MASTER

Developing a heuristic for optimizing the production wheel of polymerization plants

resolving the trade-off between sequence dependent setup costs, external storage costs and working capital costs

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Developing a Heuristic for Optimizing the Production Wheel of Polymerization Plants

Resolving the trade-off between Sequence Dependent Setup Costs, External Storage Costs and Working Capital Costs

by

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Abstract

This master thesis describes SABIC's scheduling problem, and the development of a heuristic to improve SABIC's production wheel. It will be shown that solving the problem as a trade-off between holding cost (cycle stock, safety stock and external storage cost) and setup cost (off-spec production) will significantly reduce total relevant cost per day, compared to the current scheduling method. The developed heuristic will be applied on six of SABIC's assets and simulation models will be used to evaluate the model in a stochastic environment.

Management Summary

Scheduling decisions are amongst the most important decisions in almost every production environment. "Which grade should we produce when?", "How much of each grade should we produce?", and "How much safety stock should we keep?" are a few of the questions that have to be answered when a production wheel is developed. In SABIC EUP's current decision-making process, sequencing decisions, inventory planning and the determination of safety stock levels are optimized individually using different sub-models. However, all these variables are heavily interdependent. In other words, every scheduling decision made in one sub-model impacts the optimal conditions of the other sub-models significantly. If these different decisions are made sequentially, the ultimate result will probably not be optimal. Therefore, it would be more appropriate to simultaneously optimize all scheduling variables in an integrated model.

This integration of different scheduling decisions was exactly the aim of this research project. Because the entire problem cannot be solved via true optimization, a heuristic method is necessary that iteratively improves SABIC's production wheel. This heuristic method should consider all relevant cost types (i.e. working capital cost of both cycle- and safety-stocks, the cost of off-spec production (setup cost), and the external storage costs) as well as SABIC-specific complexities (e.g. minimum runlengths, campaigns and technically impossible transitions). Based on an extensive literature review, it was concluded that none if the existing literature provides a heuristic that incorporates all relevant aspects of SABIC's scheduling problem.

Essentially, SABIC's scheduling problem represents a trade-off between, on the one hand, the cost of producing off-spec material instead of prime material (which can be modeled as a setup cost), and on the other hand, different types of holding costs (i.e. working capital cost of inventory, external storage cost, and cost of safety stock). Solving this trade-off will provide the optimal production wheel for any asset. Because decisions can be made with regard to sequencing (i.e. the order of production runs), production quantities (i.e. how much of a particular grade is produced in a particular production run), how much safety stock should be kept and how many production runs of a particular grade should be scheduled, there exist almost infinite options for composing the production wheel.

The heuristic presented in this report, starts from a schedule where every grade is produced exactly once per schedule. The optimal sequence of such a schedule is determined by solving a traveling salesman problem, minimizing off-spec cost. Subsequently, the effect of adding an additional production run for each of the grades on total relevant cost, is investigated. In this step, adding a production run on all possible positions in the sequence is considered. For every resulting sequence, safety stocks, production quantities and cycle time are optimized. Based on these, the expected cost of a schedule with an additional production run of one of the grades is determined. This process of adding production runs to the schedule is repeated until no improvement regarding total relevant cost is possible anymore.

The heuristic was implemented in an Excel based software tool that is used to improve the production wheels of six polyethylene polymerization plants of SABIC EUP. The proposed production wheels were compared with the current production wheel in two ways. First, the current production wheel is evaluated as if it only specifies a production sequence (i.e. for the current sequence, optimal production quantities and safety stock levels are improved by the heuristic) and this sequence is compared with the heuristically proposed sequence. Secondly, the heuristically proposed wheel is compared with the current production wheel including current safety stock levels and production quantities. This twofold comparison makes it possible to determine whether cost reductions are primarily caused by better sequencing decisions or by improved production quantities and safety stock levels.

The heuristic model assumes constant demand rates. However, in reality, SABIC faces volatile demand rates. To test how the proposed production wheel behaves in a stochastic environment, several simulation models were developed. The production wheel was tested using both actual sales data, as well as normally distributed demand rates. The former did not provide satisfactory results, because sales Figures are severely affected by breakdowns and pushed/lost sales. It would have been more appropriate to use actual demand data rather than sales data but these are currently not registered by SABIC EUP.

Both expected and simulated costs can be reduced significantly when the new heuristic scheduling tool is used. Table 1 provides an overview of the expected cost when current wheels are used (i.e. current sequence, current production quantities and current safety stocks). Subsequently Table 1 provides a similar overview when the current sequences are used (current sequence, optimal production quantities and safety stocks). Finally, it shows the overview when the improved production wheel would be used.

Table 1: Cost Comparison

	Current Schedule (current SS and Q for current Sequence)						
	FACTORY A	FACTORY B	FACTORY C	FACTORY D	FACTORY E	FACTORY F	Total
Average Total Inventory Level (MT)	27625	11652	5364	7126	10326	19582	81675
Off Spec Production/Year (MT)	3030	4928	1022	1022	2665	0	12666
Working Capital Cost/Year (€)	€ 4.148.656	€ 1.637.186	€ 751.009	€ 1.001.513	€ 1.459.135	€ 2.744.139	€ 11.741.638
External Storage Cost/Year (€)	€ 847.059	€ 316.634	€ -	€ -	€ 138.591	€ 1.640.164	€ 2.942.448
Off-Spec Cost/Year (€)	€ 4.521.299	€ 984.598	€ 149.953	€ 131.258	€ 447.924	€ -	€ 6.235.032
Total Cost Per Year (€)	**€ 9.517.014**	**€ 2.938.422**	**€ 900.966**	**€ 1.132.770**	**€ 2.045.650**	**€ 4.384.303**	**€ 20.919.117**
	Current Sequence (optimizing SS and Q for current Sequence)						
	FACTORY A	FACTORY B	FACTORY C	FACTORY D	FACTORY E	FACTORY F	Total
Average Total Inventory Level (MT)	25351	15265	2905	4850	8538	17521	74430
Off Spec Production/Year (MT)	2592	4928	1022	1022	2665	0	12228
Working Capital Cost/Year (€)	€ 3.478.333	€ 1.482.455	€ 384.133	€ 679.166	€ 1.204.920	€ 2.344.534	€ 9.573.541
External Storage Cost/Year (€)	€ 653.500	€ 257.391	€ -	€ -	€ 61.152	€ 1.393.530	€ 2.365.572
Off-Spec Cost/Year (€)	€ 3.901.835	€ 984.598	€ 149.953	€ 131.258	€ 447.924	€ -	€ 5.615.569
Total Cost Per Year (€)	**€ 8.033.668**	**€ 2.724.444**	**€ 534.086**	**€ 810.424**	**€ 1.713.993**	**€ 3.738.064**	**€ 17.554.682**
	Improved Producion Wheel (opimizing SS,Q, and Sequence						
	FACTORY A	FACTORY B	FACTORY C	FACTORY D	FACTORY E	FACTORY F	Total
Average Total Inventory Level (MT)	17492	7352	2422	4728	8325	12506	52825
Off Spec Production/Year (MT)	2665	2592	584	840	2409	0	9089
Working Capital Cost/Year (€)	€ 3.408.618	€ 1.028.501	€ 323.182	€ 670.009	€ 1.181.596	€ 1.512.206	€ 8.124.112
External Storage Cost/Year (€)	€ 644.619	€ 80.745	€ -	€ -	€ 61.532	€ 910.500	€ 1.697.396
Off-Spec Cost/Year (€)	€ 3.496.773	€ 516.001	€ 86.709	€ 109.314	€ 405.212	€ -	€ 4.614.009
Total Cost Per Year (€)	**€ 7.550.014**	**€ 1.625.246**	**€ 409.891**	**€ 779.326**	**€ 1.648.340**	**€ 2.422.706**	**€ 14.435.516**

As one can clearly see from the table above, total relevant costs can be reduced significantly when the heuristic scheduling tool is used. This is due to reductions in both off spec production and inventory levels. Simulation results show a similar picture, in which additionally, service levels are increased when the proposed production wheel is used.

When reviewing these results, one should take into account that the results are based on a situation where the production wheel is followed exactly throughout the year. In reality, due to demand volatility master production schedulers (MPS) can make ad-hoc adjustments to the production wheel. The proposed production wheels should therefore be viewed as a guideline for the MPS, rather than a strict rule. Being a guideline, is also the current role of the production wheel.

Besides providing improved production wheels for SABIC's polymerization assets, this project presents additional recommendations for SABIC EUP. First of all, reducing minimum runlenghts on particular assets can significantly reduce total costs. These minimum runlengths are sometimes ambiguously set; therefore, these values should be validated. Furthermore, the optimization tool can be used to evaluate the effect of not producing particular grades. This feature can be used to make allocation decisions based on facts rather than a trial and error approach. Finally, this project provides a starting point for a dynamic scheduling solution in which ad-hoc MPS decisions are integrated. The development of such a model could potentially improve scheduling performance even more, because scheduling decisions are then based on much more accurate demand information than the demand budgets, set once a year.

Preface

This report is the result of my Master Thesis Project conducted at SABIC Europe Polymers in Sittard. This thesis marks the final step towards the fulfillment of the degree of Master in Operations Management and Logistics.

First of all, I would like to thank my first supervisor Nico Dellaert, for his support throughout this project. I really appreciated his straight to the point comments on the project and my process, which really helped improving the overall result of this thesis. Furthermore, I would like the thank Simme Douwe Flapper, for being more than a regular second supervisor. Our specific feedback and discussion sessions really helped this thesis project to become what it is!

From SABIC EUP, I would like to thank Giuseppe Manrique, for being very involved in this project. He challenged me in every step I took, and was available whenever I needed him. Furthermore, I would like to thank Martijn Meuwissen for giving me the opportunity to conduct this project at SABIC EUP. Every time I asked for 5 minutes of his time, he made sure our discussions lasted for at least half an hour. I would also like to thank other colleagues for being open and taking the time to answer every question I had.

I would also like to thank my family for supporting me throughout my years at university, as well as my friends, who were there for me when for the necessary distraction throughout my studies. Finally, I would like to thank Sabine for supporting me and coping with all the nights we had to spend with four running laptop screens surrounding us.

Eric Vroon
September 2017

Table of Contents

List of Variables:

In this Section, all mathematical variables are listed as a reference when reviewing the mathematical descriptions in this report.

Name	Var.	Unit	Name	Var.	Unit
Asset	A	#	Inventory Offset of i	$offset_i$	MT
Average Production Time i	ATP_i	Days	Off-Spec Price	OSP	€
Fill Rate Target	α_i	%	Production Rate of i	p_i	MT/hour
Percentage demand in Bulk	$\%B_i$	%	Price of grade i	P_i	€
Campaign Transition time	CTT	Days	Exp. production days	PD	Days
Cycle Time	CT	Days	Production quantity step j	Q^j	MT
Demand Rate i	d_i	MT/year	Opt. production quantity j	$\hat{Q}^j$	MT
Detour Cost Bulk	DCB	€/MT	Density	ρ	MT/m^3
Detour Cost Packed	DCP	€/MT	Order-up-to level at step j	S^j	MT
Real Duration of step j	$\widetilde{\Delta t}^j$	Days	Safety Stock Level for i	SS_i	MT
Length of production run j	Δt^j	Days	Setup Cost transition $i \rightarrow j$	SC_{ij}	€
Ext. Sto. Occupation Rate	EOR	%	Storage Capacity Bulk	SCB	MT
Total Ext. Storage Cost	ESC	€/day	Storage Capacity Packed	SCP	MT
Ext. Storage Cost Bulk	$ESCB$	€/m^3/day	Transition Time $i \rightarrow j$	ST_{ij}	Days
Ext. Storage Cost Packed	$ESCP$	€/m^3/day	Approximated step time	$stepTime^j$	Days
Production Frequency of i	f_i	runs/cyc	SD of Demand	σ_i	MT/day
Grade	i	#	Ext. Sto. Cost Bulk Total	$TESCB$	€/day
Inventory of i during j	I_i^j	MT	Ext. Sto. Cost Packed Total	$TESCP$	€/day
Int. Sto. Occupation Rate	IOR	%	Turn-over Rate Bulk	$TORB$	Days
Production step	j	#	Turn-over Rate Packed	$TORP$	Days
Leadtime for grade in step j	LT^j	Days	Total Relevant Cost	TRC	€/day
Maximum leadtime of i	$maxLT_i$	Days	Total Setup Cost Cycle	TSC	€/cycle
Minimum Cycle Time	$minCT$	Days	Binary Production Variable	x_i^j	1/0
Minimum Cycle Time for i	$minCT_i$	Days	Weigh. avg. cost cap./Year	$WACC$	%/year
Minimum Runlength i	MRL_i	MT	WCC of Cycle Stock of i	WCC_i	€/day
Nr. of Grades in Sequence	M	%	Total WCC Cycle Stock	$WCCCS$	€/day
Nr. of grades on Asset	N	#	Total WCC Safety Stock	$WCCSS$	€/day

List of Definitions

In this Section, a list of definitions is stated. This list should be used as a reference for clarification when reading the rest of the report and is provided alphabetically. When in a definition there is a reference to another definition, this term is indicated in italics.

Campaign Transition Time	The time required to switch between two different campaigns, during which the asset is idle
Cycle	Going through the *schedule* one single round
Cycle Stock	The portion of inventory available to fulfill the expected demand until the next replenishment moment
Cycle Time	The time required to complete an entire *schedule* including all production times and transition times
Detour Costs	The cost of transferring material to an external storage location
External Storage Cost	The cost of renting external storage capacity
Fill Rate	The percentage of customer demand that is satisfied directly from on hand inventory
Frequency	The number of production runs of a grade in a *schedule*
Inventory Level	The inventory level refers to the on-hand inventory level at a specific point in time
Minimum Runlength	The minimum quantity that needs to be produced of a certain grade in a *production run*
Occupation Rate	The percentage of the storage capacity that is effectively used (both internal and external occupation rates exist)
Off-Spec Material	Material that is not according to specification as the result of switching between different grades
Production Time	The time it takes to complete one *production run*
Production Run	The production of a single grade
Production Wheel	Specifies the *schedule*, *safety stock* levels and *order-up-to levels*
Pure Rotation Schedule	A schedule in which every grade has exactly one *production run*
Safety Stock	Stock dedicated to dealing with stochasticity in demand
Schedule	Specifies *sequence* and production quantities for all *production runs*
Setup Time	The time required to switch between two *production runs*
Setup Costs	The costs associated with producing off-spec material due to setups
Sequence	Specifies the order in which grades are produced
Step	Combines the *production run* of an item with the setup time before this *production run*
Total Relevant Costs	The sum of all costs that are influenced by *production wheel* decisions (i.e. working capital costs + external storage costs + detour costs + setup costs)
Turnover Rate	The average time material remains in the external storage facility
Working Capital Costs	The opportunity cost of holding inventory

1 Introduction

This Chapter will introduce the problem that will be addressed in this research project. Thereafter, the deliverables of the project. Subsequently, the research questions will be presented and the scope of the project will be discussed, before presenting the contribution to both academic research and SABIC EUP respectively. If particular concepts are not clear at this stage, please refer to the subsequent chapter 2 in which all relevant concepts will be explained in detail.

1.1 Problem Statement

SABIC EUP operates multiple polymerization plants (i.e. assets) that each have their own grade portfolio. An entire asset can only produce one grade at a time, which means from a scheduling perspective that the process of producing a grade can be considered as a single production step. Determining the optimal schedule can be described as a trade-off between setup costs and different types of holding costs, which can be optimized. In the context of SABIC, setup costs are associated with the production of off-spec material (which is the result of a transition between producing different grades and which are significantly sequence-dependent). This off-spec material is sold for a lower price and is therefore, essentially, a setup cost. Furthermore, there are two types of holding costs relevant for the scheduling problem namely: working capital cost of holding inventory and the cost of storing material externally. The optimal schedule solves this trade-off and specifies both the order in which the grades are produced and the production quantities of each of the production runs. Together, with the determination of safety stock levels, this is called the production wheel.

Currently, the production wheel is determined once per year, based on a trade-off between an approximation of the average setup costs and the working capital cost of the cycle stock. Using a *trial-and-error* approach different *potential* production wheels are developed and evaluated. These potential wheels form the basis for the approximation of setup costs and are used in an EOQ-like method to determine optimal production quantities. Subsequently, the potential wheel with the minimum expected total cost is chosen as the *default* production wheel. Here total cost is just the combination of working capital cost of cycle stock and the cost of off-spec material. The *default* production wheel is not followed exactly because, due to volatile demand, adjustments to the wheel may be necessary on an *ad-hoc* basis. These day-to-day decisions are made by the master production scheduler who is responsible for the scheduling of grades on an operational level. To show the potential relevance of the problem Table 2 provides an overview of inventory holding costs, off-spec production/setup costs and the cost of storing material externally for the 6 assets that are investigated in this project. Although the production of grades imposes many other types of production costs, they are independent of scheduling decisions and therefore not relevant for the problem discussed in this project.

Table 3: Actual Cost Overview - Scheduling SABIC EUP

	FACTORY A	FACTORY B	FACTORY C	FACTORY D	FACTORY E	FACTORY F	Total
Average Total Inventory Level (MT)	27625	11652	5364	7126	10326	19582	81675
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The aim of this project is to develop a heuristic that determines an improved production wheel, which results in lower expected total costs. In other words, the wheel should be a guideline for the master production schedulers, who can still make ad-hoc decision to adjust the *default static* wheel. The new improved production wheel should not only be based on the working capital cost of the cycle stock and an approximation of the setup costs, but should also incorporate other relevant costs that depend on scheduling decisions, namely: working capital cost of safety stocks and the external storage cost of inventory. Therefore, a model/tool needs to be developed to determine an optimal cyclic schedule that considers all relevant cost types, while recognizing important specific concepts of SABIC's problem, including minimum runlengths, campaigns and sequence dependent transition times. Additionally, the model should allow for analyzing the effect of certain changes in the pre-conditions (e.g. adjustments in minimum runlengths, grade portfolio changes accuracy of annual budgets etc.). This problem statement leads to the following deliverables, main research question and sub-questions presented in the next sections.

1.2 Deliverables

Upon completion of this research project SABIC EUP will receive the following:

- A mathematical model, implemented in a software tool using MS Excel VBA, which improves the production wheel (including, a sequence, production quantities and safety stock levels) for all assets producing polyethylene grades.
- A user-manual explaining how to use the optimization tool
- A confidential and public report presenting the model and its implications.

Eindhoven University of Technology will receive the following:

- A public report presenting the research project and the findings regarding the scheduling problem facing sequence dependent setup costs and stochasticity in demand.
- An A1-size scientific poster, containing the main research questions, methodology, results and conclusions, according to the guidelines in the poster manual.

1.3 Research Questions:

How to Optimally Schedule Grades on SABIC's Poly-Ethylene Assets, Considering Sequence Dependent Setup Costs/Times and Non-Linear Holding Costs

1. *What are the relevant costs/concepts when scheduling different grades on SABIC's assets?*
2. *What heuristics/models are available in literature that address the relevant aspects of SABIC's scheduling problem?*
3. *Develop a model that considers all relevant aspects of SABIC's context.*
4. *How does the model perform compared to the current situation?*
5. *How does the model behave in a stochastic environment (H1 2017)*
6. *What is the effect of the Minimum Runlength on the Optimal Wheel?*

1.4 Scope

To ensure feasibility, while maintaining an adequate level of detail, several decisions/assumptions had to be made regarding the scope of this project. Since the project is conducted at SABIC Europe Polymers, other divisions, and their respective planning decisions, are considered out-of-scope. In other words, although SABIC Europe is also responsible for the cracking step of the production of plastics, only the polymerization step is in-scope for this project. With regard to the scheduling of grades on the different polymerization assets, this means that it is assumed that there is unlimited supply from the cracking step to the polymerization step.

More specifically, this project will focus on the assets that are producing polyethylene grades. Although other SABIC EUP assets will show close resemblance to these assets, they are not investigated in detail. Whereas, the model that will be developed during this project will not be directly usable on other assets, it will provide a clear starting point from which minor changes should be made to make it applicable on the other assets.

Furthermore, from a scheduling perspective, the polymerization step will be considered as a single production step. This can be assumed because every asset can only produce one type of grade at a time. Together with the unlimited supply, this makes the problem essentially a single machine problem.

Apart from producing polymers in-house, SABIC EUP also imports particular grades from production plants in Saudi Arabia (approximately 20% of total sales). These grades do not overlap the grades that are produced on the European assets and are therefore not relevant for the scheduling problem.

Additionally, the process of making ad-hoc adjustments to the production wheel remains out-of-scope because these decisions are based on specific time dependent information. Finally, the allocation of grades to specific assets is a strategic choice that is out-of-scope for this project. The effect of certain allocation decisions can be evaluated by the model, though this is not part of the model implicitly.

1.5 Contribution to Academic Research

Many researchers have addressed the issue of stochasticity in scheduling problems. Furthermore, some research is conducted on the issue of sequence dependent setup times. However, according to the extensive literature review conducted before this project, these issues are not investigated simultaneously. Investigating how a model with sequence dependent setup times behaves in a stochastic environment will fill this gap. For more information on the literature related to this problem, please refer to the literature review.

Brander (2005), Dobson (1992), Fleischmann (1994), Gupta and Magnusson (2005), Haase (1996) and Wagner and Davis (2002) have addressed the issue of sequence dependent setup costs in economic lot scheduling problems (ELSP) and capacitated lot scheduling problems (CLSP). Furthermore, many researchers (e.g. Bourland & Yano (1996), Fransoo et al. (1995), and Wagner & Smits (2004)) have addressed the issue of stochasticity through stochastic economic lot scheduling problems (SELSPs). Brander and Forsberg (2006) have developed a method to determine safety stock levels, taking the specific characteristics of a cyclic schedule into account (i.e. acknowledging the influence a cyclic schedule has on replenishment lead-times).

Additionally, the impact of minimum runlengths and variable holding costs will be addressed during this research project. Minimum runlengths are almost ignored completely in current literature. Furthermore, almost all scholars have assumed linear holding costs, whereas in many practical situations, this is not realistic. Addressing these issues specifically in the development of the model will show how they might influence the scheduling problem.

Finally, this research project will build on previous research by combining different elements of models to develop a heuristic that will recognize all relevant elements of SABIC's specific problem context. By doing so, the combination of sequence dependent setup times/costs, variable holding costs and a stochastic context will be investigated simultaneously.

1.6 Contribution to SABIC EUP

This research project will give insight into relevant scheduling costs and provide a heuristic method to schedule grades on six SABIC EUP polyethylene polymerization plants. The developed model will improve the sequencing of different grades and determine optimal runlenghts, as well as safety stock levels for all assets producing polyethylene products at SABIC EUP. The tool could be extended to other SABIC assets with relative ease. The model will potentially reduce setup and/or holding costs significantly leading to decreased total production cost. This heuristic method will be implemented in a user-friendly software tool in Microsoft Excel VBA.

1.7 Report Structure

The remainder of this report follows the structure of the research questions and is set up as follows. First, the key concepts of the petrochemical industry and SABIC specifically are explained in the following Chapter. Subsequently, the main relevant literature will be presented in Chapter 3. In Chapter 4, the problem is translated into a mathematical optimization model. Chapter 5 is dedicated to explaining the developed heuristic and the mathematical reasoning behind it. Afterwards, the improved production wheel is evaluated and compared with the current schedule in a deterministic and stochastic environment in Chapter 6. The effect of the minimum runlength on the optimal production wheel will be addressed here too. Finally, the main conclusions and recommendations are presented in Chapter 7 and Chapter 8 respectively.

2 Problem Context

Before examining the specifics of the problem, and how it should be solved, a description of the problem context is necessary. First, the definition of a petrochemical is given, followed by a general overview of the plastics supply chain. Subsequently, the current state of the industry will be discussed and the position of SABIC within this industry will be presented. Finally, the main concepts related to the production of polymers within SABIC will be defined.

2.1 What is a petrochemical?

A petrochemical is a product that is derived from petroleum or other fossil fuels. Petrochemicals can be sub-divided into several different classes, from these, olefins and aromatics are the most important ones. Olefins are primarily ethylene and propylene and aromatics are, amongst others, benzene, toluene and xylene isomers. Olefins and aromatics are the basis for a wide range of products such as adhesives, detergents and solvents. Furthermore, olefins form the basis for plastics, elastomers, fibers and resins.

Two base resources can be used to produce a petrochemical. Either crude oil is refined into Naphtha, or natural gas is processed into NGLs (e.g. ethane, propane), which are used in either Naphtha- or NGL-crackers. These crackers, in turn, produce the olefins that are used to produce different kinds of products including plastics. The process of producing plastics will be discussed more thoroughly in the next section. (Matar & Hatch, 2001)

2.2 The Plastics Supply Chain

The plastics supply chain can be described as a five-echelon system, which is shown in Figure 1. The next sub-Sections all echelons will be described separately from upstream to downstream respectively. In the figure, the production steps indicated in red are the steps in which SABIC EUP is involved directly.

