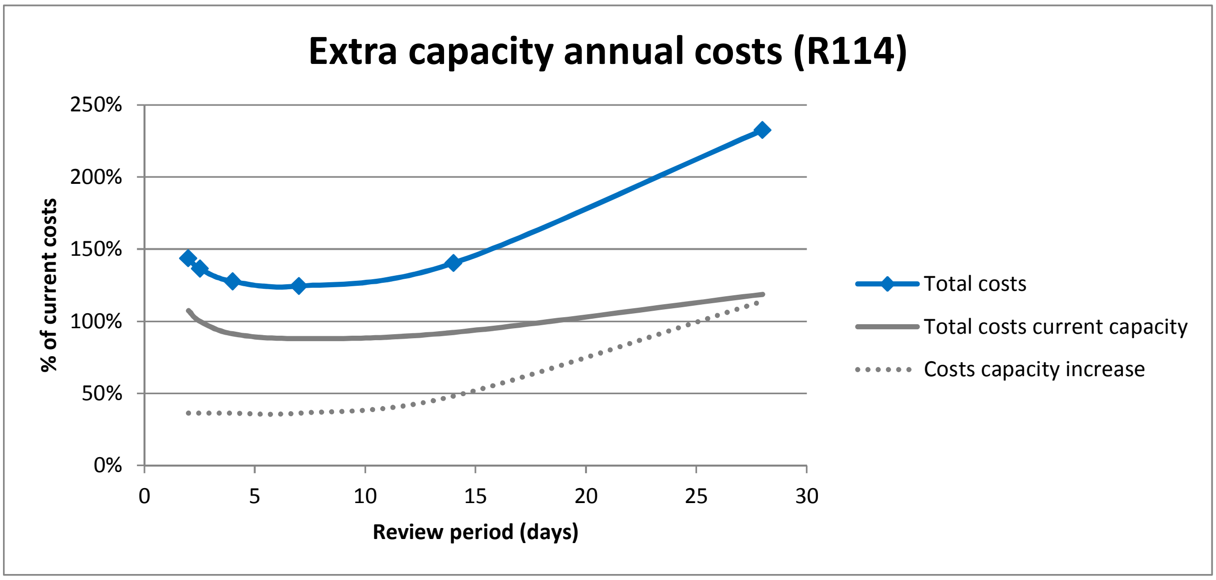


Additional inventory (containers) R113				
Review period (days)	Product F	Product H	Product G	Product I
2	0	3	0	10
4	0	3	0	10
7	0	3	0	11
14	2	5	13	16
28	20	11	107	34

REACTOR 114

The costs of capacity increase in containers does not outweigh the saving of less frequent reviewing for reactor 114.