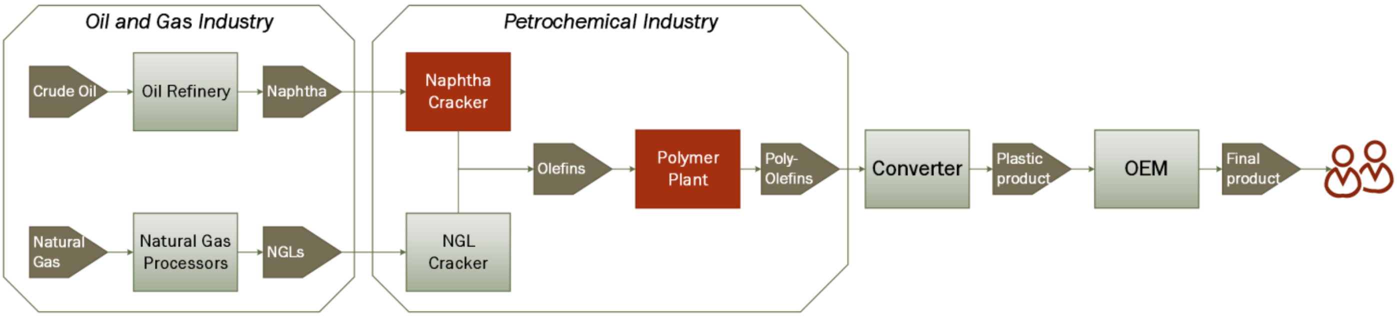

Figure 1: The plastics supply chain

2.2.1 The Oil and Gas Industry

The oil and gas industry forms the furthest upstream step of the plastics supply chain. As mentioned, the majority of plastic products are derived from a by-product of the processing of natural gas or the refining of crude oil (only 5% of the processed fossil fuels are used for the production of petrochemicals). Either crude oil or natural gas can be used as main feedstock for the production of petrochemicals. (Ophardt, 2003)

In order to make natural gas transportable and usable in applications, it needs to be as pure as possible. While natural gas is formed primarily of methane (CH_4), it also includes natural gas liquids (NGLs) (i.e. ethane (C_2H_6), propane (C_3H_8) and butane (C_4H_{10})) carbon dioxide (CO_2) Oxygen (O_2), Nitrogen (N_2), and Hydrogen Sulfide (H_2S)). These heavier hydrocarbons are, together with the other gases, separated through distillation columns into the pure natural gas liquids (NGL) ethane (C_2H_6), propane (C_3H_8), butane (C_4H_{10}), and natural gasoline. These NGLs are used as raw materials in the petrochemical industry. (Ophardt, 2003)

Crude Oil is also a combination of many hydrocarbons. To make use of these hydrocarbons, they also have to be separated. This separation is done in a refinery, where crude oil is heated, causing the crude oil to split in different gases. These gases are passed through distillation columns, which separate the different gases into gasoline, kerosene, gas oil, Naphtha, and other (by-)products. The product Naphtha is then used in the petrochemical industry as a raw material. (Ophardt, 2003)

2.2.2 The Cracker

As shown in Figure 1, the cracker is the fourth echelon in the plastics supply chain and the first production step of the petrochemical industry. A cracker is responsible for the transition from either Naphtha or NGLs into ethylene and propylene (i.e. olefins). Crackers are dedicated to cracking Naphtha or to NGLs. The type of feedstock used in a cracker determines the division of end products (Matar & Hatch, 2001). NGL crackers are relatively more efficient when only ethylene and propylene are considered useful. However, other products of the cracking process are sold separately by petrochemical companies as feedstock for other chemical companies.

Most crackers in Europe, including the ones used by SABIC, are Naphtha Crackers. Naphtha crackers specifically, can be sub-divided into thermal crackers and steam crackers. Nowadays the most used form of Naphtha cracking is steam cracking. SABIC's Naphtha crackers are also steam crackers.

2.2.3 The Polymerization plant

The polymerization plant forms the second and final step in the production of plastics as feedstock. The Naphtha cracker produces products that are called monomers. In the polymerization plant, several monomers are joined into one polymer product. Polymers can be either natural or synthetic. When a polymer is artificially created in a polymerization plant, it is called a synthetic polymer or plastic. In the polymerization plant, the monomers ethylene (C_2H_4) and propylene (C_3H_6) are transformed into polyethylene (PE) and polypropylene (PP) respectively. PE products can be subdivided into high density (HDPE), low density (LDPE) and linear low-density (LLDPE) products. Different polymers have very different properties including strength, stiffness, heat resistance, conductivity and density. Generally, PP products are much stronger than PE products.

2.2.4 The Converter & OEMs

The different plastic granules that were produced in the polymerization plants are shipped to the second echelon, the converters. Here, the granules are processed using techniques such as injection molding, blow molding or extrusion, into a desired shape. These plastic products are sold to original equipment manufacturers (OEMs) that use the plastic products to produce goods for consumers or other businesses.

2.3 The Petrochemical Industry Today

The petrochemical industry is a pure process/flow industry producing commodities (see literature review and Silver et al. 1998). The industry is very capital intensive, and therefore a few very large companies dominate the market and compete with each other. The petrochemical industry can be seen as a downstream sector of the petroleum industry, as shown in Figure 1. The top 10 petrochemical businesses are listed in 3.

Table 4: Industry Overview 2016 (in US$ billions)

Company	Country	Revenue	Profit	Assets
BASF	GER	63.75	5.74	64.87
Dow Chemical	USA	48.77	6.37	68.02
Sinopec	CHI	43.80	3.13	23.97
SABIC	**KSA**	**39.50**	**5.00**	**87.53**
Formosa Plastics	TWN	29.21	2.50	40.25
INEOS	SWI	28.49	4.25	20.78
ExxonMobil	USA	28.13	5.69	28.41
LyondellBasell Ind.	USA	26.68	6.35	n.a.
Mitsubishi Chem.	JAP	24.35	1.46	23.75
DuPont	USA	20.70	5.23	14.03

Three different macroeconomic trends have significantly influenced the petrochemical industry both globally and in Europe specifically. We will address these trends separately to evaluate the effects they had on the industry. First, the influence of the global financial crisis starting in 2008 will be discussed. Subsequently, the effect of the discovery of shale gas (primarily in the USA) will be explained. Finally, the most recent trend concerning significantly declined energy prices will be discussed.

2.3.1 Global Financial Crisis

After the collapse of Lehman Brothers in September 2008, the entire economic world was set on fire. Quickly, most businesses started to realize that short-term financing would become significantly more risky and companies stopped investing their cash. Furthermore, companies became focused on the reduction of costs, and the reduction of working capital through the reduction of stocks. This destocking led to significant drops in demand throughout the

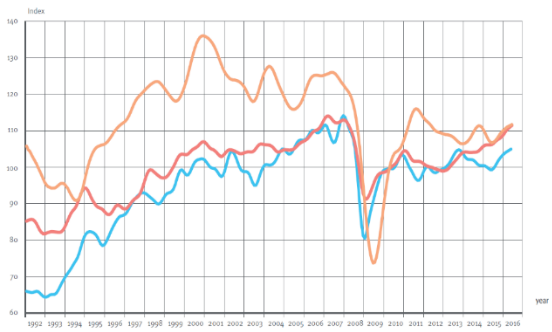

Figure 2: EU plastics Production

world economy. As shown in Figure 2, steady growth of the plastics industry was suddenly interrupted after the events starting at the end of 2008. Although there was a small increase in plastics production in 2016, levels are still significantly lower than pre-crisis levels. (APPE, 2016)

Although the world, and Europe to certain extent, has officially recovered from the crisis, its impacts are still very significant. Construction, automotive and other important industries supplied by the petrochemical industry are still experiencing low demand, leading to lower demand further upstream.

2.3.2 Shale Gas Revolution

A second factor that significantly influenced the European plastic market was the shale gas revolution in the US. Because of technological improvement, the US is now able to extract large quantities of shale gas through horizontal drilling of shale rock formations. This development has made US natural gas prices to decline considerably. As Figure 3 shows, until the shale gas revolution in 2009, natural gas prices in the EU and USA were relatively equivalent, but from then on regional prices have diverged significantly. Since natural gas is an important feedstock for the petrochemical industry, petrochemical companies in the US were experiencing lower feedstock prices than companies in the EU, weakening competitiveness of European petrochemical companies dramatically. Figure 3 shows the difference between US and EU gas prices, which reached its maximum in 2012/2013, but after that, this effect has been declining due to an overall drop in energy prices (see Section 2.3.3). (BP, 2016)

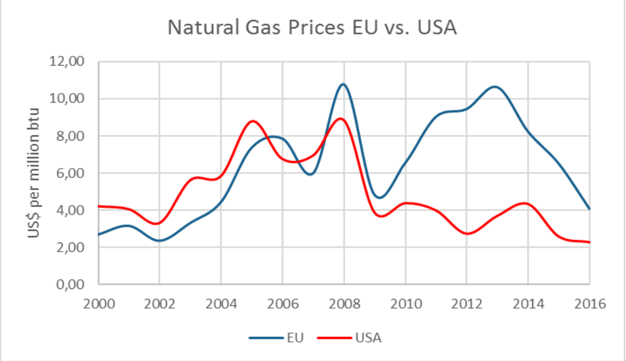

Figure 3: Natural Gas EU vs. USA

2.3.3 Energy Prices Plummeting

The third macroeconomic trend that has influenced the petrochemical industry is the energy price decline that started in 2013. Following plunging oil prices, energy prices in general experienced a significant downturn in recent years. This shock had major impacts on several aspects of petrochemical industry. Hong, Musso and Simons (2015) claim chemical companies were underprepared for the magnitude and speed of the impact of the energy price drop on their business. According to Hong et al. (2015), the effect of dropping energy prices is threefold. First, the cost structure of a petrochemical is affected since energy prices are a major cost driver. Many of the feedstock used in the production of plastics is directly produced from oil or its derivatives, causing direct costs to reduce significantly when energy prices drop.

Consequently, dropping energy prices have an effect on the price-setting mechanisms of petrochemical companies. There is a strong correlation between the price of crude oil and the price of petrochemicals (BP, 2016). Additionally, oil price volatility causes relative prices of specific petrochemicals to change (e.g. the price of polypropylene might fall below HD-polyethylene), causing downstream manufacturers to substitute particular plastics for others. (Hong et al., 2015)

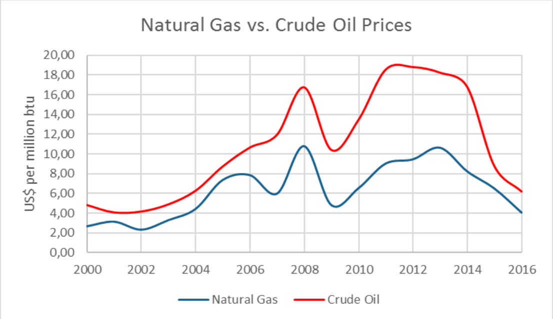

Figure 4: Natural Gas vs. Crude Oil Prices

Finally, sudden energy price changes might affect the spending patterns of individual consumers because their incomes are affected by the energy price. Hong et al. (2015) claim that: "If lower oil prices persist, investment in durables and then fixed assets ramps up, along with associated spending on chemicals used to make the durables and fixed assets". Therefore, demand for plastic products benefits from the oil price decline.

Although there is always a high correlation between oil prices and gas prices, differences are important when considering petrochemical competition. Marten et al. (2015), claim that the effects of the plummeting oil prices are different for specific regions. As shown in Figure 4, oil prices dropped more severely than natural gas prices. Most European steam crackers use Naphtha as their feedstock, most Asian and American steam crackers, on the other hand, are fed by natural gas. Since Naphtha is directly produced from crude oil, its price is more directly impacted by the crude oil price. Declining oil prices therefore increase the competitiveness of European Polymer producers using Naphtha as feedstock.

2.4 Saudi Arabia Basic Industries Company (SABIC)

The Saudi Arabia Basic Industries Company (SABIC) was founded to make a useless by-product of the petroleum industry profiable. SABIC was founded in Riyadh in 1976 in order to convert crude oil by-products into useful chemicals and is active in the production of chemicals and intermediates like polymers, fertilizers and metals. It is the largest public company in Saudi Arabia, but still 70 percent of its shares are owned by the Saudi Arabian government.

After establishing an enormous chemical complex in Al-Jubail (Kingdom of Saudi Arabia), SABIC started joint ventures, first with small chemical companies from Japan and Taiwan, but later with spin-offs of major oil companies like Shell and ExxonMobil. After this joint venture phase, SABIC started to acquire petrochemical companies throughout the world. Today SABIC has operations in over 40 countries and employs a global workforce of over 40.000 people. Since its founding, the company grew rapidly both organically and through mergers and acquisitions all over the world.

SABIC is organized through five different strategic business units (SBUs): Chemicals, Polymers, Specialties, Agri Nutrients and Metals. The research of the master's thesis will be conducted in the polymers SBU of SABIC Europe (SABIC EUP). Hence, the remainder of this report will focus on this part of the company.

2.5 SABIC Europe Polymers

One of the many acquisition SABIC did at the beginning of this century was the acquisition of the petrochemicals division of DSM in 2002. This acquisition included assets in Geleen, The Netherlands and Gelsenkirchen, Germany, and resulted in the establishment of SABIC Europe. Additionally, in 2007, SABIC Europe acquired Huntsman Corporations' plants in Wilton (United Kingdom) and General Electric's plastics division, consisting of plants in Bergen op Zoom (The Netherlands) and Cartagena (Spain). Finally, in 2009, a factory was founded in Genk (Belgium) to supply the automotive industry specifically.

In total, SABIC Europe Polymers (SABIC EUP) sells more than 400 different products, which are called grades. All grades differ from each other in their chemical properties. These properties range from density and color to environmental stress-resistance and processability. Based on these characteristics, grades are classified into specific applications and manufacturing technique classes. Additionally, grades are clustered in market segments (e.g. construction, automotive, packaging etc.). Grades are used in many applications but generally, polyethylene products are used in different types of flexible packaging (carrier bags, food packaging, film etc.) and rigid packaging (bottles, can, boxes, crates etc.). Polypropylene products, on the other hand, are more rigid and are usually used in industrial environments (e.g. automotive, fibers and pipes).

Apart from European production of grades in one of SABIC EUP's assets, the European division also imports specific grades from SABIC Saudi Arabia (KSA) to sell in the European market. There are several reasons why grades are imported from KSA. First, a grade might not be producible on one of SABIC EUP's assets but there is demand for that grade in Europe. Secondly, demand of a grade that is produced by SABIC EUP is so high that SABIC EUP's capacity does not suffice. Lastly, if there is not enough demand for a specific grade produced in KSA, the grade is send to one of the regional offices to be sold in the local market. These grades are produced in one of SABIC's production facilities in KSA, and transported, using sea freight, to one of the distribution hubs of SABIC EUP in Europe. These distribution hubs are solely used to shorten the customer lead-time of KSA produced grades. For both European production and imports from KSA, the customer order decoupling point (CODP) is situated at the storage facilities.

The next sub-Sections will focus on the key concepts that are relevant for the project and the production of polymers at SABIC Europe.

2.5.1 Grades

The polymer division at SABIC is responsible for the production of approximately 400 different plastic products, called grades. Grades can be subdivided into different product categories, namely: polyethylene (i.e. PE), polypropylene (i.e. PP), automotive and engineered thermoplastic polymers (i.e. ETP). This research project is focused on the PE-business, which can be further branched into the following sub-categories: High density PE (HDPE), low density PE (LDPE) and linear low density PE (LLDPE). Furthermore, HDPE grades can be subdivided into uni-modal, bi-modal and injection molding grades.

After production, the plastic granules are transported to storage facilities. If available, grades are stored in internal storage facilities, which are owned by SABIC and located on the production sites. If internal storage capacity is insufficient, one makes use of external storage facilities (usually) in close proximity to the production sites, which are rented from logistics service providers. The type of storage facility depends on whether the granules are packed or not (i.e., bulk): packed granules are stored in warehouses, whereas bulk granules are stored in silos. Every grade-packaging combination is a unique stock keeping unit (SKU) within SABIC.

2.5.2 Assets

SABIC EUP consists of multiple polymerization plants that all produce a fraction of the polymer products at SABIC. Every polymerization plant is called an asset. SABIC has four production sites in Europe, situated in The Netherlands (Geleen), Germany (Gelsenkirchen), the United Kingdom (Wilton) and Belgium (Genk). On Chemelot, the industrial complex in Geleen, seven polymerization plants are located, whereas in Gelsenkirchen five plants are operated. Furthermore, in Wilton, one polymerization plant is located. All these plants are supplied by Naphtha crackers, located as usual on the same production site. The crackers in Geleen and Wilton are fully owned by SABIC, whereas the polymerization plants in Gelsenkirchen are supplied by a cracker, which is jointly owned by SABIC and BP.

Since this project will focus on the production of polyethylene grades, these assets will be described here specifically. All PE grades (97 in total) are allocated to one (or occasionally two) of eight different assets. The allocation is a strategic decision made periodically, based a discussion between manufacturing and supply chain management and is therefore left out-of-scope for this project. Although some grades can be produced on different assets, also the volume of a grade that is being allocated to a specific asset is pre-determined and therefore out of scope for this project. As an illustration, Figure 5 shows which assets are responsible for the production of which grade categories. As shown, only LD5 is producing products of two different grade categories. Although, the production of a polymer in an asset consists of different chemical steps, because a plant can only produce one grade at a time, from a scheduling perspective the production of a grade can be seen as a single production step. Therefore, because the decision, which grades are produced on which assets is made before the scheduling step and the polymerization step can be seen as a single production step, the scheduling problem is a single machine problem.

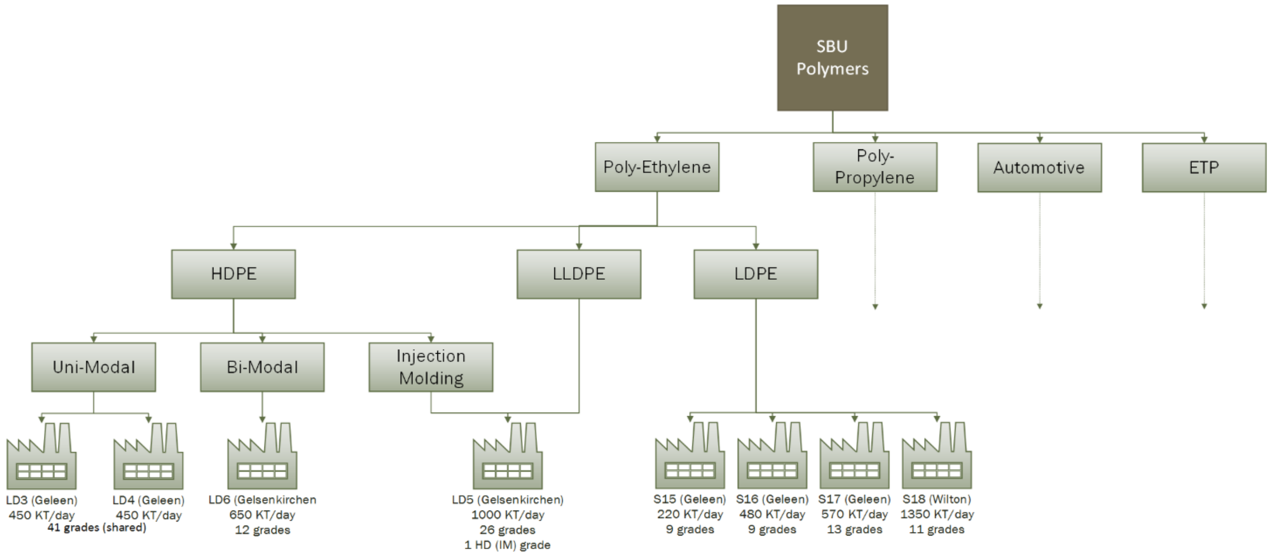

Figure 5: Asset Overview SABIC Poly-Ethylene

2.5.3 Supply Chain Planning

The supply chain management (SCM) department of SABIC EUP has three main divisions: *customer service, sourcing & contracting* and *supply chain planning*. The latter is where this project is conducted. Silver at al. (1998) present a hierarchical decision-making process, where planning decisions can be categorized into strategic, tactical and operational levels. Following this categorization, within SABIC EUP, the setting of production budgets and the allocation of grades to specific assets fall into the strategic decision category. These strategic decisions set the boundaries for the tactical planning level, in which the production wheel is determined. These tactical decisions, in turn, form a guideline for operational decisions, which are made on a day-to-day basis. This research project focusses on the tactical planning level, in which an optimal medium-term production wheel is determined.

Production Budgets and Production Rates

Within SABIC, the production capacity of an asset can be defined in two ways: Firstly, the yearly production capacity can be defined as the sum of the production budgets of all the grades that are produced on a particular asset. Once per year, business managers, together with sales, manufacturing and supply chain representatives, determine the yearly production and sales budgets. The production budgets are taking lost time due to setup times (due to transitions), expected outages and maintenance into account. Production budgets and sales budgets are always in balance and form the input for further tactical decision making, including the production wheel.

Apart from production budgets, production capacity can be defined in production rates (MT/hour). The production rate is defined as the amount of material that can be produced of a particular grade on a particular asset per hour when the asset is running at 100% utilization. The aggregate mean of all production rates is always higher than the production budget per hour, because the production rates do not take the lost time into account.

Allocating Grades to Assets

Some grades are produced on different assets. The allocation of grades to specific assets is a strategic decision made before the beginning of a year, in parallel with production budget decisions, and before the determination of production wheels. Most grades are allocated to a single asset, but when a grade is produced on different assets, the production volumes per asset are also strategically pre-determined and therefore out of scope for the tactical production wheel decisions considered in this project.

2.5.4 The Production Wheel

The order in which grades are produced on an asset is defined as the production sequence and is specified in the production wheel. Furthermore, this production wheel defines the optimal runlength (production quantity) for each grade during each production run. The production wheel is essentially the result of a trade-off between Setup Costs and Holding Costs for all grades together. The production wheel is determined once per year using the budgets as input and is not followed exactly, but is rather used as a guideline that can (occasionally) be adjusted by the MPS to deal with demand volatility. Currently, the determination of the production wheel is based on an ambiguous trial and error approach. This project will focus on improving this production wheel by minimizing the total relevant costs (solving the trade-off) consisting of different cost types that will be presented now.

Holding Costs

As mentioned in the literature review, schedules can be optimized by considering two different cost categories. Holding costs are the first cost component and, within SABIC, this component can be divided into external storage costs, detour costs and working capital costs. All SABIC assets have a specific amount of internal storage capacity for packed and for bulk material. When the total inventory level exceeds this internal storage capacity, material must be stored externally by renting external storage capacity from third parties. Storing an amount of the material externally imposes an external storage cost and a detour cost. Since the internal storage capacity is fixed, storing material internally will be considered free of cost. On the other hand, both internal and external inventory is imposing a working capital cost, which can be calculated using the given weighted average cost of capital and the price of a grade.

Off-Spec Costs (Setup Cost A)

Next to holding costs, the second type of relevant cost is related to the transition between the production of different grades. When switching from one grade to another, the chemical reaction does not stop, but for a certain amount of time the asset will produce material that is not in line with the specifications (i.e. non-prime/off-spec). Although this material is not prime it can still be sold, but for a discount as off-spec material. The amount of off-spec material produced depends on the grade that was being produced before, the next grade that will be produced, and the production rate of the two grades. The money lost by producing off-spec material instead of prime material can be considered as setup cost, which can be calculated by multiplying off-spec volume, by the price difference between prime and off-spec material. Because the volume of off-spec depends on the sequence, these setup costs are sequence dependent.

Campaign Switching Costs (Setup Cost B)

Apart from the off-spec costs, another setup cost should be taken into account. Sometimes, a transition between two grades is so substantial that the chemical reaction needs to stop completely to avoid an unstable reaction or pollution in the reactor. If a transition like this is necessary, the asset needs to be idle for a certain amount of time, this is called the campaign transition time. If this is the case at an asset, the grades can be divided into different campaigns, which are essentially product families from a production perspective. A transition like this does not create any off-spec material (except the off-spec created by starting up the chemical process again), instead the asset will not produce anything during this idle period. The cost of a switch between two campaigns can therefore be calculated by multiplying the average margin made, with the duration of this idle period, times the average production rate.

Safety Stocks

To deal with demand volatility, safety stocks are necessary. The outcome of the determination of the production wheel, provides a certain total cycle time. This total cycle length is used as the lead-time for the safety stock calculations, which are based on a target fill rate and normally distributed demand with a given standard deviation. Currently, safety stock levels are determined without taking the details of the production wheel into account. However, because items are produced in different frequencies in the schedule, using the same lead-time for all grades does not seem to be appropriate. Safety stock levels should rather be based on the actual expected lead-time for a specific grade. In this situation, the effect of the schedule on the safety stock levels should be taken into account explicitly. In this project, the latter will be incorporated in the model to improve safety stock decisions.

Together, the cost types explained above, define the total relevant costs for the production wheel, which have to be minimized to determine the optimal wheel. This minimization problem is subject to two important technical constraints that are discussed now.

Minimum Runlengths

When producing a grade, there is a minimum quantity that needs to be produced before starting he production of the next grade; this concept is called the minimum runlength. Minimum runlengths are specified in metric tons and are due to technical constraints. Minimum runlenghts are often due to the use of a particular catalyst that needs to be used completely or they can be set to increase the stability of an asset. Every transition imposes a certain risk on the asset, to mitigate this risk as much as possible, minimum runlengths can be imposed. Finally, using short runlengths reduces the overall product quality. Although a shorter runlength would create a grade that, on average, is prime, the grade will be less consistent than when using longer runlengths, causing lower customer satisfaction in the long-run.

Technically Impossible Transitions

There are specific transitions that are *technically* not possible. These technical constraints can have many reasons, ranging from causing an unstable reaction to significantly polluting the reactor. Although some technical constraints are less strict than others, this project assumes all technical impossible transitions must be avoided.

After explaining the main concepts relevant to the problem, a method needs to be found/developed to solve SABIC's scheduling problem. To gain some insight in scheduling in general, and to find potential solution methods, an extensive literature review was conducted. The main articles and findings from this literature review will be presented in the next chapter.

3 Literature Review

An extensive literature review was conducted before the start of this research project. Because scheduling is crucial in almost any production context, a lot of research attention has been devoted to this field.

The literature review conducted as a starting point for this research project started by introducing basic literature on inventory management. Subsequently, the concept of scheduling was investigated specifically, and finally different types of scheduling models were investigated. Silver et al. (1998) define the scheduling problem (i.e. the economic lot scheduling problem specifically) as follows:

> *"The ELSP is to find a cycle length, a production sequence, production times, and idle times, so that the production sequence can be completed in the chosen cycle, the cycle can be repeated over time, demand can be fully met, and annual inventory and setup costs can be minimized"*

In the table below, an overview is given of the most important articles that were investigated in the literature review. The articles are categorized using the following classifications:

- Type of Model considered (ELSP, SELSP, DLSP, or CLSP)
- Solving method used
- Objective function
- Is Sequence Dependency (SD) of setups considered
- Are Minimum Runlengths considered?
- Safety Stock Levels simultaneously Optimized

Table 5: Literature Review Article Overview

	Type	Method	Objective	SD Setups	Min Runlengths	Variable Holding Costs	Safety Stocks	Special Characteristics
Bomberger (1966)	ELSP	dynamic programming	min cost	-	-	- **	-	
Bourland & Yano (1996)	SELSP	simulation study	min cost	-	-	- **	-	overtime
Brander (2007)	ELSP	heuristic	min cost	+	-	- **	- **	first TSP -> increasing freq.
Brander & Forsberg (2006)	SELSP	simulation study	min cost	- *	-	- **	+	only SS
Dobson (1987)	ELSP	heuristic	min cost	-	-	- **	- **	
Dobson (1992)	ELSP	heuristic	min cost	+	-	- **	- **	first TSP -> decreasing freq.
Doll & Whybark (1973)	ELSP	heuristic	min cost	-	-	- **	-	
Fleischmann (1994)	DLSP	heuristic	min cost	+	-	- **	-	
Fransoo et al. (1995)	SELSP	heuristic	max profit	-	-	- **	+	fixed sequence, fixed CT
Gallego (1992)	SELSP	heuristic	min cost	-	-	- **	+	fixed sequence, var. CT
Gupta & Magnusson (2005)	CLSP	MIP	min cost	+	-	- **	-	
Haase (1996)	CLSP	priority rule	min cost	+	-	- **	-	
Leachman & Gascon (1988)	SELSP	heuristic	min cost	-	+/-***	- **	-	fixed sequence, var. CT
Maxwell (1964)	ELSP	heuristic	min cost	-	-	- **	-	
Qui & Loulou (1995)	SELSP	semi-Markov	min cost	-	-	- **	-	dynamic sequence, var. CT
Rogers (1958)	ELSP	heuristic	min cost	-	- **	- **	-	
Wagner & Davis (2002)	ELSP	heuristic	min cost	+	-	- **	-	first TSP -> decreasing freq.
Wagner & Smits (2004)	SELSP	local search heuristic	min cost	-	-	- **	+	fixed sequence, var. CT
Zipkin (1986)	SELSP	queueing approach	min cost	-	- **	- **	-	
Zipkin (1991)	ELSP	parametric quadratic	min cost	-	-	- **	-	

* input sequence with Sequence Dependent Setups could be used
** not used but could be implemented into the model
*** Concept is used as a feasibility check

Conclusions from Literature

The following conclusions were drawn from the literature review. With regard to the optimal production wheel at SABIC, major decisions are to be made concerning the assumptions of the desired model. When following Winands et al.'s (2011) classification of the scheduling problem, first two different characteristics of the problem need to be specified:

1. Presence or Absence of Setup Times/Costs

Setups are essential in the production process of polymers at SABIC EUP. More specifically, these setups are significantly sequence dependent. Therefore, this sequence dependency should be taken into account in the model for improving the production wheel.

2. Assuming Stochastic or Deterministic Demand

The issue of stochasticity still needs to be addressed. Given the fact that there is stochastic demand in SABIC's situation, the choice needs to be made whether to incorporate this stochasticity directly in the model or to specify a specific safety stock level to deal with this volatility, and first solve the scheduling problem as if it experiences deterministic demand.

After analyzing the models discussed in the literature review and mentioned in this Chapter, one can conclude that all scholars solve the problem using a heuristic solution method, rather than true optimization. This is due to the NP-hard characteristics of the scheduling problem. For more details on NP-hardness, and why a scheduling problem specifically is NP-hard, please refer to the literature review document. Furthermore, one can see that much research has been done during the 1990's and early 2000's, after which research attention has been shifted away from generic scheduling heuristics. A reason for this could be that scheduling problems are often very different in different environments. Therefore, heuristics should be developed that are specifically applicable to a particular case.

Analysis of Table 4, on the previous page, shows that essential concepts of SABIC's problem are not considered by the models that are available in current literature. Especially the minimum runlength constraint, which will turn out to be essential for SABIC's situation, is ignored almost completely. Therefore, these models are not directly appropriate to the problem under consideration. Nonetheless, the already existing heuristic methods can be very valuable as an inspiration and starting point for developing a heuristic that is applicable to SABIC's situation specifically.

Deterministic scheduling heuristics can be subdivided into two broad categories. A heuristic can either start by determining production frequencies (i.e. the number of times a grade is produced in a cycle) and subsequently sequence the individual production runs (e.g. Brander, 2005), or start from a pure rotation schedule (i.e. a schedule in which every product is produced exactly once), and subsequently alter specific production frequencies heuristically. Starting from a pure rotation schedule, there are many methods to increase production frequencies. Wagner and Davis (2002) increase production frequencies one-by-one and Dobson (1992) proposes a heuristic that duplicates the entire sequence and then skips particular production runs in the duplicate sequence to alter production frequencies. These procedures can be repeated multiple times using different cost reduction methods (e.g. the steepest descent method) considering total relevant costs.

Furthermore, stochastic scheduling models specifically, can also be divided into different sub-categories. Generally, SELSPs can be categorized into dynamic models and fixed models. In a dynamic model, adjustments to the sequence (e.g. Zipkin, 1986 and Qui and Loulou, 1995) and/or cycle length (e.g. Fransoo et al., 1995) are possible to deal with stochasticity in demand (and/or supply). In fixed models, stochasticity is dealt with by using safety stocks (e.g. Brander & Forsberg, 2006 and Erkip et al., 2000). Essentially every model needs some method to deal with stochasticity in demand either through dynamic scheduling or safety stocks.

Parts of the models provided in literature are used as an inspiration (e.g. Dobson (1992), Wagner & Davis (2002) and Brander & Forsberg (2006)) to develop a suitable heuristic for SABIC's specific problem. Before explaining the developed heuristic, a mathematical description of the model will be given in the following Chapter. The heuristic will be explained in detail in the subsequent chapter.

4 Developing a Model

As mentioned in Chapter 3, scheduling problems are generally solved using heuristics. Before presenting the developed heuristic in Chapter 5, this Chapter will focus on the development of a model that defines SABIC's scheduling problem mathematically. The general goal of this project is to improve the production wheel by minimizing total relevant costs (setup cost, working capital cost, and external storage cost). Because the cycle time is also variable, costs should not be evaluated per cycle, but rather per day.

A schedule can be described as a number of consecutive production runs and the setups in-between these runs. Together, the setup just before a production run, and the production run itself are defined as a production step. In every production step, a certain quantity of one grade is produced (and potentially off-spec material during the transition is produced). The duration of a production step is determined by the time it takes to produce the specific quantity and the setup time before that production run. Although only one grade is produced, all grades experience demand during each step. The change in inventory during a production step can therefore be described as the potential production of the grade minus the demand for this grade during this production step.

There exist almost infinite options for composing the production wheel. Choices can be made with regard to the sequencing of grades, production quantities per production run, safety stock levels and the length of a schedule (i.e. cycle time). The optimal combination of these variables, which minimizes the total relevant costs, will be the optimal production wheel. Because the production wheel is determined for an entire year, SABIC required the schedule to be repetitive, meaning that the schedule should be cyclic (i.e. after the last grade is produced, the schedule will return to the first grade of the schedule). The production wheel should therefore propose a schedule in which the end situation is the same as the begin situation (i.e. inventory levels at the beginning of the schedule are the same at the end of the schedule).

Essentially, determining the optimal production wheel can be modeled as a trade-off between four different cost types:

- Working Capital Cost of Safety Stock per day
- Working Capital Cost of Cycle Stock per day
- External Storage Cost (including detouring cost) per day
- Setup Costs (Off-Spec Production + *potential campaign switch*) per day

A model assuming constant deterministic demand rates is used to improve the production wheel. In literature, the problem described in such a model is defined as an economic lot-scheduling problem (ELSP) with sequence dependent setup times/costs. Although scheduling decisions are based on deterministic demand rates (for which demand budgets are used as input), in reality SABIC experiences stochastic demand. To deal with this volatility, safety stocks are necessary. Because scheduling decisions have a significant impact on how much safety stock should be stored (i.e. more production runs of a grade per schedule reduces the leadtime of this grade, in turn, reducing safety stock level), this effect is taken into account as the working capital cost of safety stock when the cost of a schedule is determined. The concept of determining safety stock levels for a model that assumes deterministic demand is similar to Brander and Forsberg's (2006) approach of determining safety stocks for fixed cyclic schedules. In line with Brander and Forsberg, normally distributed demand is assumed, and the maximum lead-time for a certain grade in combination with a given target fill rate is used to determine the required safety stock levels for each grade.

Regular inventory levels (i.e. the cycle stocks) are considered separately from the safety stock levels (safety stock levels essentially only increase the total inventory level by a certain constant amount throughout the cycle). The working capital cost of the cycle stock can be calculated by determining the average inventory level (excl. safety stocks) during every production step in the schedule. Throughout this report, inventory levels are defined as the on-hand inventory levels, unless, specified otherwise.

Only a limited amount of inventory can be stored in-house, all inventory that is above this threshold must be stored externally, imposing an external storage cost. Apart from a cost for renting external storage facility, transferring the material to the facility imposes an additional detouring cost. Together both costs are defined as the external storage cost per day.

Setup Costs are the result of producing off-spec material instead of prime material, during a certain amount of time, when production is switched from one grade to another. All setups together, determine the setup cost per schedule. Dividing this by the total duration of the schedule (i.e. cycle time) gives the setup cost per day.

Minimizing the total relevant cost (i.e. the sum of the four cost types) is subject to different constraints. First, all demand needs to be fulfilled within the cycle, and regular inventory levels (the inventory level excluding the safety stock) should never be negative. Additionally, production quantities can never be lower than the minimum runlength, and technical impossible transitions should be avoided. Before the mathematical model is presented in detail, first, the main assumptions behind the model are presented.

4.1 Assumptions

Demand rates are assumed deterministic and constant

For the determination of the optimal production wheel, constant, deterministic demand rates are assumed, which are determined based on given yearly demand budgets.

Safety Stock levels are based on normally distributed demand

Although the production wheel is based on constant demand rates, in reality demand is volatile, for which safety stocks are necessary. Safety stock levels are determined by assuming normally distributed demand.

Price and off-spec price of all grades are deterministic and constant

Although prices in the polymer market are relatively volatile, from a production wheel perspective, this price variance is not very important. The difference between off-spec prices and sales prices determines the transition cost, and this difference is relatively stable. Because of this, for the purpose of this project, it is assumed that prices and off-spec prices are deterministic and constant throughout the year.

Breakdowns

Breakdowns causes the MPS to deviate from the production wheel significantly. Because the production wheel is used as a tactical guideline, these breakdowns are not relevant. Therefore, the model assumes all plants are operating 24 hours per day and 365 days per year.

Sales are lost in out-of-stock situations

In a commodity market, in which SABIC Polymers operates, one can assume that when a grade is out-of-stock the sale will be lost and the customer will buy the product from a competitor.

Transition times, minimum runlengths, production rates and storage capacity are constant and deterministic

Changing these parameters would need long-term investments and in the short run they can be assumed deterministic and constant.

All material becomes available at the end of a production run

It is assumed that all produced material becomes available as a batch when the entire production run for that grade is finished.

External Storage Space is rented for an entire cycle and Capacity is infinite

The external Storage Space is rented for a relatively long period. Therefore, the amount can be assumed stable throughout the cycle. Furthermore, there are no restrictions on the amount of rented space.

External storage cost rate is deterministic and constant

External storage cost rates are often the result of long negotiations with external storage providers. Therefore, external storage cost rates are known beforehand and constant throughout the year.

Production during the setups is always off-spec

It is assumed that during a transition material is always off-spec. This means that during a transition the material can never become prime nor complete junk. The amount of off-spec that results from a setup is deterministic and depends on the grade that is produced before and after the setup.

Production outside the transition periods is always prime

It is assumed that when a product is produced the quality is always 100% except for transition periods in which off-spec material is produced.

4.2 The Optimization Problem

After the reasoning behind the model was explained and all relevant assumptions have been defined in the previous section, it is possible to describe the problem mathematically. As mentioned in the previous section, the goal of the problem is to minimize the sum of all expected relevant cost types. This can be described as follows (for the sake of clarity, expectation signs, $E[x]$, are not included in all formulas):

$$\min TRC = \min(SC + WCCCS + WCCSS + ESC) \tag{4.1}$$

Before discussing constraints of the minimization problem, first some general terminology will be explained. The goal of the optimization problem is to find the optimal schedule (cycle), which defines a sequence, production quantities per production run, the number of production runs and the safety stock levels. A sequence is defined as the order of production runs, where every grade is produced at least once per cycle and after the last grade in the sequence, a new identical cycle is started. Throughout the following explanation, subscripts are used to refer to the type of grade, and superscripts are used to specify the position in the sequence. For example, in a situation where there are four grades (A, B, C, D), $i = 1$ refers to $grade\ A$ and $N = 4$ (N is the total number of grades produced by the asset). If these four grades are scheduled as follows: $\{B \to C \to A \to B \to D\}$, $j = 1$ refers to the first production run of $grade\ B$, $M = 5$ (M is the total number of production steps in a cycle), and the production frequency f is then $\{1{,}2{,}1{,}1\}$ for grades A, B, C and D.

Which grade is produced during which production step is defined by the binary variables x_i^j, which is one when item i is produced during step j and zero otherwise:

$$x_i^j = \begin{cases} 1 & if\ item\ i\ is\ produced\ during\ step\ j \\ 0 & otherwise \end{cases} \qquad \forall i\ \forall j \tag{4.2}$$

To determine the inventory levels during every step of the cycle, the change of inventory during a production step is considered. During each production step (a production step is the combination of a production run and the setup just before this production run) every grade is subject to a certain level of demand. For each grade i, this demand can be calculated by multiplying the constant demand rate (d_i) with the duration of step j (Δt^j). The setup time during production step j defined as: $ST^{j-1;j}$, resulting in a production time of: $\Delta t^j - ST^{j-1,j}$. Additionally, for one grade, the inventory level is increased. The quantity produced can be calculated by multiplying the production rate (p_i) with the production time.

The inventory level of grade i at the end of a step j can therefore be defined as the on hand inventory level at the end of the last step, minus the demand during the step, plus the potential production of the grade during this step:

$$I_i^j = I_i^{j-1} - d_i * \Delta t^j + x_i^j * p_i * (\Delta t^j - ST^{j-1,j}) \qquad \forall i\ \forall j \tag{4.3}$$

where, I_i^j is the inventory level at the end of step j for grade i and I_i^{j-1} the inventory level at the end of the previous step (the end of a step is defined as the end of a production run, before the next transition).

Because it takes some time before a grade is produced for the first time in a cycle, initial inventory (I_i^0) (i.e. the inventory level at the beginning of a cycle) is necessary. The required initial inventory level should be at least the demand for grade i until that grade is produced for the first time in the schedule. Because the inventory level is not always zero just before the replenishment of a grade, the initial inventory level could also be higher than this minimum quantity (i.e. it might be optimal for the schedule to have a production run of a grade that has more than zero inventory). This means that the zero-switch rule, as discussed in Roundy (1989) and many others, is *not* imposed in our approach. This essentially makes the initial inventory levels another set of decision variables for the optimization problem.

Running an asset at 100% utilization may cause inventory levels to rise indefinitely. This is because theoretical production rates are higher than the sum of all demand rates, due to the fact that demand rates are based on budgets (more information on production and demand budgets can be found in Section 2.6.3), which take expected outages and maintenance into account. To compensate for this effect, a stabilization factor μ^* is introduced. μ^* balances the production and demand rates for a given schedule, taking production quantities and setup times into account. Essentially μ^* makes the production during a cycle equal to the demand during this cycle. Mathematically μ^* can be described as follows:

$$\mu^* = \frac{\sum_{j=1}^{N} \frac{Q^j}{p^j} + ST^{j-1,j}}{\sum_{j=1}^{N} \frac{Q^j}{\sum_{i=1}^{N} d_i} + ST^{j-1,j}} \qquad (\mu^* < 1 \; otherwise\; infeasible) \tag{4.4}$$

The duration of a step Δt^j depends on the theoretical production rate of the grade produced, the quantity of the grade produced, and the setup time between the previous grade and the grade produced. To make production equal to demand, this term is multiplied by the stabilization factor μ^*.

$$\Delta t^j = \left(\frac{Q^j}{p^j} + ST^{j-1,j}\right) * \frac{1}{\mu^*} \qquad \forall j \tag{4.5}$$

The sum of all Δt^js is the total length of the schedule, which is defined as the cycle time (CT):

$$CT = \sum_{j=1}^{M} \Delta t^j \tag{4.6}$$

Every grade is produced during a certain amount of runs in a schedule. The amount of runs is defined as the production frequency of a grade (f_i), which can be described mathematically as follows:

$$f_i = \sum_{j=1}^{M} x_i^j \qquad \forall i \tag{4.7}$$

As mentioned before, although the schedule is optimized assuming deterministic and constant demand rates, in reality safety stocks are necessary to deal with demand volatility. The main goal of safety stocks is to absorb the variability of customer demand. Indeed, production scheduling is based on a forecast (i.e. the budget), which is (by definition) different from the real demand. By absorbing these variations, safety stock improves the service level (i.e. fill rate). Since required safety stock levels are significantly impacted by scheduling decisions, the cost of holding safety stock is incorporated in the optimization model. To determine safety stock levels, Brander and Forsberg's (2006) approach, determining safety stock levels for fixed cyclic schedules, is followed. They propose to use the maximum leadtime for every grade during a cycle to establish constant safety stock levels. The standard deviation of demand is calculated for this maximum leadtime, and is defined as $\sigma_i^{\mathrm{maxLT_i}}$ for all grades i.

Assuming normally distributed demand, for the given fill rate targets α_i for each grade i, the safety stock level is set at:

$$SS_i = k_i * \sigma_i^{maxLT_i} \qquad \forall i \tag{4.8}$$

where, k_i is defined as the inverse cumulative normal distribution for a given fill rate α_i (i.e. $k_i = \Phi^{-1}(\alpha_i)$). Essentially, the safety stock level is determined by the probability that demand is below the safety stock level and the cycle stock level combined, during a certain leadtime. Using the maximum leadtime, causes safety stock levels to be higher during the production runs facing shorter leadtimes.

Figure 6 shows the production process and its characteristics graphically for the example of three grades that are produced in a sequence of four steps. In this example $N = 3$, $M = 4$, and $f = \{2,1,1\}$. This Figure also shows that grades that are produced multiple times in a schedule are subject to different leadtimes.

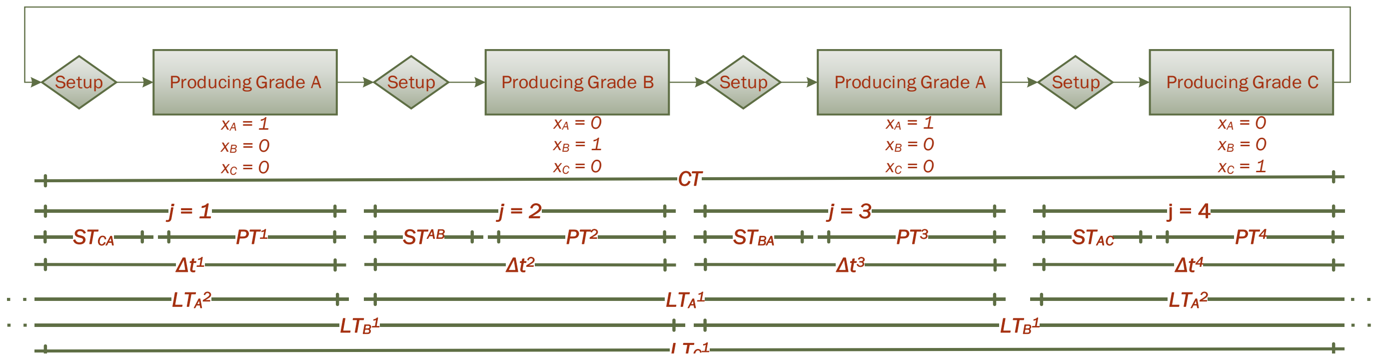

Figure 6: Graphical Representation of the Production Wheel

Considering all of the above, the following constraints can be set for the minimization problem:

$$I_i^M \geq I_i^0 \qquad \forall i \tag{4.9}$$

$$I_i^j \geq 0 \qquad \forall i \quad \forall j \tag{4.10}$$

$$Q^j \geq \sum_{i=1}^{N} (x_i^j * MRL_i) \qquad \forall j \tag{4.11}$$

$$\sum_{i=1}^{N} x_i^j = 1 \qquad \forall j \tag{4.12}$$

$$SS_i = k_i * \sigma_i^{maxLT_i} \qquad \forall i \tag{4.13}$$

The first constraint states that inventory levels for grade i at the end of the cycle ($j = M$) must be at least as high as inventory levels at the beginning of the cycle ($j = 0$). The second constraint makes sure all demand is met. The third constraint states that production quantities are at least the minimum runlength of all the grades produced during all steps j. The fourth constraint defines that during every step, exactly one specific grade is produced. The final constraint defines the safety stock level for every grade that is required for a particular schedule. As mentioned before, all demand is fulfilled within the cycle because of the first two constraints. Therefore, safety stock is only used to deal with volatility in demand.

Because it takes some time before an item is produced for the first time in the cycle, initial inventory is necessary. Along with the production quantities Q^j, these initial inventory levels I_i^0 are another set of decision variables. Additionally, the number of steps during a sequence (M) and all binary variables x_i^j are decision variables. Now the general problem is defined, all cost types will be explained one-by-one

Setup Cost per Day

Setup Costs are the result of producing off-spec material, during a transition between the production runs of two different grades. Because off-spec material is sold for a lower price than prime material, this imposes a setup cost. The cost of producing off-spec is essentially the cost of not producing prime during a transition period. To determine the cost of a transition, the transition time is multiplied by the aggregate mean of the sales price minus the off-spec price, multiplied by the aggregate mean of the production rates. Aggregate means are used because the "lost time" of a transition, is reducing the productivity of prime material for all grades, rather than only the grades involved in the transition specifically. This is described in formula 4.14

$$SC_{ab} = ST_{ab} * \left(\sum_{i=1}^{N} \left(P_i * \frac{d_i}{\sum_{i=1}^{N} d_i} \right) - OSP \right) * \sum_{i=1}^{N} \left(p_i * \frac{d_i}{\sum_{i=1}^{N} d_i} \right) \tag{4.14}$$

The total setup cost (TSC) of a sequence is the sum of all transition costs, defined in formula 4.15:

$$TSC = \left(\sum_{j=1}^{M-1} SC^{j,j+1} \right) + SC^{M,1} \tag{4.15}$$

The formulas show that the setup cost of a schedule only depend on the order in which the products are produced and not on the quantities produced during the different steps. Setup Costs per day can be simply calculated by dividing the total Setup Costs by the total cycle time:

$$SC = \frac{TSC}{CT} \tag{4.16}$$

Working Capital Cost of Cycle Stock per day

The second cost type is the working capital cost of the cycle stock. This cost is directly related to the inventory levels during all steps j. The working capital cost of inventory is calculated for every step as the average inventory level during a step (i.e. because of constant demand rates this is the average of I_i^j and I_i^{j-1}), times the working capital cost of holding one MT for one day (i.e. the WACC, times the price of a grade, divided by 365), times the portion of the cycle, the cycle is in step j (i.e. Δt^j / CT).

$$WCC_i = \sum_{j=1}^{M} \left(\frac{I_i^{j-1} + I_i^j}{2} * \frac{WACC * P_i}{365} * \frac{\Delta t^j}{CT} \right) \tag{4.17}$$

For all grades together, total working capital cost of the cycle stock per day can now be defined as follows:

$$WCCCS = \sum_{i=1}^{N} WCC_i \tag{4.18}$$

Working Capital Cost of Safety Stock per day

The model is set-up in a way that Safety Stock levels are a result of the decision variables, rather than decision variables in themselves. The working capital cost of holding safety stocks per day is the sum of all safety stock levels multiplied by the grade price and is mathematically defined as follows:

$$WCCSS = \sum_{i=1}^{N} \frac{SS_i * WACC * P_i}{365} \tag{4.19}$$

External Storage Cost per Day

The last relevant cost is the cost of storing material externally. When internal storage capacity is insufficient, material needs to be stored externally. The costs of storing material externally is twofold. First, storage space needs to be rented from a third party, and secondly, the transportation of the material to the external storage provider imposes a detour cost. Because detouring is relatively expensive, to avoid a high amount of detouring, once material is stored externally, it is strategically decided to first sell internally stored material rather than externally stored material. This causes the external storage level to be relatively stable throughout a cycle. Because of this, to determine the external storage costs, the maximum total level of inventory in a cycle is used.

The first step in determining the external storage cost, is calculating the amount of material that needs to be stored externally. Internal storage capacity is not used entirely, but is subject to an internal occupation rate (IOR) which is defined as the average utilization of the internal storage facilities. Internal storage capacity cannot be used fully because even when very little material is stored in a particular storage silo, this entire silo is occupied. This effect is only relevant for bulk material because for packed material the practical storage capacity is equal to the theoretical capacity (packed material is not stored in silos). Also external storage silos are subject to a similar occupation rate (EOR), which has to be taken into account. Because the amount of material stored externally is more stable than the internal amount, the external occupation rate is usually significantly higher than the internal one.

As mentioned, the cost of storing material externally is not only the renting of external capacity; a major component of storing material externally is the cost of transferring material to the external facility. This concept is called detouring. To avoid a lot of detouring, once material is stored externally, first the internal inventory is sold. To determine how often material is detoured (this is equal to the average time material will in the external storage facility), the average turnover rate is used ($TORB$ and $TORP$ for bulk and packed material respectively).