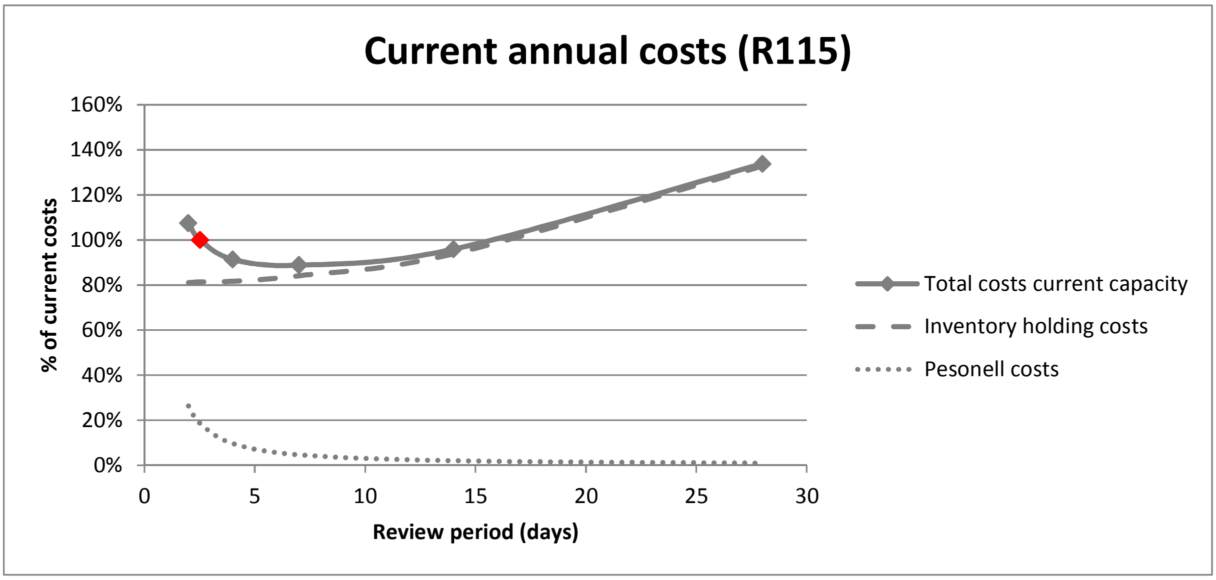


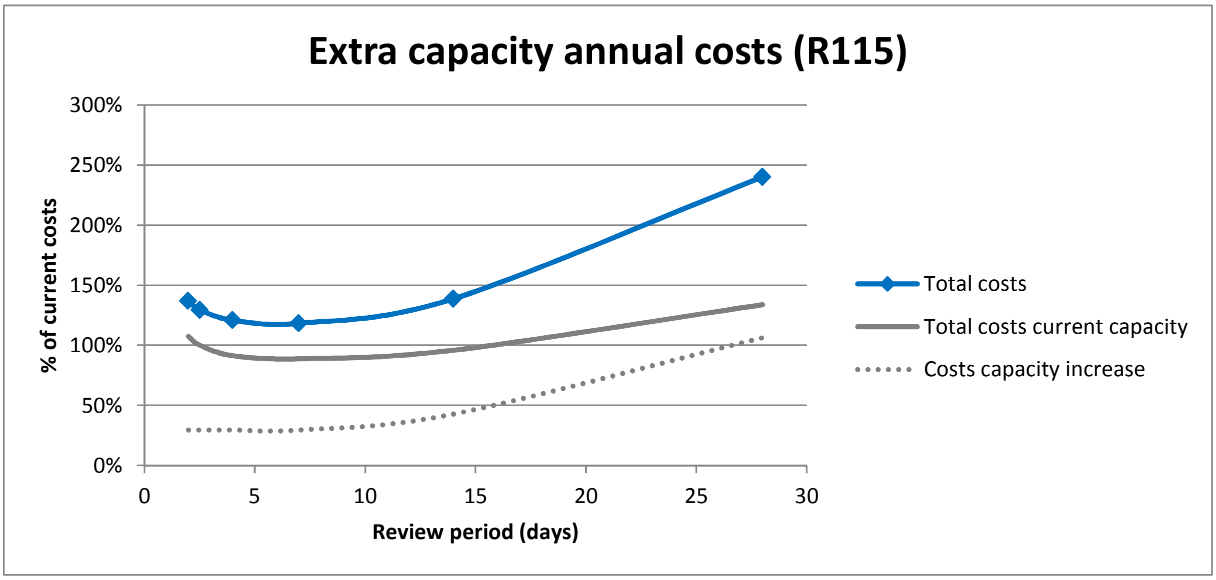


Additional inventory (containers) R114						
Review period (days)	Product X	Product V	Product W	Product X	Product AA	Product CC
2	0	17	0	11	7	2
4	0	17	0	11	7	2
7	0	17	0	11	7	2
14	0	21	0	13	9	6
28	3	34	18	21	16	24

REACTOR 115

The costs of capacity increase in containers does not outweigh the saving of less frequent reviewing for reactor 115.





Additional inventory (containers) R115				
Review period (days)	Product Z	Product BB	Product DD	Product FF
2	0	8	11	1
4	0	8	11	1
7	0	8	11	1
14	0	10	16	3
28	11	18	35	8

APPENDIX M: SENSITIVITY ANALYSIS PROCESS PERFORMANCE

The pictures below show the results of the sensitivity analysis using the input as described in Section 6.4.4. As can be seen in the pictures below, the model is very robust for changes in the process performance model.