For both bulk and packed material, the total external storage cost can be calculated by first defining the amount of material that needs to be stored externally by determining the maximum inventory level during a cycle and then subtracting the internal inventory capacity. This external storage level is multiplied by the external storage cost rate to determine the cost of renting external storage space. Together with the detouring costs, which can be calculated by considering the turnover rate, this defines the total external storage cost. Mathematically, this can be described as follows (where the internal max function makes sure externally stored material cannot be negative in the case of sufficient internal capacity):

$$TESCB = \max(\max_{j \in M}\left(\sum_{i=1}^{N} \%B_i * I_j^i\right) - SCB * IOR; 0) * \left(\frac{ESCB}{\rho * EOR} + \frac{DCB * 365}{TORB}\right) \tag{4.20}$$

$$TESCP = \max(\max_{j \in M}\left(\sum_{i=1}^{N} (1 - \%B_i) * I_j^i\right) - SCP; 0) * \left(\frac{ESCP}{\rho} + \frac{DCP * 365}{TORP}\right) \tag{4.21}$$

$$ESC = TESCB + TESCP \tag{4.22}$$

Summarizing the Problem

<u>Objective Function</u>

$$\min TRC = \min(SC + WCCCS + WCCSS + ESC)$$

<u>Constraints</u>

$$I_i^M \geq I_i^0 \qquad \forall i$$

$$I_i^j \geq 0 \qquad \forall i \quad \forall j$$

$$Q^j \geq \sum_{i=1}^{N} (x_i^j * MRL_i) \qquad \forall j$$

$$\sum_{i=1}^{N} x_i^j = 1 \qquad \forall j$$

$$SS_i = k_i * \sigma_i^{maxLT_i} \qquad \forall i$$

<u>Decision Variables</u>

$$Q^j \ \forall j, \qquad I_i^0 \ \forall i, \qquad x_i^j \ \forall i \ \forall j \qquad and\ M$$

Intermezzo: Non-Linearity in the Cost Model

This paragraph will explain why the model described above is non-linear. In order to reduce calculation time and to make it usable on current SABIC software (i.e. limited version of *OpenSolver*), it has to be transformed into a model that is linear. Formula 4.23 shows how the holding cost of a grade i is calculated during a production step j and formula 4.24 shows how I^j is related to I^{j-1}.

$$WCC^j = \frac{I_i^{j-1} + I_i^j}{2} * \frac{WACC * P_i}{365} * \Delta t^j \tag{4.23}$$

$$I_i^j = I_i^{j-1} - d_i * \Delta t^j + Q^j \tag{4.24}$$

Now suppose $ST^{j-1\rightarrow j} = 0$, then substituting formula 4.3 into both formulas gives:

$$WCC_i^j = \frac{I_i^{j-1} + I_i^j}{2} * \frac{WACC * P_i}{365} * \frac{Q^j}{p^j} \tag{4.25}$$

$$I_i^j = I_i^{j-1} - d_i * \frac{Q^j}{p^j} + Q^j \tag{4.26}$$

Substituting formula 4.26 into formula 4.25 gives:

$$WCC_i^j = \left(\frac{Q^j}{p^j}\right) * \left(\frac{I_i^{j-1} + I_i^{j-1} - d_i * \frac{Q^j}{p^j} + Q^j}{2}\right) * \left(\frac{WACC * P_i}{365}\right) \tag{4.27}$$

Simplifying this gives the following:

$$WCC_i^j = \left(\frac{1}{2} * \frac{\boldsymbol{(Q^j)^2} * d_i}{(p^j)^2} * I_i^{j-1} + \frac{1}{2} * \frac{\boldsymbol{(Q^j)^2}}{p^j}\right) * \left(\frac{WACC * P_i}{365}\right) \tag{4.28}$$

The fact that the objective function depends on a quadratic function of the decision variables Q^j (indicated with red in formula 4.28) makes the model non-linear and therefore not solvable in an efficient way (i.e. solving non-linear programming problems takes significantly more time than linear programming problems. Because the heuristic requires the problem to be solved many times, a non-linear model will not be practical).

To translate the non-linear program into a linear program the concept of $stepTime^j$s average production times APT_i and the $minCT$ is introduced. These concepts will be introduced in the next chapter, where the developed heuristic is explained in detail. Because of NP-hardness and non-linearity characteristics, the problem is not solvable via true optimization methods. Therefore in the next chapter a heuristic will be developed that will determine a near-optimal solution for the problem explained in this Chapter.

5 The Heuristic

As mentioned in the previous chapter, there is an almost infinite amount of production wheel options. Simultaneously optimizing all decision variables is therefore not possible. Therefore, the problem needs to be split into different optimization steps. This is called a heuristic model, which is defined by as:

An approach to problem solving that employs a practical method not guaranteed to be optimal or perfect, but sufficient for the immediate goals

- Emiliano (2015) -

The scheduling heuristics developed in literature do not incorporate all relevant concepts for SABIC's scheduling problem. For example, minimum runlengths and non-linear holding costs are not considered. Both Brander's (2005) and Wagner and Davis' (2002) heuristics were implemented, but these did not give satisfactory results. Although these heuristics are therefore not applicable directly, they are used, together with others (e.g. Dobson, 1992), as an inspiration and starting point for developing a heuristic that considers all relevant aspects of SABIC's scheduling problem. This heuristic will be presented in this Chapter.

In order to solve the scheduling problem, a generic (i.e. one that can be used for multiple SABIC assets) heuristic was developed and implemented into an optimization tool. This Chapter will focus on explaining the different steps of the heuristic and the reasoning behind it. Essentially the heuristic contains three main elements.

The heuristic starts by solving the well-known traveling salesman problem to determine a pure rotation schedule (i.e. a schedule where every grade is produced exactly once per cycle) with minimum setup costs.

Subsequently, the heuristic evaluates all options of increasing the production frequency of one of the grades (e.g. producing $grade\ i$ twice per cycle instead of once). The heuristic considers all possible positions to place the *additional* production run in the current schedule. The effect of placing an *additional* production run on a specific position in the current schedule is evaluated by the third element of the heuristic: *the cost model.*

For every proposed schedule, the cost model determines the total cost per day of a specific schedule, taking into account setup costs, external storage costs and the working capital cost of both safety stocks and cycle stocks. For each grade, the optimal position to add a production run is determined, and based on this, the grade for which adding an additional production causes the biggest overall cost reduction is selected. For this grade, a production run is added and placed on the optimal position. Through this cost model, for every proposed sequence, optimal production quantities and an optimal cycle time is determined iteratively.

This process of adding production runs to the schedule continues until adding a production run for none of the grades causes a cost reduction anymore. The three elements, and how they are connected, will be discussed in detail in the following paragraphs.

5.1 Determining the Optimal Pure Rotation Schedule

This paragraph describes the first step of the heuristic, where the optimal pure rotation schedule is determined. More specifically, this step determines the sequence, in which all grades are produced exactly once per cycle, resulting in the lowest setup costs. Optimizing a pure rotation schedule can be done by initially only focusing on the setup costs. This is because in an optimal pure rotation schedule inventory levels, and therefore holding costs, are only dependent on the total cycle length and not on the sequence in which the products are scheduled (i.e. the lead-time for all grades is the same and therefore cycle stocks and safety stock levels only depend on this *general* lead-time). The decision for the optimal cycle time can be made independent of the sequencing decision (see also formula 4.14 and 4.16)

Although the total cycle time depends slightly on the sequencing decision, because a sequence with higher setup times might lead to a longer cycle time as well, since minimizing setup costs is proportional to minimizing setup times (in SABIC's situation), this effect can be ignored. Therefore, an optimal pure rotation schedule can be determined by first minimizing the total setup cost of the sequence and subsequently determining the optimal cycle time to get the optimal pure rotation schedule.

To find the optimal sequence of the pure rotation schedule, first, the transition time matrix is transformed into a transition cost matrix. The transition cost of going from $grade\ A$ to $grade\ B$ can be determined in line with formula 4.14.

$$SC_{ab} = ST_{ab} * \left(\sum_{i=1}^{N} \left(P_i * \frac{d_i}{\sum_{i=1}^{N} d_i} \right) - OSP \right) * \sum_{i=1}^{N} \left(p_i * \frac{d_i}{\sum_{i=1}^{N} d_i} \right) \qquad \forall a\ \forall b \tag{5.1}$$

The setup cost is calculated for all transitions of all grades and together this is called the *setup cost matrix*. There are specific transitions that are *technically* not possible. These technical constraints can have many reasons, ranging from causing an unstable reaction to significantly polluting the reactor. Although some technical constraint are less strict than others, for this project it is assumed that all technical impossible transitions should be avoided. For these transitions their respective transition time is set to 100000, which makes the cost of this transition essentially infinite (i.e. the traveling salesman will almost never use this arc, and when it does, this is dealt with in a subsequent improvement step, see Section 5.2).

Figure 7 shows an example of how the transition time matrix is translated into a transition cost matrix (if $\underline{OSP = 700}$).

$SC_{i \to j}$	Grade A	Grade B	Grade C
Grade A	0	0.6	1
Grade B	0.6	0	0.3
Grade C	1	1.5	0

×

	p_i	P_i	d_i
Grade A	15	1000	5
Grade B	10	900	7
Grade C	20	1200	6

=

$SC_{i \to j}$	Grade A	Grade B	Grade C
Grade A	0	3157	5262
Grade B	3157	0	1579
Grade C	5262	7893	0

Figure 7: Translating the Setup Time Matrix to the Setup Cost Matrix

Total setup cost can be calculated by taking the sum of all the individual transition cycle costs. Minimizing the total cost of a sequence that produces every item once and then returns to the first grade produced can be solved using a traveling salesman problem (Dobson, 1992). According to Papadimitriou and Steiglitz (1998), the traveling salesman problem can be represented as an integer linear program. Translating this to our problem gives the following mathematical representation of determining the pure rotation schedule, where the binary variables $y_{i \to j}$s are the decision variables that are defined as follows:

$$y_{ij} = \begin{cases} 1 & if\ tansittion\ is\ fom\ grade\ i\ to\ grade\ j \\ 0 & otherwise \end{cases} \qquad \forall i\ \forall j \tag{5.2}$$

The traveling salesman problem can now be written as follows:

$$\min \sum_{i=1}^{N} \sum_{j \neq i, i=1}^{N} SC_{ij} * y_{ij} \tag{5.3}$$

Subject to:

$$\sum_{i=1, i \neq j}^{N} y_{ij} = 1 \qquad \forall j \tag{5.4}$$

$$\sum_{j=1, j \neq i}^{N} y_{ij} = 1 \qquad \forall i \tag{5.5}$$

The objective function (formula 5.3) minimizes the total setup cost of the sequence, and the constraints (formula 5.4 and formula 5.5) make sure that every grade i is exactly produced once during the sequence. This problem is solved using the standard Microsoft Excel Solver add-in.

Apart from being the starting point of the heuristic, the pure rotation schedule could also be the sequence of the optimal schedule. Therefore, the expected total relevant cost of this pure rotation schedule is first determined. For this, the optimal cycle time, optimal production quantities and safety stock levels are determined using the cost model, explained in Section 5.3.

5.2 Increasing Production Frequencies

After the optimal pure rotation schedule has been determined, the effect of increasing the frequency of every grade is evaluated individually. For each grade, the expected total cost when inserting an additional production run in the schedule on every possible position in the sequence is determined by the cost model (see Section 5.3). From these possible positions, the position that causes the biggest decrease in total relevant cost is chosen. After this procedure is performed for all grades, for the grade that causes the biggest cost decrease, the frequency will be increased by 1 on the position that was optimal for that grade. To clarify this procedure, a graphical representation is shown in Figure 8 for a simple scheduling problem with four different grades ($N = 4$), where the TSP gives the following optimal pure rotation sequence$\{A \rightarrow B \rightarrow C \rightarrow D\}$. (The cost values are fabricated and only serve as clarification for the process).

Figure 8: Graphical Representation of the Improvement Process

As can be seen in Figure 8, adding an additional production run for $grade\ B$ in-between the production of $grade\ C$ and $grade\ D$ causes the biggest decrease in total relevant cost (from 20 to 16) in improvement step 1. This optimal sequence after one improvement step is indicated in red. After adding $grade\ B$ on the optimal position (i.e. between $grade\ C$ and $grade\ D$) this will be the base sequence for the next improvement step. For the next iteration, sequence$\{A \rightarrow B \rightarrow C \rightarrow B \rightarrow D\}$ will be used as the starting point. The heuristic continues evaluating every possible frequency increase, on every possible position until no further cost reduction is found by adding a production run for any of the grades. As mentioned before, every grade/position combination is evaluated by a cost model that will now be explained in detail. For pseudocode of this procedure, please refer to Section 5.3 of this report.

5.2.1.1 Exception: Single Arc Grades

By default, the production frequencies of grades are increased one by one, as explained in the previous section. There is one exception to this rule, where this is not feasible. There are grades that can only be produced after and/or before one specific grade. If a grade has only one grade that can be produced in advance, this previous grade is called a *fixed incoming grade*. When a grade has only one grade that can be produced afterwards, the latter grade is referred to as the *fixed outgoing grade.* This is visible in the transition matrix as a grade with only one feasible (i.e. not technically impossible) incoming or one outgoing transition respectively (e.g. grade GRADE D has both, see Figure 9 where GRADE E (yellow) and GRADE C (blue) is the fixed incoming and outgoing grade respectively). If a situation like this occurs, when increasing a frequency for such a grade is considered, automatically, the incoming or outgoing grade is added before or after the grade in the sequence.

FACTORY E (minutes)	GRADE A	GRADE B	GRADE C	GRADE D	GRADE E	GRADE F	GRADE G	GRADE H	GRADE I	GRADE J	GRADE K	GRADE L	GRADE M
GRADE A		22	64	100000	22	0	45	45	100	100	45	35	41
GRADE B	22		86	100000	37	32	87	87	120	120	87	90	120
GRADE C	35	54		100000	15	28	28	30	33	33	28	20	20
GRADE D	72	100000	100000		100000	100000	100000	100000	100000	100000	100000	100000	100000
GRADE E	19	90	40	0		28	25	37	60	60	25	0	45
GRADE F	0	25	72	100000	0		58	62	60	60	58	72	64
GRADE G	51	111	36	100000	100000	74		0	35	35	22	57	35
GRADE H	58	60	24	100000	100000	33	0		34	34	22	57	40
GRADE I	60	75	85	100000	100000	54	14	14			22	100000	100000
GRADE J	60	75	85	100000	100000	54	14	14			22	100000	100000
GRADE K	58	111	36	100000	100000	74	17	20	35	35		57	35
GRADE L	30	120	27	100000	0	45	54	54	90	90	54		0
GRADE M	50	120	0	100000	23	30	70	0	60	60	70	16	0

Figure 9: Exemplary Transition Matrix with fixed Incoming/Outgoing Grades

5.3 The Cost Evaluation Model

Section 5.2 explains how the heuristic generates different potential sequences. The *cost model* evaluates these sequences by finding the optimal schedule for every proposed sequence. In other words, for every given sequence generated in Section 5.2 the optimal production quantities are determined that minimize the total relevant cost per day. Because optimizing the individual production quantities, while the total cycle time is variable, creates a non-linear problem (as explained in Chapter 4), these two decisions are isolated and solved iteratively.

First, for a given total cycle time (initially using the minimal cycle time explained in detail in Section 5.3.2) production quantities are optimized. For this sub-problem, where the cycle time is given, and the sequence is fixed, setup costs per day are constant for any combination of production quantities. Therefore, minimizing total relevant costs can be reduced to minimizing holding costs for this sub-problem. In this Section, first, a mathematical description of this sub-problem will be given. For the same reasons as explained in Section 4.2, μ^* is introduced again to balance demand rates and production rates.

To transform the non-linear problem, explained in the previous chapter, to a linear problem, the average production times (APT_i) for the production of a particular grade will be used (i.e. the APT_i is defined as the average time it takes to produce grade i in a particular schedule). This approximation will be used to optimize individual production quantities for a given sequence, with a given cycle time. Because in reality, this cycle time is also variable, the effect of increasing this cycle time will be evaluated next.

5.3.1 Mathematical Representation of the Cost Model

Essentially, the sub-problem is now reduced to a problem of finding the optimal schedule for a given sequence and a fixed cycle time. The setup cost of such a schedule is constant for any feasible (i.e. production quantities should fit within the given cycle time) combination of production quantities. Furthermore, safety stock levels, and external storage cost levels are proportional to the level of cycle stock of a specific grade. Therefore, minimizing total relevant costs, for the schedule under consideration here, can be reduced to a problem of minimizing the working capital cost of the cycle stock.

$$\min\ WCCCS = \sum_{i=1}^{N} WCC_i \tag{5.6}$$

In line with the model presented in Chapter 4, the working capital cost per day (WCC_i), for a grade i, depend on the average inventory level during a particular step, the working capital cost per MT per day, and the fraction in which the cycle is in step j. The average inventory during a particular step j is calculated as the average of the inventory level at the end of the last production step (I^{j-1}) and the inventory level at the end of current production step (I^j) (because constant demand rates are assumed).

$$WCC_i = \sum_{j=1}^{M} \left(\frac{I^j + I^{j-1}}{2} * \frac{WACC * P_i}{365} * \frac{\Delta t^j}{CT} \right) \qquad \forall i \, \forall j \tag{5.7}$$

Similar to the model of Chapter 4, the variable j represents the different production steps in the sequence with a total of M steps. The time of a production step (Δt^j) incorporates the duration of a production run of a particular grade and the setup time between this grade and the previous grade in the sequence. The difference between the inventory level of different steps depends on the duration of the step j, the demand rate of a grade i, and possibly the production of grade i during this specific step.

All I_i^j's can be calculated recursively for all j and i with formula 5.8, which states that the inventory level at a particular step j is equal to the inventory level at the end of the previous production step minus the demand during the step plus the possible production of grade i during this step j.

$$I_i^j = I_i^{j-1} - d_i * \Delta t^j + x_i * p^j * \Delta t^j \qquad \forall i \, \forall j \tag{5.8}$$

where, x_i is a binary variable that is 1 if the production in step j is of grade i and 0 otherwise.

For reasons explained in Section 4.2, initial inventory levels (I_i^0) are a set of decision variables rather than dependent variables because the *zero-switch rule* is not imposed (i.e. inventory levels, just before the replenishment of a grade, are not necessarily zero).

Both demand and production during a step are dependent on the duration of a step, all Δt^js can be determined using formula 5.9 and depend on the quantity produced (Q^j) during step j, the production rate (p^j) of the grade which is produced during step j, and the transition time between the production of the grade produced in step j and the grade produced in $j-1$.

$$\Delta t^j = \frac{Q^j}{p^j} + ST^{j-1 \to j} \qquad \forall j \tag{5.9}$$

As explained before, substituting formula 5.9 into formula 5.7 creates a non-linear function. Because non-linear problems are causing significantly higher calculation times, and current SABIC software (limited version of *OpenSolver*) is unable to deal with non-linear problems, the problem is transformed into a linear problem by approximating the average production times of a production run of a grade i as the average Δt^j when producing grade i. This concept will be defined as the APT_i, and is explained in the next sub-Section. First, a lower bound of the cycle time will be determined using the $minCT$ concept.

5.3.2 Minimum Total Cycle Time and Approximating Step Times

As mentioned before, production quantities are first optimized based on a given cycle time (CT) and approximated production times, which will eventually be increased iteratively to find the optimal CT for a given sequence. Initially, CT is set at its minimum value. In order to get a stable schedule (i.e. a schedule where no inventory level is rising to infinity), a minimum cycle time exists. Leachman and Gascon (1988) define a somewhat similar concept, which they call the operational cycle time. The minimum cycle time is calculated as follows for all the grades, where the frequency f_i follows directly from the given sequence:

$$minCT_i = \frac{f_i * MRL_i}{d_i} \qquad \forall i \tag{5.10}$$

Because all grades have a minimum runlength, the amount of material produced during a cycle is at least this minimum runlength multiplied with the number of production runs of a grade during a cycle (i.e. the production frequency f_i). In order for demand to match this production volume, a certain cycle time is necessary ($minCT_i$). After calculating the individual $minCT_i$s for all grades, selecting the maximum $minCT_i$ will give the minimum cycle time necessary to cover the minimum production quantities of all the items:

$$minCT = \max_{i \in N}(minCT_i) = \max_{i \in N}\left(\frac{f_i * MRL_i}{d_i}\right) \tag{5.11}$$

Section 5.3.5 explains how the cycle time is iteratively increased to determine the optimal cycle time for a given sequence. Since $minCT$ is the minimum feasible cycle time, this will be used as the starting point for marginally increasing CT. First, $minCT$ is used to find the optimal production quantities when $minCT$ is being set as the given cycle time for the problem defined in formulas 5.6-5.9. Because of the non-linearity characteristics of the problem, the duration of a production run is approximated as the average time for producing grade i (APT_i), which is defined as the CT times the demand rate d_i for grade i, divided by the frequency (f_i) times the production rate p_i for the grade.

$$ATP_i = \frac{CT * d_i}{f_i * p_i} \qquad \forall i \qquad (initially\ CT \equiv minCT) \tag{5.12}$$

Similar to the calculation of Δt^j in formula 4.5 in Chapter 4, again μ^* is used to avoid forever-increasing stock levels because demand rates are lower than production rates. μ^* is calculated the same way as in formula 4.4 but now ATP_i is used instead of Q^j.

$$\mu^* = \frac{\sum_{i=1}^{N}\left(\frac{APT_i * f_i}{p_i}\right) + \sum_j^M (ST^{j-1,j})}{\sum_{i=1}^{N}\left(\frac{APT_i * f_i}{\sum_{i=1}^{N} d_i}\right) + \sum_j^M (ST^{j-1,j})} \tag{5.13}$$

Now the $stepTime^j$ (i.e. the approximated duration of a specific production step j) can be determined as follows:

$$stepTime^j = \left(ST^{j-1,j} + \sum_{i=1}^{N} x_i * APT_i\right) * \frac{1}{\mu^*} \qquad \forall j \tag{5.14}$$

Using these approximated step times instead of the actual step times makes the model linear and solvable using the simplex method. Substituting $stepTime^j$ for Δt^j as a parameter into formula 5.7, 5.8 and 5.9, gives the following optimization problem:

$$\min WCCCS = \sum_{i=1}^{N} WCC_i \tag{5.15}$$

$$WCC_i = \sum_{j=1}^{M}\left(\frac{I_i^{j-1} + I_i^j}{2} * \frac{WACC * P_i}{365} * \frac{stepTime^j}{minCT}\right) \qquad \forall i\ \forall j \tag{5.16}$$

Where:

$$I_i^j = I_i^{j-1} - d_i * stepTime^j + x_i * Q^j \qquad \forall i\ \forall j \tag{5.17}$$

Together 5.15, 5.16 and 5.17 describe the linear program optimization problem that is subject to the following constraints:

$$I_i^M \geq I_i^0 \qquad \forall i \tag{5.18}$$

$$I_i^j \geq 0 \qquad \forall i\ \ \forall j \tag{5.19}$$

$$Q^j \geq \sum_{i=1}^{N}(x_i^j * MRL_i) \qquad \forall j \tag{5.20}$$

$$\sum_{i=1}^{N} x_i^j = 1 \qquad \forall j \tag{5.21}$$

This problem will be optimized (i.e. optimal levels for $Q^j (= \hat{Q}^j)$ will be determined) using the *openSolver* add-in for linear-problems in *MS Excel.* Doing so will result in the optimal production quantities and initial inventory levels for a given cycle with $minCT$ as cycle time. The cycle time will be increased in at a later stage (see 5.3.5).

5.3.3 Production Quantities and Inventory Levels

Optimal production quantities and initial inventory levels are determined by solving the mathematical optimization problem explained before (see formulas 5.15 - 5.21), where instead of using the actual Δt's, the $steptimes^j$ are used to determine the change of inventory during a production step. By solving the LP defined in the formulas 5.15-5.22, the optimal production quantities ($\hat{Q}$'s) and initial inventory levels (I^0's) are determined. Using these optimal quantities ($\hat{Q}^j$), the $stepTime^j$s are translated back into real production times (i.e. the $stepTimes^j$ are based on the average production time for a specific grade, but because Q^j is not identical for every run of a particular grade, production times are also not the same). The actual duration of a production step is defined by $\widetilde{\Delta t^j}$, which depends on the production quantity and the setup time before the respective production run. The real duration of a production step ($\widetilde{\Delta t^j}$) is calculated as follows:

$$\widetilde{\Delta t^j} = \left(\frac{\hat{Q}^j}{p^j} + ST^{j-1\to j}\right) * \frac{1}{\mu^*} \qquad \forall j \tag{5.22}$$

Subsequently these real production times are used to determine the actual inventory levels during a cycle. The inventory levels during the entire cycle are calculated as follows (similar to formula 4.3 and 5.8):

$$I_i^j = I_i^{j-1} - d_i * \widetilde{\Delta t^j} + x_i * p^j * \widetilde{\Delta t^j} \qquad \forall i\ \forall j \tag{5.23}$$

where all I^0's are output from the approximate optimization problem using the $StepTime^j$'s (5.15-5.21. Since the model considered is still deterministic in this phase of the problem, it is optimal to go for the minimum level of inventory during the cycle for every grade to be zero. Because of the difference between $stepTime^j$ and $\widetilde{\Delta t^j}$ the minimum amount of inventory of a grade is not necessarily zero. If this is not the case, all inventory levels of the cycle can be offset by this minimum amount (which can be both negative and positive). This will reduce the average inventory level of a specific grade with the $offset_i$ amount. If this offset amount is negative, the offset will increase all inventory levels to avoid out-of-stock situations. The inventory offset is calculated as follows for all products.

$$Offset_i = \min_{j\in M} I_i^j \qquad \forall i \tag{5.24}$$

Subsequently, for all grades, the inventory levels during the cycle are translated as follows:

$$I_i^j \to I_i^j - Offset_i \qquad \forall i\ \forall j \tag{5.25}$$

This gives the inventory levels of all grades during an entire cycle, which can be used to determine the expected cost the sequence. The effect of the $Offset_i$ concept is shown in Figures 10 and 11. Figure 11 shows that the minimum inventory level during a cycle is exactly zero for all grades i.

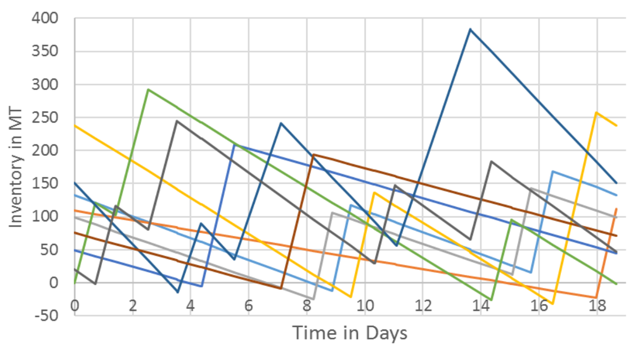

Figure 10: FACTORY C Inventory Levels without Offset

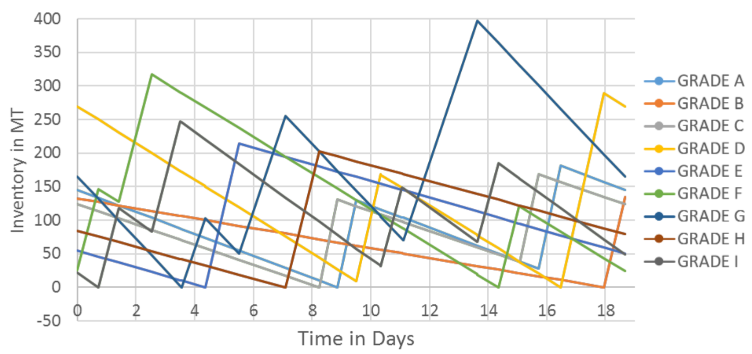

Figure 11: FACTORY C Inventory Levels with Offset

Both figures show that increasing the inventory levels at the end of every production step by the $Offset_i$ amount (i.e. moving from Figure 10 to Figure 11), makes the minimum level of inventory at the end of a step exactly zero.

5.3.4 Determining the Expected Total Cost of a Particular Schedule

Based on the expected optimal inventory levels during a cycle, the working capital cost of the safety stocks, the working capital cost of the cycle stocks and the external storage costs can be determined using the same formulas as in Chapter 4. Together, these form the holding cost component of the sequence. The setup costs are independent on the individual production quantities and the inventory levels and are therefore independent of the outcome of the cost model. To determine the expected working capital cost of keeping safety stocks, obviously, safety stock levels need to be specified first.

5.3.4.1 Determining Safety Stock Levels and Costs:

In order to keep the safety stock level stable, in line with what Brander and Forsberg (2006) propose, the maximum lead-time of a particular grade should be used to determine the safety stock levels of a grade. The standard deviation of demand during the maximum leadtime is defined for every grade as: $\sigma_i^{\max(LT_i)}$. Subsequently, safety stock levels are determined as follows, where k_i represents the inverse normal cumulative distribution of a prescribed grade-dependent fill rate target of α_i (e.g. $k_i = \Phi^{-1}(\alpha_i)$):

$$SS_i = k_i * \sigma_i^{\max(LT_i)} \tag{5.26}$$

Based on this, the working capital of safety stocks can be determined as follows:

$$WCCSS = \sum_{i=1}^{N} \left(SS_i * \frac{WACC * P_i}{365} \right) \tag{5.27}$$

5.3.4.2 Working Capital Cost of Cycle Stock

The working capital cost of the cycle stock is the second type of holding cost in the problem. These costs are directly related to the inventory levels I_i^j and are calculated using the same logic as in Section 4.2.

$$WCCCS = \sum_{i=1}^{N} \sum_{j=1}^{M} \left(\frac{I_i^j + I_i^{j-1}}{2} * \frac{WACC * P_i}{365} * \frac{\widetilde{\Delta t^j}}{CT} \right) \tag{5.28}$$

5.3.4.3 External Storage Costs

Using the same logic as in Section 4.2 external storage costs (including detouring costs) for bulk and packed material can be calculated as follows:

$$TESCB = \max\left(\max_{j \in M} \left(\sum_{i=1}^{N} \%B_i * I_j^i \right) - SCB * IOR; 0 \right) * \left(\frac{ESCB}{\rho * EOR} + \frac{DCB * 365}{TORB} \right) \tag{5.29}$$

$$TESCB = \max\left(\max_{j \in M} \left(\sum_{i=1}^{N} (1 - \%B_i) * I_j^i \right) - SCP; 0 \right) * \left(\frac{ESCP}{\rho} + \frac{DCP * 365}{TORP} \right) \tag{5.30}$$

$$ESC = TESCB + TESCP \tag{5.31}$$

5.3.4.4 Total Cost of Sequence

The total cost of a particular sequence forms the output of the cost model and is calculated by summing all different holding cost types plus the setup cost of the sequence. All holding cost Figures are already expressed per day, therefore the setup cost of the sequence should also be expressed per day:

$$TRC = WCCSS + WCCCS + ESC + \frac{TSC}{CT} \tag{5.32}$$

The TSC is determined as follows:

$$TSC = \sum_{j=2}^{M} (SC^{j-1;j}) + SC^{M \to 1} \tag{5.33}$$

Where:

$$SC^{ij} = ST^{ij} * (P_j - OSP_A) * \frac{(p_i + p_j)}{2} \tag{5.34}$$

5.3.5 Increasing Cycle Time (CT)

Until now, optimal quantities for a particular sequence proposed through the method explained in Section 5.2, are only determined for a given cycle time in the sub-problem explained in Section 5.3.4. For the comprehensive problem of optimizing the entire schedule, the cycle time is not fixed but is instead one of the decision variables. In this last step of evaluating the expected optimal cost of a given sequence, the cycle time will become a variable again. Since initially, the minimum cycle time was used to determine production quantities, only cycle times that are equal or longer than this $minCT$ should be evaluated (i.e. CT can only be equal or higher than $minCT$).

Increasing the CT will decrease the setup costs per day and increase the holding costs per day. Especially, when setup costs per day are high compared to the holding costs, it is often advantageous to increase the cycle time for a sequence. Ideally, one would solve the LP-problem defined in the formulas 5.15-5.21, for every possible CT. Because this would require an extremely long calculation time, this is not feasible. Therefore, along with marginally increasing the CT, also production quantities (Q^j), initial inventory levels (I_i^0), and ATP_is are increased marginally. After every increase of CT, the total relevant costs of the schedule are determined using the formulas 5.26-5.34. The process of marginally increasing these variables will continue until total costs do not decrease anymore. Figure 11 shows that the total cost function for increasing values of CT is convex. In a convex function, any local minimum is also a global minimum, therefore, when a marginal increase in CT increases the total relevant costs for the first time, this defines the global minimum of the cost function.

Because all variables are increased linearly, this final combination of $\hat{Q}^j$s and I^0s is not necessarily optimal for the new optimal cycle time. Therefore, after the optimal CT is found for a particular sequence, the linear program determining $\hat{Q}^j$ and I_i^0 is run again to find the optimal Q^js and I_i^0s for the increased cycle time. This means that in formula 5.12 ATP_is are calculated using the determined CT rather than the $minCT$. Based on the new values for APT_i, values for μ^* and the $stepTime^j$s are calculated using formula 5.13 and 5.14, and the optimization problem defined in formulas 5.15-5.21 is solved again. Figure 11, visualizes the effect of increasing the CT on all relevant cost types using an example of one of the assets (FACTORY F). As one can see, this Figure shows a clear resemblance with the well-known pattern of the EOQ-model but the optimal point is <u>not</u> where total holding costs (WCC Cycle Stock + WCC Safety Stock + External Storage Cost) and setup costs are equal.

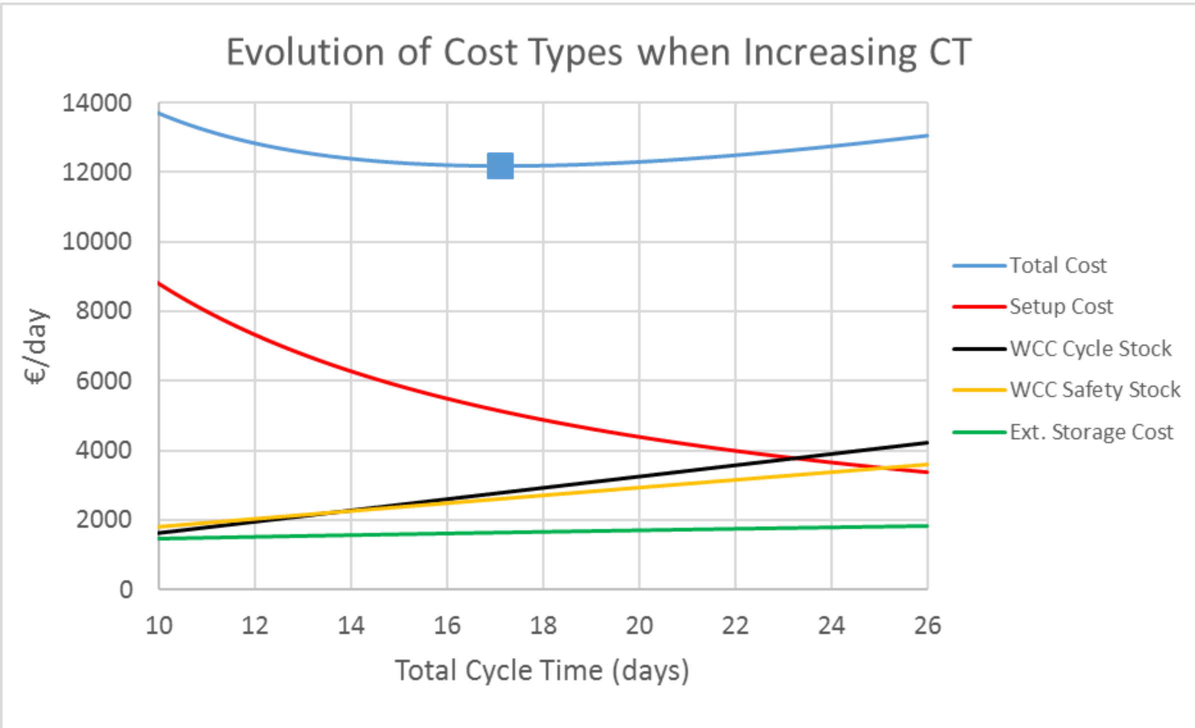

Figure 11: Increasing Cycle Time for a given Sequence

5.4 Calculation Time Reduction Methods

Because the tool, in which the heuristic is implemented, requires a long calculation time. Since 96% of the calculation time is required for solving all LP-problems described in formulas 5.15-5.21, some methods were developed to reduce the number of times the cost model needs to run. The main strategy for this, is to determine patterns to be able to predict the outcome of adding a particular run on a particular position or adding a particular run at all. First, a method to reduce the number of position options for adding a production run will be discussed. Subsequently, a way to determine whether a grade should be considered for an additional run whatsoever is explained. Finally, the calculation time is reduced based on the effect of adding a production run on a specific position on the total setup time of the sequence. The methods used will be presented one by one in the following paragraphs.

5.4.1 Reducing maximum number of Steps between consecutive Runs

Apart from reducing the number of times the cost model needs to run, this method also reduces the maximum *lead-time* for a particular grade and makes the cycle more *evenly distributed (*i.e. production runs of a particular grade are spread-out in the schedule). This method starts from the moment where a grade is already at least produced twice in a cycle (with only one production run per cycle, there is only one leadtime interval, so all *positions* should be considered). The method is best explained via an example. Imagine a situation where the current cycle is as follows: $\{A_1 \rightarrow B_1 \rightarrow C_1 \rightarrow D_1 \rightarrow E_1 \rightarrow F_1 \rightarrow A_2 \rightarrow D_2 \rightarrow F_2\}$, and the heuristic is evaluating increasing the frequency of $grade\ A$. In a situation like this after the first run of $grade\ A$, five grades are produced until the second run. After the second run of $grade\ A$ only two grades are produced until $grade\ A$ is produced again. The number of position options are reduced significantly because only the options within the *longest lead-time* are considered (so only between B_1 and C_1, C_1 and D_1, D_1 and E_1 and E_1 and F_1).

5.4.2 Reducing Number of Grades Considered

Increasing the production frequency of some grades, can increase the $Cycle\ Time$ by a significant amount. Because of this the on hand stock levels of all other grades can increase significantly, which causes the total cost of the sequence to increase. Therefore, the concept of the minimum cycle time is used: grades that cause the $minCT$ to increase by more that 50% compared to the original $minCT$ are not considered for that specific improvement step.

5.4.3 Not Considering High Setup Positions

As mentioned before, some transitions are technically not possible. Because these transitions are in the transition matrix as an artificially high number, they are still considered by the model. Therefore, to not consider these options, when the setup costs of adding a production run at a particular location are increasing more than a certain threshold, this location is skipped.

Together, these methods have resulted in a significant decrease in average calculation time (from an average of 12 hours per asset to 4 hours per asset) for the software tool and therefore, they are implemented in the heuristic that will be summarized in the next section using pseudocode.

5.5 The Heuristic Step-By-Step

1. Use traveling salesman algorithm to find the optimal pure rotation cycle
2. Set $f_i = 1$ for all grades
3. Determine TRC of the pure rotation cycle using the cost model:
    a. Calculate $minCT$ (formula 5.11)
    b. Determine all APT_is, μ^*, and $stepTimes^j$s for the pure rotation cycle (formulas 5.12-5.14)
    c. Determine the optimal $\hat{Q}^j$ and I_i^0 for all grades using the LP (formulas 5.15-5.21)
    d. Calculate all I_i^j during all steps for all grades (formula 5.23)
    e. Translate all I_i^j using $offset_i$ for all grades (formulas 5.24 and 5.25)
    f. Determine optimal SS_i (formula 4.26)
    g. Calculate TRC for the optimal pure rotation cycle (formulas 5.27-5.34)
4. Set $oldCost = TRC$, $newCost = 0$
5. Do while $newCost < oldCost$
    a. Calculate $minCT_{old}$ (formula 5.11)
    b. For each $grade$ in N
        i. $i = i + 1$
        ii. Set $f_i = f_i + 1$
        iii. Calculate $minCT_{new}$ (using the new frequencies) (formula 5.12)
        iv. If $minCT_{new} > 1.5 * minCT_{old}$ then → skip $grade\ i$ → Go To step <u>*5.b.*</u>
        v. Determine $\max(\#steps)$ in-between two consecutive runs of $grade\ i$ (see 5.4.1)
        vi. Determine TSC_{old} using original sequence
        vii. For each $location$ in-between the two runs of step <u>*5.b.v.*</u>
            1. if $TSC_{new} > 10 * TSC_{old}$ then → skip $location\ j$ → goto step <u>*5.b.vii.*</u>
            2. Determine TRC_j of new sequence where $grade\ i$ is added at $location\ j$
                a. Calculate $minCT$ (formula 5.11)
                b. Approximate all APT_i and $stepTimes^j$s for the schedule (formulas 5.12-5.14)
                c. Determine the optimal $\hat{Q}^j$ and I_i^0 for all grades using the LP (formulas 5.15-5.21)
                d. Do while $TRC_{new} < TRC_{old}$
                    i. Calculate all I_i^j during all steps for all grades (formula 5.23)
                    ii. Translate all I_i^j using $offset_i$ for all grades (formulas 5.24 and 5.25)
                    iii. Determine optimal SS_i (formula 5.26)
                    iv. Calculate TRC for the production wheel (formulas 5.27-5.34)
                    v. Set $\hat{Q}^j = \hat{Q}^j * 1.001, I_i^0 = I_i^0 * 1.001, ATP_i = ATP_i * 1.001$
                    vi. If $TRC_{new} > TRC_{old}$ → Set $\hat{Q}^j = \frac{\hat{Q}^j}{1.001^2}, I_i^0 = \frac{I_i^0}{1.001^2}, ATP_i = \frac{ATP_i}{1.001^2}$
                        1. Determine μ^* for new ATP_is
                e. If $newCT = true$ then
                    i. Go To step 5.b.viii and consider next location
                    ii. Else:
                        1. set $newCT = true$
                        2. Go To step 5.b.vii.2.b. using the new CT as $minCT$
        viii. Next $location$
        ix. Determine $TRC_i = \min(TRC_j)$
    c. Determine $newCost = \min(TRC_i)$
6. Select optimal sequence of the loop <u>before</u> the last *while iteration* that had the lowest TRC because the last loop increased TRC

5.6 Model Verification and Validation

Before presenting the results of the heuristic, the methods that were used to validate and verify the model will shortly be discussed in this Section. Hillston's (2003) overview of validation and verification methods was used to structure this step in the process. Hillston (2003) describes verification as the process of ensuring that the model does what it is intended to do. Validation is defined as demonstrating that the model is a reasonable representation of the actual system.

5.6.1 Verification

Throughout the modeling process, anti-bugging techniques were used to check the behavior of the model. Hillston (2003) describes anti-bugging as the process of: "including additional check and outputs in a model". An example of anti-bugging in the development of the heuristic is the outputting of all potential sequences (i.e. during every improvement step, every grade/position combination was outputted to check whether the heuristic made the right improvement decisions. Similar checks were made during every step of the heuristic.

Hillston (2003) argues that: "the developer may become aware of bugs simply by studying the model carefully and trying to explain how it works". This project report, as well as discussions with different stakeholders about the step-by-step analysis of the model have served as another form of model verification. Hillston (2003) describes this process as structured walk-through verification.

Apart from anti-bugging and walk-through analyses, the heuristic was also verified with three sensitivity checks. First, continuity testing was used to check that a small change in an input value would not result in very large changes in the corresponding output (i.e. the production wheel). Because, running the heuristic model once, already takes a relatively long time (i.e. approximately 4 hours per asset), running continuity tests extensively and completely for all assets and all variables is impossible. Therefore, a limited version of continuity testing was performed (i.e. the effect of changing particular variables within a certain range, for one specific asset was investigated).

Secondly, degeneracy testing was used to determine what happens to the outcome of the heuristic when extreme input variables were used. For example, zero transition times (both after and before the production of a particular grade) leads to higher production frequencies.

Finally, consistency testing was used to check whether particular input combinations result in the similar output values (e.g. doubled demand rates in combination with halved allocation percentages gives equivalent results).

5.6.2 Validation

Model verification was continuously carried out during the development of the heuristic by discussing the structural components with subject matter experts. Hillston (2003) defines three separate aspects that should be considered during model verification, namely: *assumptions, input parameter values and distributions,* and *output values and conclusions.* Before and during the project, all assumptions and input variables were extensively discussed with and challenged by the project sponsors and other important stakeholders.

From a relatively early stage, a prototype of the heuristic model was able to generate results and determine production wheels. Continuously, these results were discussed with both master production schedulers, inventory managers and demand planners. In many occasions, their input led to adjustments in both input parameters and the structure of the model itself. Exemplary are discussions based on intermediate outcomes of improving the production wheel of FACTORY E, which led to the introduction of the *single arc exception* discussed in 5.2.1.1 and the addition of detouring costs. Furthermore, many of the intermediate heuristically developed production wheels were challenged by experts, for example leading to additional technically impossible transitions. Essentially, these discussions led to a model that was iteratively improved throughout the development process.

Additionally, all calculations made by the model were tested individually to validate correct behavior. Every calculation step in the heuristic was checked manually. This type of validation is closely related to the one-step analysis discussed in the previous section on model verification.

6 Results

This Chapter will present the results of the previously explained heuristic for SABIC's polyethylene assets. First, the step-by-step results of the heuristic will be presented for an example asset (FACTORY C). Subsequently, the results of different simulation models will be presented and discussed. Finally, the results of all assets are compared with the currently used production wheel, showing how the model performs in both a deterministic and a stochastic context.

6.1 *Example:* Improving the Production Wheel of FACTORY C

The Pure Rotation Schedule

As explained in the previous chapter, the process of optimizing the production wheel starts with determining the optimal pure rotation schedule for the grade portfolio. Input for this step is the transition cost matrix, shown in Table 6 that can be calculated from the transition time matrix, shown in Table 7. First, Table 5 shows the general grade input for the optimization model.

Table 6: Input Data for FACTORY C

	Demand (MT/year)	Min Runlength (MT)	Price (€/MT)	Production Rate (MT/hour)	% Bulk	% Packed	SD Demand (MT/day)	Allocation %
GRADE A	7470	140	€ 1.400	10	70%	30%	42,3	80%
GRADE B	2427	140	€ 1.400	9	50%	50%	16,5	100%
GRADE C	19075	140	€ 1.400	10,1	20%	80%	41	25%
GRADE D	9971	140	€ 1.400	10,1	70%	30%	30,4	100%
GRADE E	22386	140	€ 1.400	9,1	20%	80%	20	20%
GRADE F	8914	140	€ 1.400	9	70%	30%	24,8	100%
GRADE G	16873	140	€ 1.400	8	50%	50%	38,8	100%
GRADE H	4230	140	€ 1.400	8,6	20%	80%	15,4	100%
GRADE I	11519	140	€ 1.400	9	50%	50%	28,2	100%

Table 7: Transition Time Matrix FACTORY C

FACTORY C transition Time in Minutes		To Grade								
		GRADE A	GRADE B	GRADE C	GRADE D	GRADE E	GRADE F	GRADE G	GRADE H	GRADE I
From Grade	GRADE A		90	0	0	30	60	120	90	30
	GRADE B	90		49	30	38	0	94	73	0
	GRADE C	0	0		0	75	20	161	92	48
	GRADE D	15	0	0		45	60	90	55	28
	GRADE E	100000	26	40	40		26	0	0	40
	GRADE F	60	0	40	60	54		75	30	0
	GRADE G	100000	46	90	90	15	46		0	25
	GRADE H	100000	95	0	66	0	95	34		30
	GRADE I	60	30	27	62	54	0	64	30	

Table 8: Setup Cost Matrix FACTORY C

FACTORY C transition Cost in €/transition		To Grade								
		GRADE A	GRADE B	GRADE C	GRADE D	GRADE E	GRADE F	GRADE G	GRADE H	GRADE I
From Grade	GRADE A		1985	0	0	669	1323	2352	1896	662
	GRADE B	2205		1213	742	847	0	1842	1538	0
	GRADE C	0	0		0	1672	441	3156	1938	1058
	GRADE D	368	0	0		1003	1323	1764	1159	617
	GRADE E	2450000	573	990	990		573	0	0	882
	GRADE F	1470	0	990	1485	1204		1470	632	0
	GRADE G	2450000	1014	2227	222	15	46		0	551
	GRADE H	2450000	2095	0	1633	0	2095	666		662
	GRADE I	1470	662	668	1534	1204	0	1254	632	

Solving the traveling salesman problem gives the following pure rotation schedule for FACTORY C. In Table 8, all transitions made during the pure rotation schedule are indicated in red.

$$GRADE\ F \rightarrow GRADE\ I \rightarrow GRADE\ E \rightarrow GRADE\ G \rightarrow GRADE\ H \rightarrow GRADE\ C \rightarrow GRADE\ A \rightarrow\ GRADE\ D \rightarrow GRADE\ B \rightarrow (GRADE\ F)$$

Table 9: The Solved Traveling Salesman Problem

FACTORY C transition Cost in €/transition		To Grade								
		GRADE A	GRADE B	GRADE C	GRADE D	GRADE E	GRADE F	GRADE G	GRADE H	GRADE I
From Grade	GRADE A		1985	0	0	669	1323	2352	1896	662
	GRADE B	2205		1213	742	847	0	1842	1538	0
	GRADE C	0	0		0	1672	441	3156	1938	1058
	GRADE D	3[illegible]8	0	0		1003	1323	1764	1159	617
	GRADE E	2450000	573	990	990		573	0	0	832
	GRADE F	1470	0	990	1485	1204		1470	632	0
	GRADE G	2450000	1014	2227	222	15	46		0	551
	GRADE H	2450000	2095	0	1633	0	2095	666		662
	GRADE I	1470	662	668	1534	1204	0	1254	632	

This schedule results in the following minimum setup costs per cycle:

$$€\ 1203.93\ per\ cycle$$

Next, the optimal pure rotation schedule is evaluated by the cost model, which determines the production quantities Q^j and the initial inventory levels I_j^0. For the pure rotation schedule this gives trivial results because in this case, production quantities are simply the demand during the entire cycle time. More interesting is the result for the cycle time itself, which will be the starting point of the following improvement steps. Total relevant cost and the cycle time are as follows for a specified service level of 95%:

$$TRC\ (= oldCost) = WCCSS + WCCCS + ESC + \frac{TSC}{CT} \tag{6.1}$$

$$TRC\ = 684.63 + 608.02 + 0 + \frac{1203.93}{21.05} = €\ 1349.84\ per\ day$$

After this step, usually the total cycle time is iteratively increased (see Section 5.3.5), but in this case increasing the cycle time directly leads to a cost increase and therefore the cycle time remains at 21.05 (i.e. the $minCT$). This is the case because the setup costs are already relatively low compared to the holding costs.

Increasing Production Frequencies

After this, the first improvement step starts. The description of the process in this report will start very detailed, and will become more and more general while the improvement process continues. The improvement step (step 5 of the heuristic) starts with evaluating the effect of increasing the frequency of $GRADE\ A$ on the $minCT$.

$$minCT_A = \frac{f_A * MRL_A}{d_A} = \frac{2 * 140}{97.51} = 17.10\ days < minCT_{old} (= 21.05\ days) \tag{6.2}$$

Because $minCT_{new} < 1.5\ minCT_{old}$, the heuristic continues with evaluating adding an additional production run at every possible position in the sequence. First the position in-between $GRADE\ D$ and $GRADE\ B$ (i.e. position 9, because after adding it is the 9th grade in the sequence) is evaluated, after this between $GRADE\ B$ and $GRADE\ I$ (position 10), etc. Table 9 shows the effect of adding an additional production run of $GRADE\ A$ in the cycle at all potential positions. The positions that result in N.A. are due to the calculation time reduction methods explained earlier (e.g. adding $GRADE\ A$ on position 4 results in a $GRADE\ E \rightarrow GRADE\ A$ transition, which is technically impossible).

Table 10: Considering all possible positions for inserting GRADE A

	$WCCSS_1^j$	$WCCCS_1^j$	ESC_1^j	$SC\ per\ day_1^j$	TRC_1^j
position 9	€ 674,95	€ 600,54	€ -	€ 168,89	**€ 1.444,37**
position 10	€ 672,39	€ 598,56	€ -	€ 224,74	**€ 1.495,70**
position 2	€ 664,24	€ 588,63	€ -	€ 158,42	**€ 1.411,29**
position 3	**€ 652,61**	**€ 586,55**	**€ -**	**€ 101,58**	**€ 1.340,74**
position 4	N.A.	N.A.	N.A.	N.A.	N.A.
position 5	N.A	N.A	N.A	N.A	N.A
Position 6	N.A.	N.A.	N.A.	N.A.	N.A.

Adding a production run of grade $GRADE\ A$ to the pure rotation cycle is optimal at *position 3* (i.e. between $GRADE\ I$ and $GRADE\ E$) and results in total relevant cost of € 1340.74 per day.

$$TRC_1 = TRC_1^3 = € \, 1340.74$$

After this, the same procedure is performed for all other grades. The results of this are shown in Table 10. Adding a production run of $GRADE\ B$ increases the $minCT$ more than the 1.5 threshold and therefore this grade is not considered in this improvement step.

Table 11: Overview Improvement Step 1

$grade\ i$	$location\ j$	$WCCSS_1^j$	$WCCCS_1^j$	ESC_1^j	$SC\ per\ day_1^j$	TRC_1^j
$GRADE\ A$	3	€ 101,58	€ 568,73	€ -	€ 652,61	€ 1340.73
$GRADE\ B$	N.A.	N.A	N.A.	€ -	N.A.	N.A.
$GRADE\ C$	6	€ 57,18	€ 583,56	€ -	€ 677,11	€ 1340.26
$GRADE\ D$	6	€ 74,64	€ 579,09	€ -	€ 676,81	€ 1347.31
$GRADE\ E$	2	€ 67,39	€ 634,34	€ -	€ 700,72	€ 1413.69
$GRADE\ F$	7	€ 57,18	€ 582,36	€ -	€ 674,87	€ 1317.57
$GRADE\ G$	9	€ 85,70	€ 573,00	€ -	€ 667,53	€ 1322.64
$GRADE\ H$	9	€ 195,91	€ 677,00	€ -	€ 729,00	€ 1623.09
$GRADE\ I$	**4**	**€ 57,18**	**€ 582,36**	**€ -**	**€ 673,53**	**€ 1313.94**

As one can conclude from the table 10, *grade* $GRADE\ I$ is added on its optimal *position 3*, giving the following optimal schedule after 1 improvement step:

$$GRADE\ F \rightarrow GRADE\ I \rightarrow GRADE\ E \rightarrow \mathbf{GRADE\ I} \rightarrow GRADE\ G \rightarrow GRADE\ H \rightarrow GRADE\ C \rightarrow GRADE\ A \rightarrow\ GRADE\ D \rightarrow GRADE\ B\ \rightarrow (GRADE\ F)$$

Because step 5.c. shows that the total relevant cost decreased from $€\,1349.84$ to $€\,1313.94$, the heuristic will continue and go back to step 5 and use the *new sequence* as a starting point. Table 11 gives an overview of the rest of the improvement steps for *FACTORY C*. For the *optimal* schedules after every improvement step, please refer to Appendix J. Please refer to Appendices A-E to see a similar overview for the other assets.

Table 12: Overview Improvement Steps FACTORY C

	TRC	$SC\ per\ day$	$WCCCS$	ESC	$WCCSS$	Added grade
Pure Rotation	€ 1.349,84	€ 57,18	€ 591,22	€ -	€ 684,63	
iteration 1	€ 1.313,94	€ 57,18	€ 582,36	€ -	€ 629,77	$GRADE\ I$
iteration 2	€ 1.251,89	€ 75,46	€ 563,76	€ -	€ 612,67	$GRADE\ G$
iteration 3	€ 1.237,27	€ 75,46	€ 556,38	€ -	€ 605,43	$GRADE\ C$
iteration 4	€ 1.234,39	€ 75,46	€ 556,38	€ -	€ 602,55	$GRADE\ F$
iteration 5	€ 1.231,67	€ 75,46	€ 556,38	€ -	€ 599,83	$GRADE\ D$
iteration 6	€ 1.215,73	€ 75,46	€ 547,34	€ -	€ 592,92	$GRADE\ A$
iteration 7	€ 1.208,55	€ 136,52	€ 497,83	€ -	€ 574,21	$GRADE\ I$
iteration 8	€ 1.168,80	€ 151,80	€ 457,39	€ -	€ 559,62	$GRADE\ F$
iteration 9	€ 1.154,04	€ 232,44	€ 397,41	€ -	€ 524,19	$GRADE\ G$
iteration 10	**€ 1.122,99**	**€ 237,56**	**€ 375,15**	**€ -**	**€ 554,04**	$GRADE\ I$

The information in Table 11 is translated into a graph (Figure 12) that visualizes how the different cost types change when the frequency of one of the grades is increased after an improvement step. One can clearly see that the different types of holding cost decrease significantly, while the setup cost increases slightly. Furthermore, the table shows that the cycle time does not increase while production frequencies are added. Setup Cost do increase when production frequencies are added. This is because there are more transitions during the same cycle time.

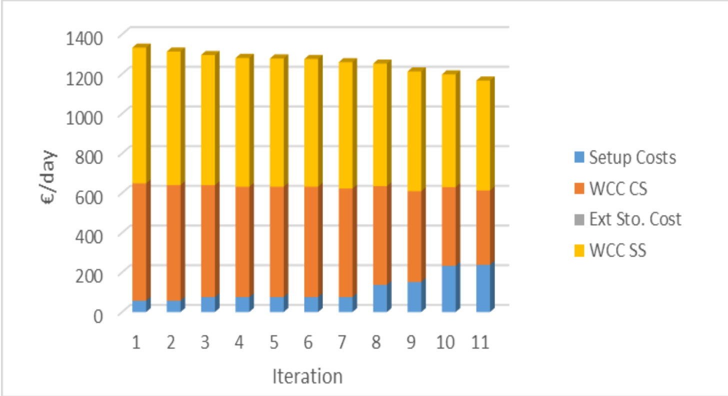

Figure 12: Evolution of Cost Types during Improvement Process

Table 12, on the right, shows the final cycle, including all Q^js. Furthermore, the table 13 shows all proposed safety stock levels SS_i, the expected average cycle stock when the sequence is followed and the amount of production runs per cycle.

Table 12: Optimal Production Wheel (Part 1)

Final Schedule	
Grade	***Runlength (MT)***
GRADE F	140,0
GRADE I	140,0
GRADEF	219,4
GRADE I	195,5
GRADE G	140,0
GRADE I	229,0
GRADE G	279,3
GRADE H	216,3
GRADE C	140,0
GRADE A	140,0
GRADE D	180,6
GRADE I	140,0
GRADE G	443,7
GRADE I	140,0
GRADE F	140,0
GRADE C	140,0
GRADE A	165,6
GRADE D	329,3
GRADE B	140,0

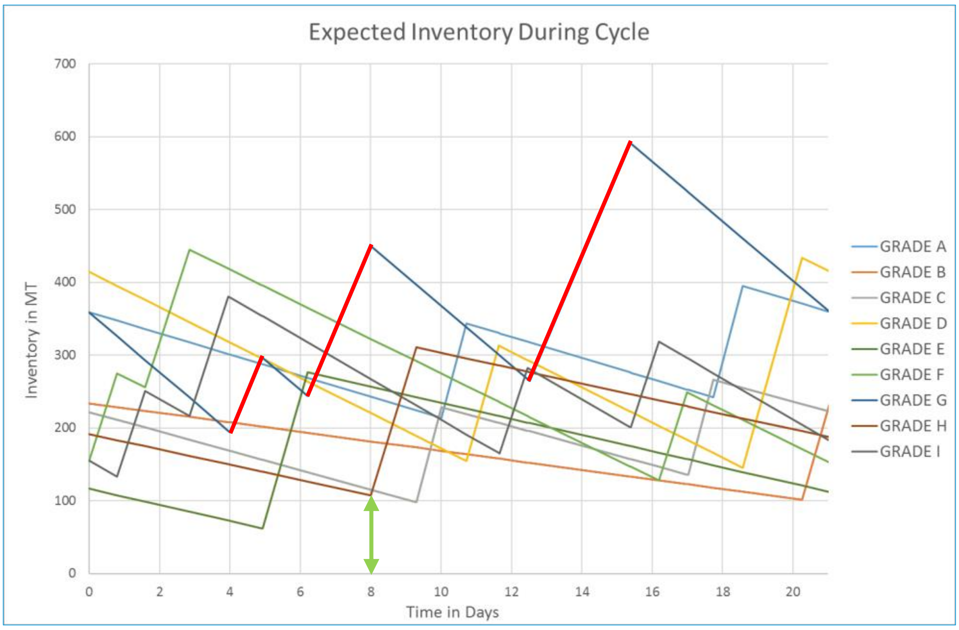

Figure 13: Inventory Levels throughout the Cycle

Table 13: Optimal Production Wheel (Part 2)

Expectation	Safety Stock Level	Avg Cycle Stock	Runs per Cycle
GRADE A	226,1	85,4	2
GRADE B	124,5	67,3	1
GRADE C	123,1	84,2	2
GRADE D	176,4	149,6	2
GRADE E	181,6	99,7	1
GRADE F	153,4	142,2	3
GRADE G	207,8	144,0	3
GRADE H	116,2	98,2	1
GRADE I	135,3	107,4	4

It is clearly visible in the figure that production quantities are not equal for the same grade throughout the cycle (e.g. as indicated in red in both Figure 13 and Table 12, the first two production runs of $GRADE\ G$ are significantly smaller than the third run). Furthermore as an example, the safety stock level of *GRADE H* is indicated in green in both Figure 13 and Table 13.

The expected inventory flow of the proposed production wheel is shown in the figure below when demand would be stable and deterministic. How the proposed production wheel behaves in a stochastic context will be the subject of the following Section.

6.2 Simulations of Stochastic Demand

In order to test the *optimal* production wheel proposed by the heuristic in a stochastic environment, a simulation model was developed. The simulation model assumes that sales are lost when there is no stock available. This is a realistic assumption because in the commodity business of SABIC polymers, customers can easily switch between suppliers. The model simulates how the production wheel would have performed during first six months of 2017. This period is used because this is the most recent data available, and the production wheel was optimized for this specific period and grade portfolio (i.e. input was used from December 2016 to develop a wheel for 2017). For reasons that will be explained in Section 6.2.1, using sales data might not give appropriate results. Furthermore, several things have to be taken into account when evaluating these simulations. First, in reality the production wheel is not strictly followed by the master production scheduler (MPS). In situations with unexpected, significantly higher or lower demand, the MPS will adjust both the sequence and the production quantities to deal with this.

It is not possible to incorporate these ad-hoc decisions into the simulation model. To still gain some insight in how the production wheel (and the respective levels of safety stock) would have performed in a stochastic environment (and to be able to compare this with the current situation), the simulation will run the production wheel as if it was followed strictly. To do so, first, the order quantities proposed by the heuristic are translated into order-up-to levels (S^j) (similar to Brander & Forsberg, 2006). The order up-to level of a production step j, is defined as the sum of the safety stock level for a particular grade, the proposed optimal production quantity Q^j, and the expected initial inventory level (EI^j) before the production run of step j. This last term is used because during the optimization of production quantities, when a production run starts, the inventory level is not necessarily zero (i.e. even though demand is assumed deterministic when quantities are optimized, if a grade is produced multiple times in a cycle, a run might start before the inventory level is zero because the zero-switch rule is not imposed).

$$S^j = \sum_{i}^{N} \left(x_i^j * SS_i\right) + \hat{Q}^j + EI^j \tag{6.3}$$

where, S^j is step dependent rather than grade dependent (i.e. the order up to levels of different production runs of the same grade are different, in line with how production quantities are different for different instances of producing a particular grade).

When demand is structurally lower than the budget (i.e. expectation) for a specific grade, following the wheel exactly would still cause inventory levels of this grade to rise. This is due to the fact that inventory during a production step rises by at least the MRL_i. This problem is dealt with as follows: suppose grade i is produced in a particular step j, the actual production quantity (Q^j) will then be defined as follows in formula 6.4:

$$Q^j = \begin{cases} S^j - I_i^{j-1} & if \quad MRL_i < S^j - I_i^{j-1} \\ MRL_i & if \quad S^j - MRL_i < I_i^{j-1} < S^j \\ 0 & if \quad I_i^{j-1} > S^j \end{cases} \tag{6.4}$$

When $Q^j = 0$ (i.e. the grade is not produced during step j), the production run is skipped, which obviously has an effect on the overall setup cost of the sequence. This effect can be described mathematically (formula 6.5) as follows and can be both positive and negative:

$$\Delta SC = SC^{(j-1 \to j+1)} - \left(SC^{j-1 \to j} + SC^{j \to j+1}\right) \tag{6.5}$$

Grades will only be skipped when the newly created transition is technically possible. When this is not the case, the grade is still produced, even if the inventory level is higher than the reorder point. This causes some problems, because inventory levels will rise indefinitely because of this. This effect will be explained later when the simulation results are presented.

Based on this, the inventory flow of all grades can be simulated during the first half of 2017. From this, the different cost types are calculated and an overview can be given on the important statistics of the simulation (i.e. cost, off-spec production and service level). Before showing the results of the simulation for the example of FACTORY C, some of the main issues with regard to the simulation are addressed.

6.2.1 Simulation Issues

6.2.1.1 Increasing Inventory Levels (Utilization 100%)

One of the main requirements/assumptions of the heuristic/model was that the facility runs with 100% utilization (i.e. the facility will either produce prime material or off-spec material, while outages should be ignored). Because in reality, assets do experience outages and lower production rates are possible, the actual production capacity of an asset is lower than the aggregated mean of the theoretical production rates of the asset, which is used by the model to determine production times. This imposes a couple of issues with regard to the simulation of inventory levels. First, inventory levels will rise indefinitely when production rates are, on average, significantly higher than the total demand rate for all products. Secondly, this indefinite rise of inventory levels will, initially cause the production steps of the grades with relatively low demand to get skipped almost every time. This, in turn, will reduce the lead-time of the other items, which will reduce their respective production steps as well.

Altogether, this causes:

- Many production steps will be skipped
    - The production sequence is not optimal anymore
- On average production quantities will reduce significantly
- Total cycle time reduces
- Average inventory levels rise
- Transition costs will rise

Especially for the assets that have performed relatively bad (in terms of production volumes) during the simulation period, the simulation results will be significantly off. To deal with this issue, μ^* is introduced again. To recall from Chapter four, and formula 4.3 specifically, μ^* avoids production rates to be structurally higher than demand rates, which would cause production during a cycle to be higher than overall demand. Here, μ^* is used in the simulation again to reduce the production rates of all grades again when necessary. In the next section, first the simulation results for example asset FACTORY C will be presented without the introduction of μ^*. One will acknowledge that this will cause inventory levels to rise indefinitely. Subsequently, the results after the introduction of μ^* will be presented.

Essentially, μ^* balances the production rates with the demand budget. When determining the demand budget, deviations from the theoretical production rates are taken into account. Reducing the production rates with μ^* makes them essentially in balance with demand budget. Therefore, using μ^* in the simulation as well, will potentially give a more realistic perspective on the performance of the production wheel in a stochastic context.

6.2.1.2 Demand Dependency on the Production Wheel

Demand during the simulation period is not entirely independent of production wheel decisions. This is caused by two things. First, when a particular grade is out-of-stock, the demand during that period is not registered. The simulation is based on actual sales during the first half of 2017, where this *unfulfilled* demand is not taken into account. When an asset experienced for example an outage during the first half of 2017, the sales data that are used in the simulation is significantly impacted by this (i.e. because nothing is produced, nothing can be sold)

Secondly, when the inventory level of a particular grade is very high and demand is relatively low, sales can be *pushed*. This means that the inventory is sold for a lower price because the inventory of that grade is considered too high. As an effect of this, the sales Figure used in the simulation increase, while actual demand in reality was not as high.

These two effects together make the sales Figures not entirely appropriate to run a simulation. It would be more appropriate to use the actual demand Figures, without the *pushed* sales and with the demand during outage periods, but this information is not registered by SABIC and therefore not available. The second issue can be solved by considering demand to be normally distributed with the expected mean and standard deviation. The results of this type of simulation are presented in in Section 6.2.3.

Because of the two important drawbacks of the simulation, when reviewing the simulation results, one should always recognize this. More specifically, the overall result of the simulation should not be seen as a KPI of the model/production wheel, due to the significant influence of these issues. Nonetheless, the simulation results assuming normally distributed demand do give some insight in how the production wheel would perform in a stochastic context and can therefore be valuable when comparing different production wheels.

6.2.2 *Continuing Example:* Wheel of FACTORY C with Actual Sales H1 2017 (100% utilization)

Simulating the proposed production wheel in the first half of 2017 gives the following results when theoretical production rates are used (i.e. utilization is 100%). As one can see from Figure 14, where all inventory levels during the first half year of 2017 are shown, two grades experience out-of-stock situations ($GRADE\ D$ and $GRADE\ B$), which are highlighted by the red circles. This is also visible in Table 14, where the fill rate of both grades is below 100%.

Furthermore, the right side of the graph shows the effect of the first of the two issues explained in the previous section. Because demand structurally reduces after a certain point (t=2000), inventory levels will increase (indicated by the red slope line on the right). Consequently, production runs of specific items are skipped, reducing the lead-time for other items as well and increasing inventory levels even more. Specifically, inventory levels of $2501N0$ rise significantly because this item cannot be skipped (i.e. skipping grade $2501N0$ creates a technically impossible setup, and therefore it will not be skipped). This effect is indicated by the two red circles at the top right.

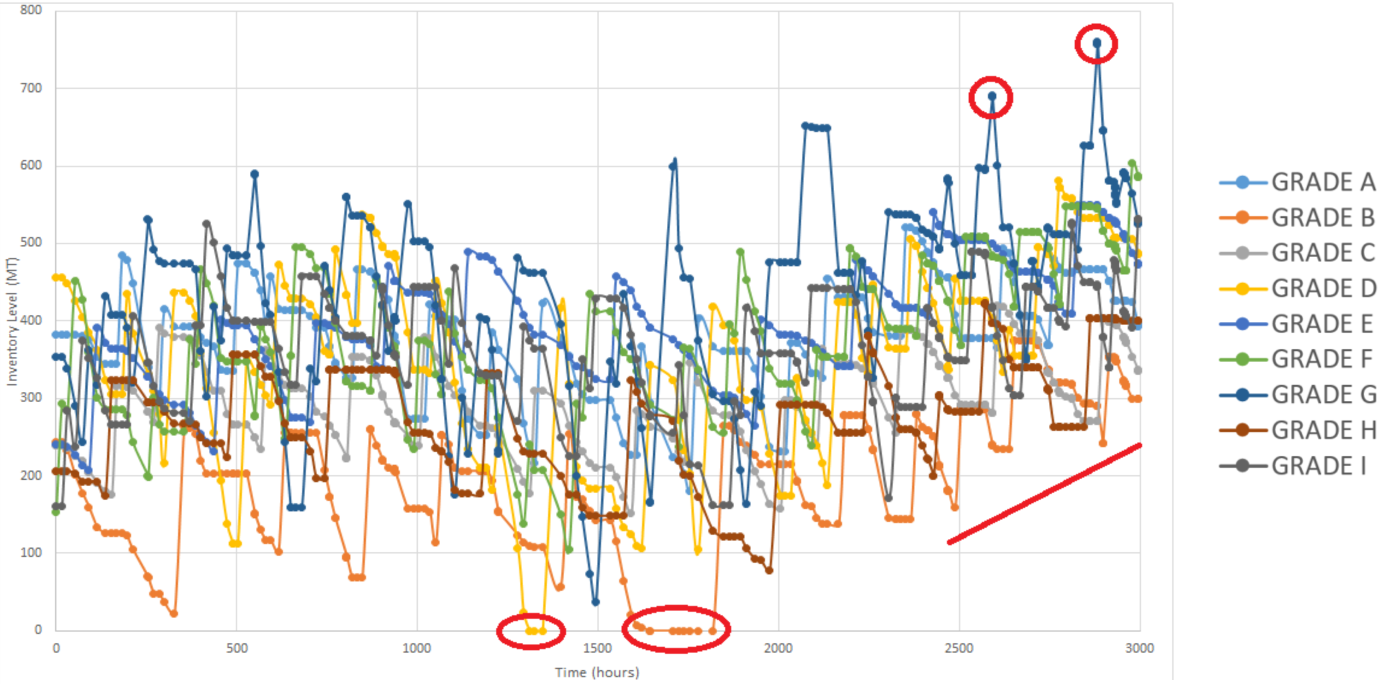

Figure 14: Simulation of FACTORY C in H1 2017

Table 14: Results of Simulation FACTORY C in H1 2017

Simulation	Average Stock	Runs in H1 2017	Fill Rate	Budget Demand	Actual Demand	Actual/Budget	Skips
2308N0	393,4	22	100,00%	2.988,0	3.202,5	107,18%	22
2402CX0	208,0	18	96,60%	1.213,5	2.855,5	235,31%	4
2404H4	311,4	19	100,00%	2.384,5	2.490,5	104,45%	25
2404N0	376,8	29	99,67%	4.985,5	5.502,4	110,37%	15
2501N0	412,0	13	100,00%	2.238,5	1.679,9	75,05%	9
2502X0	378,8	32	100,00%	4.457,0	4.587,1	102,92%	34
2600H0	450,7	48	100,00%	8.436,5	9.457,3	112,10%	18
2601X1	293,6	15	100,00%	2.115,0	2.191,4	103,61%	7
2602X1	368,1	33	100,00%	5.759,5	4.442,0	77,12%	55

For both grades that are experiencing stock-outs, the budget was significantly lower than the actual sales.

Because 100% utilization does not give a realistic view on the production wheel's performance, the next section will evaluate the production wheel using lower practical production rates via the introduction of μ^*.

6.2.3 *Continuing example:* Balancing Production and Demand Rates with μ^*

As mentioned in Section 6.2.1 and 6.2.2 using theoretical production rates (100% utilization) will cause inventory levels to increase indefinitely (see Figure 15). Therefore, μ^* is introduced again, balancing production rates with expected demand rates, while taking the effect of setup times into account. The results of this simulation for FACTORY C show promising results. These results are presented in this Section. The subsequent section will address the simulation using normally distributed demand.

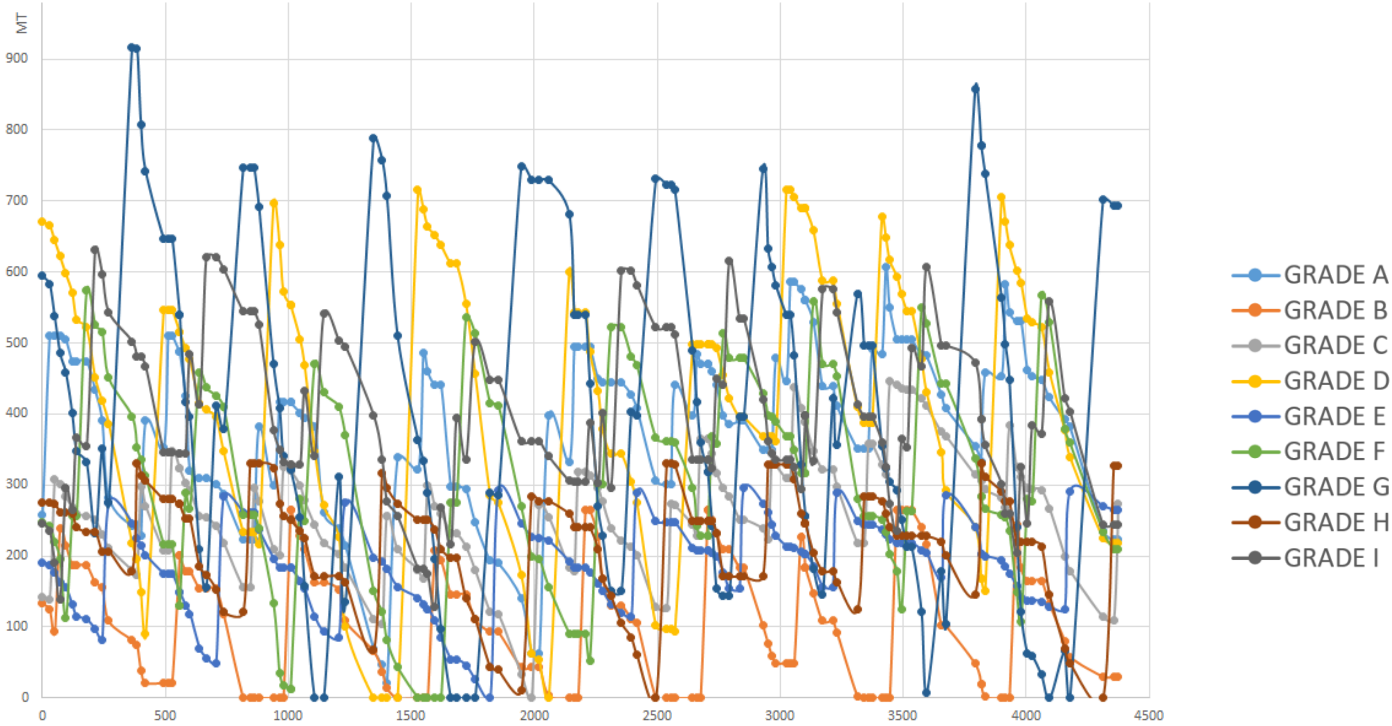

Figure 15: Actual Sales using μ^* to balance production rates (FACTORY C)

As one can see from Figure 15, using μ^* makes sure the indefinite rise of inventory is avoided and inventory levels are more stable over time (this is only done when actual demand rates are close to expected demand rates). Implicitly μ^* takes the expected production rates (that are balanced with demand budgets) into account rather than the theoretical production rates when utilization would be 100%. Comparing the expected results of the heuristic with the simulated results when the proposed production wheel would have been used gives the following overview in Table 15. As one can see from Table 15, the average cycle time is slightly longer than the expected total cycle time (demand is higher than expected), this causes the total off-spec cost per day to decrease. Furthermore, working capital cost of inventory is slightly reduced, because stocks are slightly lower due to stochastic demand. This is caused by the fact that, when demand is lower during a particular period, stocks are replenished until a re-order point (i.e. inventory can never rise above $S_i + MRL_i$), on the other hand, when demand is higher than average, stocks can be lower than the safety stock level. In other words, inventory is always between 0 and $S_i + MRL_i$, expected stock levels are always between SS_i and S_i. Therefore, when $MRL_i < SS_i$ simulated inventory levels are on average lower than expected inventory levels. This effect causes the working capital cost of inventory to be slightly lower than expected.

Table 15: Simulated vs. Expected Results

	Expected	***Simulation***
	Cycle Time Statistics	
Total Cycle Time (Days)	21,1	26,1
	Cost Statistics	
Total Cost Per Day (€)	€ 1.122,99	€ 994,91
Total Off Spec Cost Per Day (€)	€ 237,56	€ 191,32
Total Working Capital Cost Per Day (€)	€ 885,43	€ 803,59
Total External Storage Cost Per Day (€)	€ 0,00	€ 0,00
	OffSpec Statistics	
Total OffSpec Per Cycle (MT)	34,0	34,0
Total Offspec Per Day (MT)	1,6	1,3
	Service Level Statistics	
Aggregate Fill-Rate	95,00%	**95,40%**

In order to evaluate the performance of the wheel in a stochastic environment without the effect explained in Section 6.2.1.2 and the inaccuracy in demand budgets, normally distributed demand was used. The results of this third simulation are presented in the next section.

Although the simulation using actual sales to test the performance of asset FACTORY C, provided a stable cycle in a stochastic environment, this was not the case for all investigated assets. In fact, all of the assets experienced structurally increasing stock levels due to lower demand than expected (see appendices A, B, C, D, and F) except example asset FACTORY C (e.g. Figure 16 shows the increasing stock pattern for FACTORY D). In other words, when budgets are not accurate, μ^* does not compensate for this inaccuracy. Production rates are balanced with demand rates using the demand budget (expectation) rather than the actual demand rates.

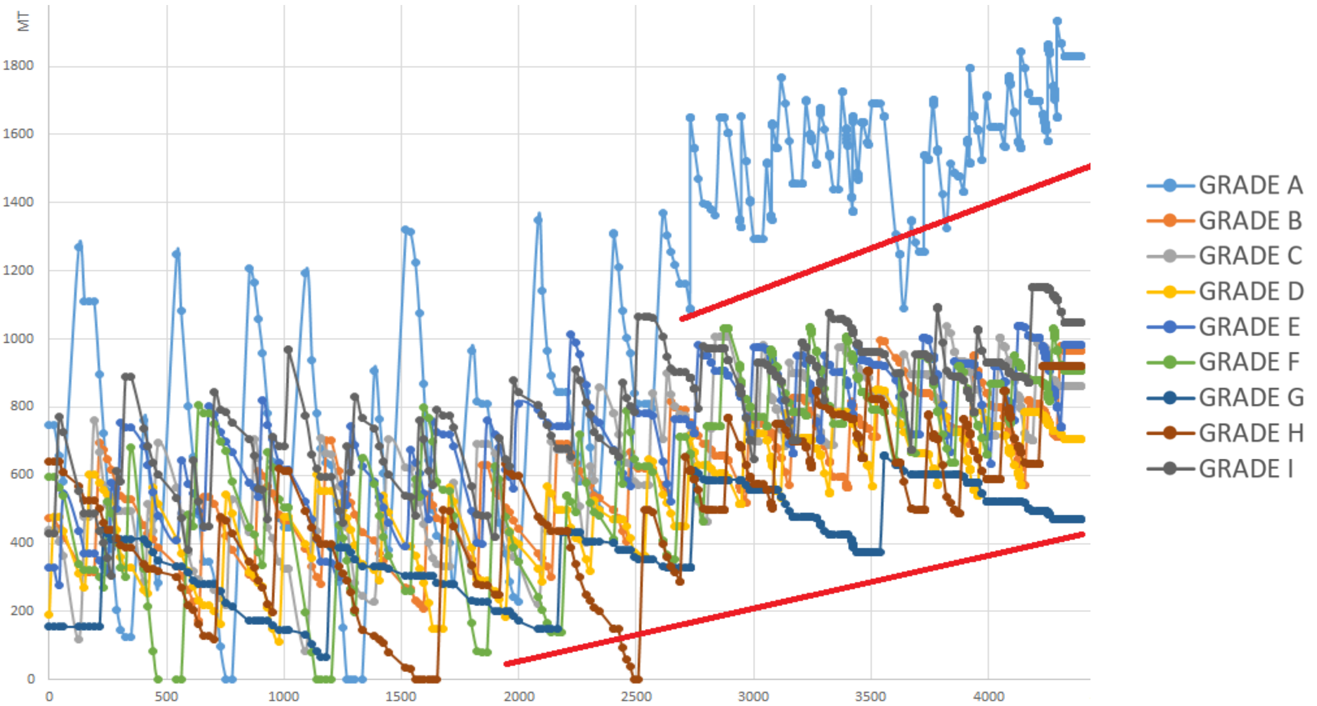

Figure 16: Actual Sales using μ^* to balance production rates (FACTORY D)

6.2.4 *Continuing Example:* Production Wheel of FACTORY C with Normally Distributed Demand

Because of these somewhat unrealistic simulation results, an additional simulation model was developed to evaluate the performance of the proposed production wheel in a stochastic context. Here the production wheel was evaluated in a stochastic environment assuming normally distributed demand using the predicted standard deviation and the demand budget as mean. The results of this simulation will be discussed in this Section. Essentially, this simulation will evaluate the production wheel in a situation where demand is volatile, but stable and in line with the expected demand budget.

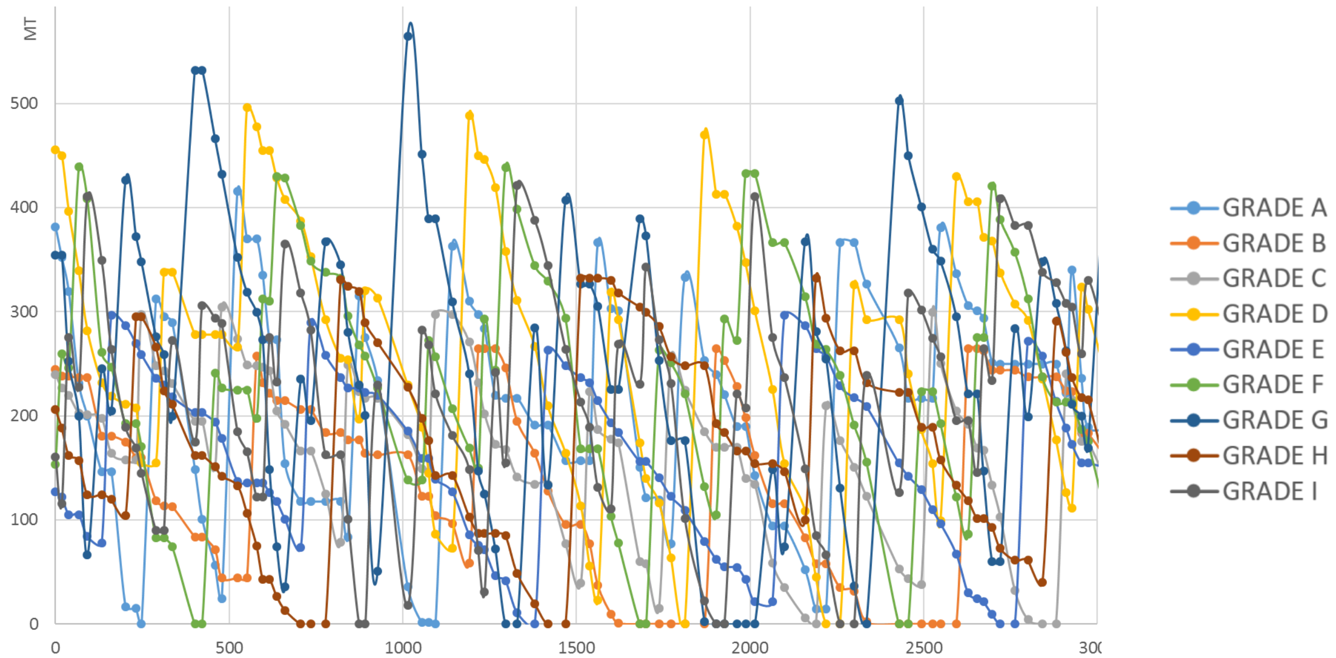

Figure 17: Inventory Flow with Normally Distributed Demand (FACTORY C)

6.2.5 Expected vs. Simulated Results

From the Sections 6.2.2 to 6.2.4, the simulation with normally distributed demand (6.2.4) provides the most realistic evaluation of the production wheel in a stochastic environment. The influence of inaccurate budgets is too high to evaluate a fixed wheel in an unstable context. The fairest comparison that can be made with regard to the simulation can be made using normally distributed demand. For FACTORY C, the simulation results are given in Table 16.

Table 16A: Simulation Results FACTORY C (A)

Simulation	Average Stock	Runs in H1 2017	Fill Rate
GRADE A	213,6	14	96%
GRADE B	127,6	6	64%
GRADE C	165,6	14	99%
GRADE D	259,9	13	98%
GRADE E	146,6	7	95%
GRADE F	220,1	21	97%
GRADE G	277,4	21	95%
GRADE H	149,6	7	90%
GRADE I	208,9	28	98%

Table 16B: Simulation Results FACTORY C (B)

Expected	*Simulation*	
Cycle Time Statistics		
21,0	22,9	*Total Cycle Time (Days)*
Cost Statistics		
€ 1.122,99	**€ 938,69**	*Total Cost Per Day (€)*
€ 237,56	€ 171,00	*Total Off Spec Cost Per Day (€)*
€ 885,43	€ 767,69	*Total Working Capital Cost Per Day (€)*
€ 0,00	€ 0,00	*Total External Storage Cost Per Day (€)*
OffSpec Statistics		
34	34	*Total OffSpec Per Cycle (MT)*
1,6	1,3	*Total Offspec Per Day (MT)*
Service Level Statistics		
95%	**96,22%**	*Aggregate Fill-Rate*

6.3 Comparing with the current Production Wheel

In this Section, the proposed *optimal production wheel,* determined by the heuristic will be compared with the current production wheel. To evaluate fairly, the comparison will be twofold. First, the current production sequence will be evaluated. This means that the current sequence is used, but safety stock levels and production quantities are optimized similar to how the heuristic does this for the optimal schedule. This implies that the cost model will, for the current production wheel's order, specify the cycle time, production quantities and safety stock levels, and subsequently calculates the total cost of this schedule. Additionally the entire current production wheel will be compared, where the current safety stock levels and the current production quantities are used to determine the cost of the production wheel.

Table 17: Comparing the Proposed Optimal Wheel with the Current Situation (FACTORY C)

FACTORY C COMPARISON	Optimal Wheel		Current Sequence		Current Schedule	
	Expected	Simulation	Expected	Simulation	Expected	Simulation
	Cycle Time Statistics					
Total Cycle Time (Days)	21,0	22,9	42,1	45,8	42,1	45,8
	Cost Statistics					
Total Cost Per Day (€)	**€ 1.122,99**	**€ 938,69**	**€ 1.463,25**	**€ 1.293,36**	**€ 2.468,40**	**€ 1.581,35**
Total Off Spec Cost Per Day (€)	€ 237,56	€ 171,00	€ 410,83	€ 395,93	€ 410,83	€ 323,52
Total Working Capital Cost Per Day (€)	€ 885,43	€ 767,69	€ 1.052,42	€ 897,42	€ 2.057,56	€ 1.257,83
Total External Storage Cost Per Day (€)	€ -	€ -	€ -	€ -	€ -	€ -
	OffSpec Statistics					
Total OffSpec Per Cycle (MT)	34	34	117,7	158,9	117,7	154,7
Total Offspec Per Day (MT)	**1,6**	**1,3**	**2,8**	**2,7**	**2,8**	**2,2**
	Service Level Statistics					
Aggregate Fill-Rate	95,00%	**96,22%**	95,00%	**94,80%**	95,00%	**92,22%**

Table 18: f_i comparison

	Improved	Curent
GRADE A	2	2
GRADE B	1	2
GRADE C	2	4
GRADE D	2	4
GRADE E	1	1
GRADE F	3	4
GRADE G	3	4
GRADE H	1	3
GRADE I	4	4

Table 17, shows that the heuristic is able to determine a schedule that reduces total relevant costs significantly, while maintaining an even higher fill rate (when normally distributed demand simulation is used). These results show that with the production wheel proposed by the heuristic, total expected cost per day can reduce from *€ 1463.25* or *€ 2468,40* to *€ 1122.99* (24% or 55%) compared with the current sequence or current schedule respectively. Additionally, expected off-spec production per day can be reduced from 2.8 to 1.6 MT (43%) by using the proposed sequence instead of the current sequence. As one can see, working capital cost per day reduce by 17%, and setup costs reduce even more, by 42%. Furthermore, noteworthy is the fact that the current cycle is significantly longer than the optimal cycle. This is due to a technicality rather than an actual difference. This technicality is shown in Table 18. As one can see, the current frequency is double the improved frequency for many of the grades. Because the cycle time is determined by the grade with the lowest frequency, it is in the current sequence determined by $GRADE\ E$. Therefore, drawing too many conclusions on just the *CT number* should be avoided. When CT is considered, one should always take frequencies and resulting stock levels, into account for a fair comparison

6.4 Summarizing Final Results of other Assets

Up to now, the results were presented for one of the six assets that were investigated for SABIC Europe polymers. This Section will present the main results for the other assets. When simulation results are presented, for reasons explained in the Sections 6.2.2 – 6.2.5, normally distributed demand is used rather than actual sales Figures. Along with the data, some special characteristics of the asset are explained shortly when necessary. For detailed results, please refer to appendix B through Appendix E.

6.4.1 Factory A

Table 19 shows that costs can be reduced by 3% and 21% compared to the current sequence and the current schedule respectively when looking at expected costs. When considering stochastic (normally distributed) demand, the cost reductions compared to the current sequence and current schedule are 10% and 17% respectively. In this stochastic environment, fill-rates of the proposed optimal schedule are also slightly higher than the current sequence and schedule.

FACTORY A is a special case, because it involves two different campaigns, with a transition grade that has to be produced in-between the two campaigns. To see how the heuristic deals with this specific situation, please refer to Appendix A, where the complete iterative improvement process is presented. Initially, due to the characteristics of the pure rotation cycle the transition grade can only be produced once in the pure rotation schedule, causing a *theoretically* infinite setup (i.e. technically impossible setup) between the campaigns between the two campaigns where the transition grade is not produced. A graphical representation of this situation is presented in Figure 18.

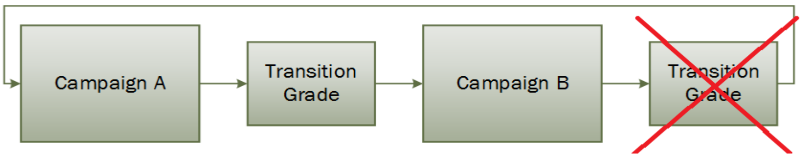

Figure 18: Impossible to have two Transition Grades in a Pure Rotation Schedule

The transition grade has be produced at the end and beginning of a campaign. Because in a pure rotation schedule, every grade is produced once, the transition grade can only be put at one of the two campaign switch moments. In the first improvement step, this transition grade is added on that location automatically solving this issue. Furthermore, this asset is an example where, the $minCT$ is not the optimal *CT* and cost improvements are made while increasing the total cycle time. For more details on the results and input for FACTORY A, please refer to Appendix A.

Another effect of the two campaigns is noticeable when looking at the total off-spec cost per day Figure for the optimal wheel and the current sequence. One can easily see that off-spec production per day is lower in the current sequence, compared to the optimal wheel (i.e. if expected Figures are considered), but total off-spec cost per day is higher for the current sequence. Although this seems contradictory, the total off-spec cost per day, includes the setup costs of switching between two campaigns. Because the cycle time for the optimal wheel is longer than the cycle time for the current sequence, in the current sequence, more campaign switches are made during the year, causing higher setup costs.

Table 19: Comparing Schedules for FACTORY A

FACTORY A COMPARISON	Optimal Wheel		Current Sequence		Current Schedule	
	Expected	Simulation	Expected	Simulation	Expected	Simulation
	Cycle Time Statistics					
Total Cycle Time (Days)	124,2	104,6	115,2	109,8	106,2	112,6
	Cost Statistics					
Total Cost Per Day (€)	**€ 20.684,97**	**€ 24.634,48**	**€ 21.428,01**	**€ 27.285,54**	**€ 26.074,01**	**€ 29.710,28**
Total Off Spec Cost Per Day (€)	€ 9.580,20	€ 11.764,35	€ 9.913,40	€ 14.087,96	€ 12.387,12	€ 14.447,22
Total Working Capital Cost Per Day (€)	€ 9.338,68	€ 10.766,15	€ 9.703,08	€ 11.069,62	€ 11.366,18	€ 12.626,27
Total External Storage Cost Per Day (€)	€ 1.766,08	€ 2.103,98	€ 1.811,53	€ 2.127,96	€ 2.320,71	€ 2.636,79
	OffSpec Statistics					
Total OffSpec Per Cycle (MT)	1030	790	880	894	880	916,8
Total Offspec Per Day (MT)	**7,3**	**7,1**	**6,6**	**8,1**	**8,3**	**8,1**
	Service Level Statistics					
Aggregate Fill-Rate	95,00%	**95,40%**	95,00%	**95,12%**	95,00%	**93,19%**

6.4.2 FACTORY B

Table 20 presents the final comparison of the optimal cycle and the current cycle and wheel for FACTORY B. One can see that expected costs can be reduced significantly by 40% (compared to the current sequence) and 45% (compared to the current schedule) and by 45% and 46% respectively when considering the simulation results. All cost types can be reduced by using a different sequence producing fewer off-spec material and keeping lower inventory levels. For more details on FACTORY B, please refer to Appendix B, which shows all input parameters, the improvement process, detailed results and the optimal production wheel for the asset according to the heuristic.

Table 20: Comparing Schedules for FACTORY B

FACTORY B COMPARISON	Optimal Wheel		Current Sequence		Current Schedule	
	Expected	Simulation	Expected	Simulation	Expected	Simulation
	Cycle Time Statistics					
Total Cycle Time (Days)	60,8	60,6	60,8	62,5	60,8	77,1
	Cost Statistics					
Total Cost Per Day (€)	**€ 4.452,73**	**€ 4.979,07**	**€ 7.464,23**	**€ 9.163,77**	**€ 8.050,47**	**€ 9.169,85**
Total Off Spec Cost Per Day (€)	€ 1.413,70	€ 1.530,05	€ 2.697,53	€ 3.794,54	€ 2.697,53	€ 5.784,70
Total Working Capital Cost Per Day (€)	€ 2.817,81	€ 3.104,22	€ 4.061,52	€ 4.505,17	€ 4.485,44	€ 3.074,29
Total External Storage Cost Per Day (€)	€ 221,22	€ 344,79	€ 705,18	€ 864,07	€ 867,49	€ 293,86
	OffSpec Statistics					
Total OffSpec Per Cycle (MT)	430	466,7	820,5	1189	1641	2228,2
Total Offspec Per Day (MT)	**7,1**	**7,7**	**13,5**	**19**	**13,5**	**28,9**
	Service Level Statistics					
Aggregate Fill-Rate	95,00%	**95,40%**	95,00%	**95,23%**	95,00%	**94,27%**

6.4.3 FACTORY D

The results for FACTORY D are depicted in Table 21. This shows that costs can be reduced by 4% and 31% compared to the current order and the current wheel respectively in terms of expected costs. When looking at the results with stochastic, normally distributed, demand, cost reductions can be made of 7% and 54% when using the optimal schedule. Noteworthy is the fact that simulation costs are lower than expected costs. This effect is similar to the effect explained in Section 6.3.2. (i.e. $MRL_i < SS_i$, causing inventory levels to be relatively lower than expected). For more details on FACTORY D, please refer to Appendix C, which shows all input parameters, the improvement process, detailed results and the optimal production wheel for this asset according to the heuristic.

Table 21: Comparing Schedules for FACTORY D

FACTORY D COMPARISON	Optimal Wheel		Current Sequence		Current Schedule	
	Expected	Simulation	Expected	Simulation	Expected	Simulation
	Cycle Time Statistics					
Total Cycle Time (Days)	38,6	40,3	38,6	30,2	38,6	25,3
	Cost Statistics					
Total Cost Per Day (€)	**€ 2.135,14**	**€ 1.521,68**	**€ 2.220,34**	**€ 1.637,77**	**€ 3.103,48**	**€ 3.280,96**
Total Off Spec Cost Per Day (€)	€ 299,49	€ 191,32	€ 359,61	€ 340,60	€ 359,61	€ 888,32
Total Working Capital Cost Per Day (€)	€ 1.835,64	€ 1.330,36	€ 1.860,73	€ 1.297,18	€ 2.743,87	€ 2.392,64
Total External Storage Cost Per Day (€)	€ -	€ -	€ -	€ -	€ -	€ -
	OffSpec Statistics					
Total OffSpec Per Cycle (MT)	88,9	88,9	106,8	120	106,8	172,9
Total Offspec Per Day (MT)	**2,3**	**2,2**	**2,8**	**2,6**	**2,8**	**6,8**
	Service Level Statistics					
Aggregate Fill-Rate	95,00%	**97,12%**	95,00%	**96,22%**	95,00%	**94,24%**

6.4.4 FACTORY E

For FACTORY E, Table 22 shows that total relevant costs can be reduced by 4% and 19% compared with the current sequence and current schedule respectively. Although, simulated costs are slightly higher for compared with the current sequence, this is due to a lower fill rate (i.e. stock levels are lower causing lower holding costs). Again, more detailed results can be found in appendix D.

Table 22: Comparing Schedules for FACTORY E

FACTORY E COMPARISON	Optimal Wheel		Current Sequence		Current Schedule	
	Expected	Simulation	Expected	Simulation	Expected	Simulation
	Cycle Time Statistics					
Total Cycle Time (Days)	69,6	91,5	69,6	91,5	69,6	91,5
	Cost Statistics					
Total Cost Per Day (€)	**€ 4.516,00**	**€ 3.596,28**	**€ 4.695,87**	**€ 3.398,28**	**€ 5.604,52**	**€ 3.787,78**
Total Off Spec Cost Per Day (€)	€ 1.110,17	€ 1.062,31	€ 1.227,19	€ 1.126,35	€ 1.227,19	€ 1.193,38
Total Working Capital Cost Per Day (€)	€ 3.237,25	€ 2.533,97	€ 3.301,15	€ 2.271,93	€ 3.997,63	€ 2.557,25
Total External Storage Cost Per Day (€)	€ 168,57	€ -	€ 167,54	€ -	€ 379,70	€ 37,15
	OffSpec Statistics					
Total OffSpec Per Cycle (MT)	88,9	578,6	508,6	613,5	508,6	650,0
Total Offspec Per Day (MT)	**6,6**	**6,3**	**7,3**	**6,7**	**7,3**	**7,1**
	Service Level Statistics					
Aggregate Fill-Rate	95,00%	**95,93%**	95,00%	**93,75%**	95,00%	**91,83%**

6.4.5 FACTORY F

The heuristic proposes a production wheel for FACTORY F that reduces the total expected costs by 35% and 45% respectively when comparing with the current sequence and the current complete wheel respectively. Simulation results also show a similar cost reduction. FACTORY F is the clearest example where the $minCT$ is always the optimal *CT*. Increasing the cycle time will only increase the holding costs while not reducing the setup costs. Because of this, the minimum runlength has a lot of influence on the optimal cycle. The effect of the minimum runlength on the optimal production wheel will be discussed in general in the next section. As discussed in Section 6.3, one should not draw to many conclusions from the CT-figure. A higher cycle time does not mean that production quantities and grade specific lead times are proportionally higher.

Table 23: Comparing Schedules for FACTORY F

FACTORY F COMPARISON	Optimal Wheel		Current Sequence		Current Schedule	
	Expected	Simulation	Expected	Simulation	Expected	Simulation
	Cycle Time Statistics					
Total Cycle Time (Days)	19,7	18,3	32,6	22,9	69,6	72,6
	Cost Statistics					
Total Cost Per Day (€)	**€ 6.637,55**	**€ 7.358,50**	**€ 10.241,27**	**€ 10.632,26**	**€ 12.011,79**	**€ 10.848,74**
Total Off Spec Cost Per Day (€)	€ -	€ -	€ -	€ -	€ -	€ -
Total Working Capital Cost Per Day (€)	€ 4.143,03	€ 4.402,84	€ 6.423,38	€ 6.388,29	€ 7.518,19	€ 6.862,55
Total External Storage Cost Per Day (€)	€ 2.494,52	€ 2.955,66	€ 3.817,89	€ 4.243,97	€ 4.493,60	€ 3.986,19
	OffSpec Statistics					
Total OffSpec Per Cycle (MT)	0	0	0	0	0	0
Total Offspec Per Day (MT)	**0**	**0**	**0**	**0**	**0**	**0**
	Service Level Statistics					
Aggregate Fill-Rate	95,00%	**97,97%**	95,00%	**100,00%**	95,00%	**95,73%**

Altogether, both in a deterministic and a stochastic demand situation significant cost reduction are possible for all investigated assets. Furthermore, expected off-spec production is decreased for all assets except FACTORY A, with the heuristically proposed production wheel. Detailed statistics on safety stock levels, expected, and simulated cycle stock levels for the optimal wheel, current sequence and the current schedule are listed in Appendix I. Before presenting the main conclusions and recommendations, first the influence of the minimum runlengths is investigated and discussed shortly in the next section.

6.5 Minimum Runlengths

The minimum runlength forms an essential part of the scheduling problem and essentially creates a lower bound on the optimal cycle time. Although the model uses the minimum runlength as a *hard* constraint, and it is considered as such in the determination of the optimal production wheel, there exists some doubt on whether this minimum runlength is legitimately the minimum in all cases. In which cases, and why, the minimum runlength might not be the genuine minimum is not under consideration, rather the effect of the minimum runlength on the production wheel is investigated here and can form a basis for discussion.

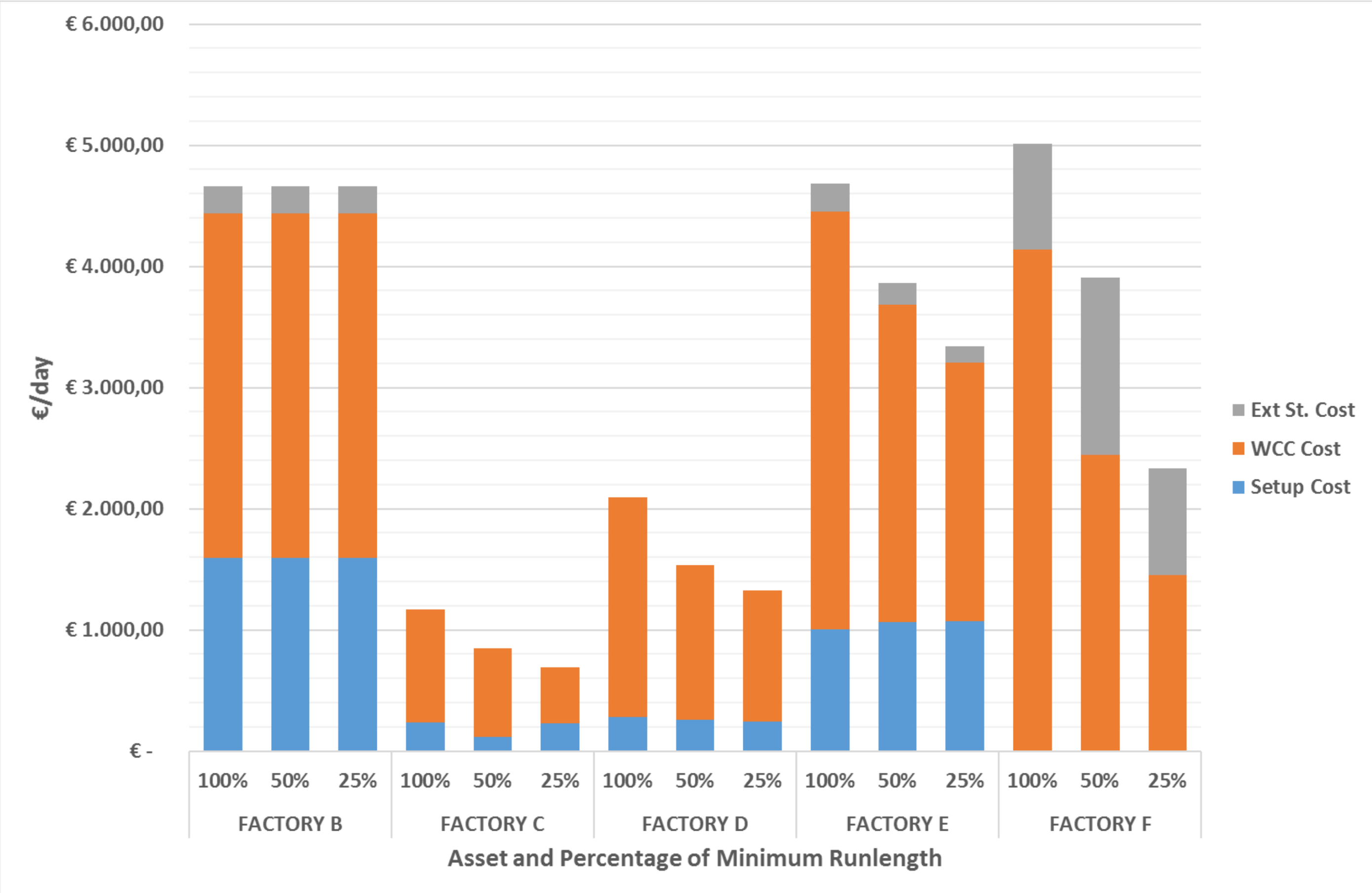

Figure 19: Reducing Minimum Runlengths

The effect of reducing the minimum runlength on the cost Figures for all assets except FACTORY A (not included to increase clearness of the graph) is shown in the figure above. As one can see, for all assets except FACTORY B, the minimum runlength has significant effect on the overall cost of the model. This is due to the fact that the overall cycle time can be reduced significantly when the minimum runlength of the grades is reduced. This effect is most significant for FACTORY F because it does not have any setup costs when the optimal wheel is used. Reducing cycle time therefore, only reduces the holding costs, while setup costs are not increased (i.e. for FACTORY F, the optimal cycle time is always the $minCT$ because of the absence of setup costs). On the other side of the spectrum, the fact that the costs for FACTORY B are not reduced due to a reduction in minimum runlengths is due to the fact that the optimal cycle time is already far above the $minCT$ in all cases.

A similar comparison was made for different levels of internal storage capacity. More specifically, the effect of increasing storage capacity was investigated. This did not give any surprising results, rather than obvious cost reduction in external storage costs.

After presenting the main results of the heuristic, it is now possible to continue with the main conclusions of the model in the next chapter. Subsequently, based on these conclusions, recommendations can be given to SABIC to improve the production wheel.

7 Conclusions

This Chapter will discuss the main conclusions that can be drawn based on the research presented in this report and will aim at answering the research questions that were specified at the start of this project:

1. *What are the relevant costs/concepts when scheduling different grades on SABIC's assets?*
2. *What heuristics/models are available in literature that address the relevant aspects of SABIC's scheduling problem?*
3. *Develop a heuristic that considers all relevant aspects of SABIC's context.*
4. *How does the model perform compared to the current situation?*
5. *How does the model behave in a stochastic environment (H1 2017)?*
6. *What is the effect of the Minimum Runlength on the Optimal Wheel?*

7.1 Relevant Costs

There are two main cost types in SABIC's scheduling problem: setup costs and holding costs. In the case of SABIC, setup costs are the consequence of off-spec production due to transitions between the production runs of different grades and switches between different campaigns. These transitions are significantly sequence dependent, making the order of the production cycle an essential part of the scheduling problem. Working capital cost of cycle stock and safety stock, and the external storage costs and detour costs, together, form the holding cost component of the scheduling problem.

Optimal safety stock levels are significantly influenced by the choice of the production sequence and the production quantities. It is therefore essential to consider these safety stock levels while optimizing the production wheel, rather than calculating them after the determination of the wheel. Furthermore, also the concept of the minimum runlenghts, campaigns, and technically impossible constraints have been implemented in the newly developed scheduling tool.

7.2 Current Literature

After analyzing the current literature (for details please refer to the literature review document specifically), one can conclude that there is no heuristic solution available to solve SABIC's scheduling problem. In any of the existing models, major elements of the problem are not considered explicitly. The combination of sequence dependent setups and minimum runlengths was never investigated, and similarly, sequence dependency in a stochastic context was not investigated directly. Wagner and Davis' (2002) heuristic did not give satisfactory results because of the absence of minimum runlengths in their model. Other heuristics showed similar limitations and therefore, the development of a different heuristic is necessary to deal with SABIC's context. Nonetheless, current scheduling research can provide a guideline on how to develop a heuristic that can be used for SABIC's situation. For example, Dobson's (1992) idea to use the traveling salesman problem to develop an optimal pure rotation schedule was used as starting point for the developed heuristic.

7.3 The Heuristic

The developed heuristic forms the core of this research project and is able to deal with all relevant concepts of SABIC's specific scheduling problem, including campaigns, minimum runlenghts, external storage costs and implicitly determines safety stock levels. This combination creates a heuristic that is not available in current literature. The developed heuristic does not only specify the optimal sequence, but simultaneously optimal safety stock levels and production quantities are determined. The heuristic was implemented in a user-friendly tool that is able to investigate all combinations of grades on an asset, and in which changes to grade characteristics and transitions are easy to make. Therefore, although the heuristic leaves the allocation of grades to specific assets out-of-scope, the model is able to evaluate different *allocations* individually. Furthermore, the model is able to investigate the effect of not including a particular grade in the portfolio, which can be used as guidance for portfolio decisions.

7.4 Comparison (Deterministic Demand)

The heuristic is able to achieve major cost reductions compared to the current production wheel for all assets (ranging from reductions of 1% to 38% of total relevant costs) when deterministic demand is assumed. The percentage differences between the current schedule and the optimized schedule are given in the tables below for constant demand rates. Table 24 shows the comparison between the heuristically developed wheel and the current sequence with optimal production quantities and safety stock levels. Table 25 shows the comparison between the optimal wheel and the current wheel entirely (i.e. using current production quantities and safety stock levels).

When reviewing these results, one should take into account that in reality the production wheel is not followed exactly throughout the year. However, it is used as a guideline for the master production scheduler (MPS) to schedule the production of grades on an operational level. Therefore, the cost reductions mentioned should not be considered explicitly. The cost comparison shows that cost reductions are possible when changing this *guideline* schedule. It does not claim that using the proposed schedule completely, provides these exact cost Figures. In order to see how the proposed production wheel would perform in combination with decisions by the MPS a more dynamic scheduling model is necessary, which incorporates all available information at a specific point in time. These dynamic decisions were out-of-scope for this project, and are often hard to translate into mathematical rules, because they are based on, often hardly quantifiable, *experience* of the MPS.

Table 24: Difference Optimal Wheel and Current Sequence with Optimized Q and SS (constant demand)

	FACTORY A	FACTORY B	FACTORY C	FACTORY D	FACTORY E	FACTORY F
$\Delta\, Total\ Cost$ (€)	-3%	-40%	-23%	-4%	-4%	-35%
$\Delta\, Cycle\ Stock\ (MT)$	-31%	-52%	17%	-3%	-2%	-29%
$\Delta\, Safety\ Stock\ (MT)$	-5%	-15%	-11%	0%	-4%	-26%
$\Delta\, OffSpec\ (MT)$	11%	-47%	-43%	-18%	-10%	N.A

Table 25: Difference between optimal Wheel and current Wheel, current Q and SS (constant demand)

	FACTORY A	FACTORY B	FACTORY C	FACTORY D	FACTORY E	FACTORY F
$\Delta\, Total\ Cost$ (€)	-21%	-45%	-55%	-31%	-19%	-45%
$\Delta\, Cycle\ Stock\ (MT)$	-37%	-37%	-55%	-34%	-19%	-36%
$\Delta\, Safety\ Stock\ (MT)$	-29%	-16%	-44%	-22%	-27%	-43%
$\Delta\, OffSpec\ (MT)$	-12%	-47%	-43%	-18%	-10%	N.A.

In terms of total relevant costs, an overview is given in the table below. Table 26 specifies the total relevant cost when the current production wheel is used, when the current sequence is optimized with regard to safety stock levels and production quantities and when the heuristically developed production wheel would be used.

Table 26: Cost Comparison Overview

	Current Schedule (current SS and Q for current Sequence)						
	FACTORY A	FACTORY B	FACTORY C	FACTORY D	FACTORY E	FACTORY F	Total
Average Total Inventory Level (MT)	27625	11652	5364	7126	10326	19582	81675
Off Spec Production/Year (MT)	3030	4928	1022	1022	2665	0	12666
Working Capital Cost/Year (€)	€ 4.148.656	€ 1.637.186	€ 751.009	€ 1.001.513	€ 1.459.135	€ 2.744.139	€ 11.741.638
External Storage Cost/Year (€)	€ 847.059	€ 316.634	€ -	€ -	€ 138.591	€ 1.640.164	€ 2.942.448
Off-Spec Cost/Year (€)	€ 4.521.299	€ 984.598	€ 149.953	€ 131.258	€ 447.924	€ -	€ 6.235.032
Total Cost Per Year (€)	**€ 9.517.014**	**€ 2.938.422**	**€ 900.966**	**€ 1.132.770**	**€ 2.045.650**	**€ 4.384.303**	**€ 20.919.117**
	Current Sequence (optimizing SS and Q for current Sequence)						
	FACTORY A	FACTORY B	FACTORY C	FACTORY D	FACTORY E	FACTORY F	Total
Average Total Inventory Level (MT)	25351	15265	2905	4850	8538	17521	74430
Off Spec Production/Year (MT)	2592	4928	1022	1022	2665	0	12228
Working Capital Cost/Year (€)	€ 3.478.333	€ 1.482.455	€ 384.133	€ 679.166	€ 1.204.920	€ 2.344.534	€ 9.573.541
External Storage Cost/Year (€)	€ 653.500	€ 257.391	€ -	€ -	€ 61.152	€ 1.393.530	€ 2.365.572
Off-Spec Cost/Year (€)	€ 3.901.835	€ 984.598	€ 149.953	€ 131.258	€ 447.924	€ -	€ 5.615.569
Total Cost Per Year (€)	**€ 8.033.668**	**€ 2.724.444**	**€ 534.086**	**€ 810.424**	**€ 1.713.993**	**€ 3.738.064**	**€ 17.554.682**
	Improved Producion Wheel (opimizing SS,Q, and Sequence						
	FACTORY A	FACTORY B	FACTORY C	FACTORY D	FACTORY E	FACTORY F	Total
Average Total Inventory Level (MT)	17492	7352	2422	4728	8325	12506	52825
Off Spec Production/Year (MT)	2665	2592	584	840	2409	0	9089
Working Capital Cost/Year (€)	€ 3.408.618	€ 1.028.501	€ 323.182	€ 670.009	€ 1.181.596	€ 1.512.206	€ 8.124.112
External Storage Cost/Year (€)	€ 644.619	€ 80.745	€ -	€ -	€ 61.532	€ 910.500	€ 1.697.396
Off-Spec Cost/Year (€)	€ 3.496.773	€ 516.001	€ 86.709	€ 109.314	€ 405.212	€ -	€ 4.614.009
Total Cost Per Year (€)	**€ 7.550.014**	**€ 1.625.246**	**€ 409.891**	**€ 779.326**	**€ 1.648.340**	**€ 2.422.706**	**€ 14.435.516**

7.5 Simulation Results

A few lessons can be learnt from evaluating production wheels in a stochastic demand context. The performance of the model in a stochastic environment was investigated using three different simulations. First, the actual sales during the first half of 2017 were used to determine the actual costs, inventory levels and service levels during this period when the heuristically determined optimal production wheel would have been used and theoretical production rates were considered. Two issues arose when this was done. First, one of the main assumptions of the model states that the facility will always run on full capacity. In reality production capacity is not always 100% because of a variety reasons, ranging from a strategic decision not to produce because prices are very low, to actual technical breakdowns. Therefore, production capacity will exceed average sales volumes (which are influenced by the actual sales Figures, i.e. reduced production leads to reduced sales), causing inventory levels to rise indefinitely in the long run. This effect is dealt with by introducing the variable μ^*, which reduces the production rates until expected demand rates equal production rates. Although this shows some improvement, still, when demand budgets are underestimated, inventory levels will rise indefinitely in the long run.

Furthermore, in reality, sales are significantly influenced by current inventory levels and the current production wheel. When inventory levels are zero, sales are *lost*, and when inventory levels are high, sales are *pushed*. Therefore, simulating with actual sales Figures does not give a fair view on the performance of the production wheel. This effect is dealt with by using normally distributed demand, rather than actual sales Figures to simulate the proposed production wheel.

When normally distributed demand is used, the production wheel is evaluated in a stochastic situation, where demand is volatile, but stable in the long run. This type of simulation was used to compare the heuristically proposed production wheel with the current sequence (i.e. current order, but SSs and Qs are optimized) and the current schedule (using current SSs and Qs) in a stochastic environment. The results of this comparison are shown in Table 27 and Table 28.

Table 27: Difference Optimal Wheel and Current Sequence with Optimized Q and SS (normally distributed demand)

	FACTORY A	FACTORY B	FACTORY C	FACTORY D	FACTORY E	FACTORY F
$\Delta\, \boldsymbol{Total\ Cost}$ (€)	-4%	-38%	-23%	-6%	-0,3%	-35%
$\Delta\, \boldsymbol{Cycle\ Stock}\ (\boldsymbol{MT})$	-33%	-36%	-24%	-5%	6%	-41%
$\Delta\, \boldsymbol{Safety\ Stock}\ (\boldsymbol{MT})$	-15%	-15%	-11%	0%	2%	-26%
$\Delta\, \boldsymbol{OffSpec}\ (\boldsymbol{MT})$	7%	-41%	-43%	-21%	-18%	0%

Table 28: Difference between optimal Wheel and current Wheel (normally distributed Demand)

	FACTORY A	FACTORY B	FACTORY C	FACTORY D	FACTORY E	FACTORY F
$\Delta\, \boldsymbol{Total\ Cost}$ (€)	-19%	-42%	-53%	-33%	-16%	-45%
$\Delta\, \boldsymbol{Cycle\ Stock}\ (\boldsymbol{MT})$	-39%	-44%	-65%	-43%	-2%	-46%
$\Delta\, \boldsymbol{Safety\ Stock}\ (\boldsymbol{MT})$	-29%	-16%	-44%	-22%	-27%	-43%
$\Delta\, \boldsymbol{OffSpec}\ (\boldsymbol{MT})$	-7%	-41%	-43%	-21%	-18%	0%

Apart from the improvements in Table 29 and Table 30, the simulation shows that maintaining a fixed schedule in a stochastic context works well in an environment with stable demand that is on average in line with expectations. However, when demand is structurally lower or higher than expected, as the simulations using actual sales show, it is essential that production quantities or even sequences will be adjusted.

7.6 Minimum Runlenghts

Minimum runlengths are essentially constructing a lower bound on the total cycle time and are significantly affecting the optimal production wheel. Experiments in which minimum runlenghts are adjusted show that total relevant costs can be reduced significantly, when these minimum runlengths are reduced. Especially for items with relatively low setup costs, this effect is very significant (e.g. FACTORY F). The question whether the minimum runlengths are valid was out-of-scope for this project, but the results of adjusting the minimum runlengths do provide an incentive to further investigate the legitimacy of these Figures.

8 Discussion

The purpose of this Chapter is to provide concrete recommendations to SABIC on how to use the outcomes of this research to improve scheduling performance. Furthermore, the limitations of the developed model and heuristic are discussed and directions for further research are proposed.

8.1 Recommendations

8.1.1 Use the Heuristic Tool to significantly reduce Total Relevant Costs

The first recommendation to SABIC is as obvious as important. SABIC should use the heuristic tool that was developed during the project to improve scheduling decisions significantly. The model shows that major reductions in terms of total relevant scheduling costs are achievable when the heuristically developed production wheel is used (i.e. 30% on average for the six assets investigated). In general, especially off-spec costs can be reduced significantly, while maintaining similar stock levels or even reducing them. The fact that also off-spec production can be reduced significantly will make change management with respect to other departments (e.g. manufacturing) relatively easy. The current *default* production wheel should be changed to the one proposed by the model. Alternatively, the model can be used to determine optimal safety stock levels and production quantities for the current production sequence, or alternative sequences.

However, one should always take into account that, as the simulation shows, *blindly* following the production wheel gives unsatisfactory results, therefore the ad-hoc adjustments made by the master production scheduler (MPS) are still necessary to retain a stable schedule. Generally, the proposed production wheel is able to deal with volatility in demand as long as the mean demand remains stable. Strong deviations from the expected demand should be dealt with by MPS.

8.1.2 Validate Minimum Runlenghts

Minimum runlengths are essential for optimizing SABIC's production wheel. Reducing the minimum runlengths on particular assets can lead to major cost reductions, as shown in Section 6.5. The validity of minimum runlengths should be reviewed, and the potential negative effects of reducing the minimum runlength (e.g. increasing transition times, increase breakdown probability, etc.) should be compared with the positive effects on scheduling costs. Based on a total cost/benefit analysis of these effects, SABIC should decide whether minimum runlenghts should be reduced.

When considering an adjustment of minimum runlengths, one should acknowledge the different perspectives of this problem. From a scheduling perspective, it might be very beneficial to decrease minimum runlenghts, but on the other hand, it might contradict the targets of manufacturing, which are directed at reducing total off-spec as much as possible. When considering adjusting the minimum runlengths, SABIC should always keep a total cost perspective in mind and communicate clearly, why an adjustment is an improvement from a total cost perspective, even if this contradicts manufacturing targets.

8.1.3 Run the Tactical Optimization Process more frequently

Currently, the optimal production wheel, including production quantities and safety stock levels, is determined once every year. However, during the year it usually becomes evident that markets develop differently than expected, causing the previously determined optimal production plans and stock targets not to be optimal any more. For instance, demand expectations per grade turn out to be different from what was expected at the beginning of the year. Additionally, seasonality of grades, although not that prevalent in the plastics industry, is not accommodated for when running the process only once a year. Therefore, it is recommended to update production wheel decisions, for instance twice a year. Running the tactical optimization process more frequently is now more effortless by having an automated scheduling tool available.

8.1.4 Not Produce Specific Grades

The model can be used to determine the effect of not producing particular grades. Grades with relatively low demand and on average high transition times cause the cycle time to increase. Because of this increase in cycle time, the leadtime of the other grades increases, which causes higher cycle stock and safety stock levels. A clear example of this is not producing $GRADE\ B$ on FACTORY C, which results in a total cost reduction of 35% for the entire asset. Not producing particular grades could be beneficial from an overall cost perspective.

The final decision of producing a grade should not be taken solely on this cost reduction but should rather be considered from a profit point of view. Doing so would require an entirely different model focusing on maximizing profit rather than minimizing costs should be used (e.g., Flapper, Gonzalez, Smith and Escobar (2010) provide a method to determine an optimal product assortment by maximizing the net profit subject to capacity constraints).

8.1.5 Adjust Safety Stock Levels

On average, the results of this research show that safety stock, even when maintaining the current production wheel, can be reduced significantly. Safety stock levels are now determined using the total cycle time as the lead-time for all the grades. When a grade is produced several times per sequence, this reduces the lead-time significantly. The maximum lead-time within a cycle should be used as a determinant for the safety stock level. Alternatively, the average lead-time could be used, leading to lower safety stocks but more out of-stock situations.

8.2 Limitations and Future Research

In this last Section of the report, some important limitations of the model will be discussed. Furthermore, ways to solve some of these issues through future research will be addressed.

8.2.1 On-Way Heuristic

The most important limitation of the developed heuristic is the fact that once an improvement step is finished it cannot be altered. More specifically, there could be situations, in which adding a production run of a particular grade causes the biggest cost reduction initially, but after a few other improvement steps, it would have been better to have added a run of a different grade at first. The heuristic will never see these possibilities because it will only continue from the last determined sequence. This limitation is best explained graphically in Figure 20.

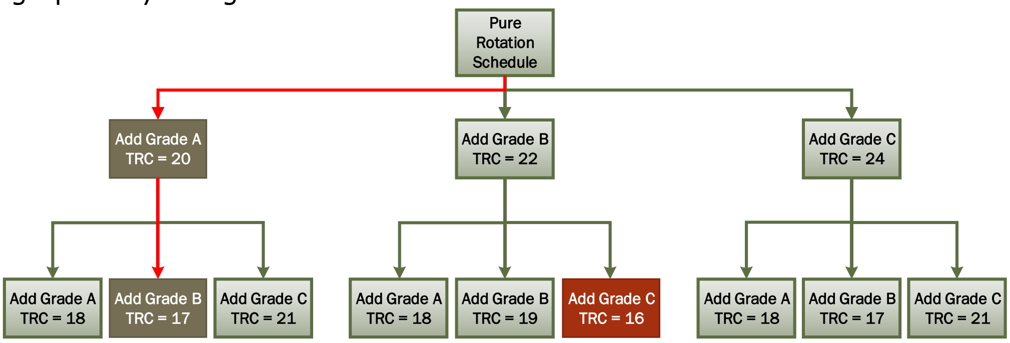

Figure 20: One-Way Limitation

The figure highlights the improvement process of the heuristic with the red arrows. As one can see, first, an additional production run of *grade A* is added, and subsequently, an additional run of *grade B* is added. Doing so leads to total relevant cost of 17. Although the cost reductions are maximized step-by-step, the heuristic does not arrive at the global optimum for a sequence with 5 production steps, which has total relevant costs of 16 after adding *grade B* and *grade C* respectively. This example demonstrates the universal drawback of heuristic solutions of finding local optima instead of a global optimum.

8.2.2 Grade Allocation

Right now, the model is able to compute the effect of a particular grade allocation explicitly. The addition of incorporating the allocation of grades into the model is conceptually very simple. Because calculation time is already very long without the allocation step, this is not incorporated in the model, and assets are only optimized individually. When every asset/allocation combination needs to be evaluated, the problem becomes incredibly *big*. If one wants to incorporate this step into the model, *smart* ways to reduce the asset/allocation options should be developed. Alternatively, different allocation options can be evaluated individually using the current model.

8.2.3 Improving the Simulation Model

Register Actual Sales

In order to improve the value of the simulation, actual demand statistics should be registered and used instead of sales Figures. Currently these statistics are not available. For reasons explained before, using sales Figures results in unrealistic outcomes of the simulation. In reality, a lot of actual demand may not be fulfilled and this demand is not registered. When the proposed sequence would be compared with the current production wheel, using actual demand statistics would give a perspective on the profit of a using another production wheel. When a particular production wheel is able to fulfill more demand, this might be more important than being a low cost sequence. Exactly this consideration, from a total profit perspective, can be made when actual demand statistics would be used to evaluate a production wheel.

Change Budget Accuracy for Normal Distribution

Alternatively, the value of the simulations can be increased by changing the parameters of the normal distribution used to simulate demand rates. Currently, the mean of the normal distribution is based on the budget, which is also used to optimize the production wheel. Therefore, the simulation using normally distributed demand only shows how the production wheel performs in a volatile environment, where on average, demand is exactly as forecasted. Changing the parameters of the normal distribution would explore how the production wheel performs in a stochastic environment with structurally inaccurate budgets.

Varying μ^* throughout the Simulation

All simulation models used, assume production rates being constant. At the start of the year, production rates are balanced with the demand budgets using μ^*. When demand budgets are inaccurate (i.e. demand rates are lower/higher than expected), production in the long run will be unbalanced with demand rates. Alternatively, μ^* could be determined based on the demand of the last month for example. Similar simulation models can be used to evaluate the effect when production rates are not constant anymore.

8.2.4 Verify the use of $MinCT$ as a $Lower\ Bound$

The heuristic uses the $minCT$ to determine a lower bound for the cycle time. When the $minCT$ is significantly increased by one grade, it might be beneficial to also consider cycle times that are below the $minCT$. The consequence of this will be that there will be not enough demand for this grade to sell all produced material (i.e. the minimum produced quantity is higher than the demand during the cycle). Therefore, sales for this grade need to be *pushed* or written off. Although this obviously is not beneficial for this particular grade, from a total profit perspective it might still be interesting to evaluate.

8.2.5 Profit Maximization Model

The development of a profit maximization model, rather than a cost minimization model should be considered. Such a model, would determine how much of every grade to produce, and whether grades should be produced at all (i.e. portfolio decisions will be based on expected profit per grade). Additionally, the effect of not selling everything that is produced can be investigated with this model (causing a decrease in minimum cycle times). Because such a model would involve many more variables, it will be even more complicated to solve mathematically and even more assumptions are necessary to make this feasible. The value of simulation models would also increase significantly with a profit maximization model, because then, the amount of material sold will become relevant (i.e. now losing sales does not impose any costs; it only determines the fill rate). Therefore, a profit maximization model would require actual demand data, instead of sales data.

8.2.6 Dynamic Sequencing

Although this was strictly not the purpose of this project, ideally, a dynamic model should be considered that incorporates the add-hoc decisions of the master production scheduler explicitly. This model would consider all information that is available at a certain point in time, to determine the optimal grade to be produced next. Essentially, this would mean that the model would determine an optimal production wheel at the end of every production run, based on current inventory levels and current expected demand for the coming period. The heuristic developed in this project could form the basis for a dynamic modeling solution for SABIC's scheduling problem.

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