MASTER

Maximizing profit with a facility network redesign including multi-level configurable bill of materials

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Award date:
2020

Department of Industrial Engineering and Innovation Sciences
Transportation track

Maximizing profit with a facility network redesign including multi-level configurable bill of materials

Master thesis

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February 10, 2020
Eindhoven

Keywords: Facility network redesign, capacitated dynamic multi-commodity multi-echelon location problem, multi-level configurable bill of materials, capacity extension investments, production industries

Abstract

Two years ago RHI and Magnesita merged to become the largest refractory producer of the world. The excess amount of capacity and increasing demand in developing countries resulted in a facility network redesign need. The complexity of the facility network redesign is high due to the multiple pieces of equipment in factories and possibility to choose a bill of materials at each equipment. That is why the facility network redesign needs to include multi-level configurable bill of materials. In this study, a mathematical model is established for solving this complex facility network redesign. The quality of the obtained optimal solution is analyzed with scenarios. The scenarios are chosen based on the business context. In the end, the results are converted to a conclusion and practical recommendations for the company.

Executive summary

Problem description

The problem RHI Magnesita (RHIM) is facing is the inability to optimize its complex facility network. RHIM has strong reasons to believe that their facility network can be optimized. Since the merge, the capacity of RHIM's production factories is too high for the obtained yearly global demand. The reason is that clients desire to have two suppliers for supply security. So, before the merge clients would have had RHI and Magnesita delivering the refractory goods, but to prevent problems the clients have searched for another supplier to assure supply security. The overcapacity of factories affects the profit of RHIM because the factories have high fixed costs that could have been saved by a better facility network design (FND). Moreover, the demand volumes are growing in developing countries, but are almost flat in the Western hemisphere. The production network has to be adapted to better fit the demand of developing countries. Furthermore, variable costs of factories can decrease due to a higher efficiency as the production amount per factory is increasing. RHIM used to fix the problem partly by focusing demand on certain factories and mothballing some factories for an undefined period of time. The mothballed factories restart when the demand is high enough or another factory has long-term manufacturing problems. However, the thesis should aim to explore the FND of RHIM extensively to fully address the problem. The thesis should overview the entire supply chain on a long term base. It will identify which factory locations should remain, expand or close. The facility network redesign (FNR) options will be included simultaneously in the optimization of the supply chain because FNR needs extensive planning. For accurateness the problem focuses on the entire supply chain at detailed level of bill of materials (BOM).

Analyses

The supply chain structure of RHIM should be understood to solve the described problem. The factories exist out of three pieces of equipment; mixers, presses and kilns. The mentioned sequence of equipment has to be conducted to produce a product. At the kilns BOMs can be chosen to produce the demanded finished goods. The presses choose BOMs to produce the semi-finished goods necessary for the kilns. The mixers choose BOMs to produce the necessary mixtures for the presses or the suppliers and raw material plants (RMPs) deliver directly the mixtures or raw materials to the presses. The material flow is very complex and the human mind is not able to choose the cheapest sequence of BOMs. Especially, if the capacities of suppliers and equipment are taken into account. That is why multi-level configurable BOMs should be included in the FNR. This project is a strategic management study to maximize the profit of FNR problems. The research question is:

What is the most profitable and robust FNR for RHIM taking the multi-level configurable BOMs into account?

The scope of the research is important for answering the main research question. The problem is a capacitated dynamic multi-commodity multi-echelon FNR.

- **Dynamic**: the FNR model makes use of time steps of one year. The time horizon of the model is 5 years, which is equal to the horizon of the business plan of RHIM.
- **Multi-commodity**: RHIM sells finished goods, mixtures and raw materials. The sales of raw materials and mixtures are not included in the scope of the research. The demand of finished goods can be assigned to six main product group (MPG) levels, which are A, B, C, D, E and F. The capacities of factory kilns are indicated with these MPG levels. On basis of the factory kilns the following division can be made: A/B, C/D and E/F. This thesis is focused on solving the A/B group.
- **Capacitated:** the RMPs have a capacity per MPG. The suppliers and factory mixers have an unlimited capacity. The factory presses have a limited capacity, but are not bounded to an MPG. The factory kilns have a capacity and are bounded per MPG. One of the factories is able to produce MPG A and C products in the same kiln. The yearly planned used capacity for MPG C in this factory is subtracted from the factory's capacity.
- **Multi-echelon:** the used echelons in the FNM are suppliers/RMPs, production factories and customer zones. The model includes 5 factories and Purchase China. Purchase China is a supplier of finished goods that is treated in the model as a factory of RHIM. Purchase China is given unlimited capacity, zero fixed cost and zero conversion cost.

This thesis includes a mathematical model for solving the research question. The mathematical model is solved with the program Gurobi. After running the model the following optimal redesign solution is recommended. Firstly, factory 5 has to be closed from the beginning of the model. Secondly, from the beginning 3 presses and an MPG B kiln have to be added to factory 1 and in the third year an extra press has to be added. Thirdly, from the beginning an MPG A kiln and 6 presses have to be added to factory 2. Fourthly, from start onwards an MPG B kiln has to be added to factory 4. After the network redesign the production flexibility is still high. Factory 3 has in every time period at least 78.1 percent of free capacity at the presses and kilns for the production of MPG A and B products. Moreover, Purchase China is able to produce as well more products of MPG A and B.

To test the robustness of the optimal solution, several scenarios are tested that can have an influence. The first scenario is analyzing the model with and without FNR options. The redesign decision of closing facilities delivers 43.8 million euro and the investment decision in kilns and presses delivers 52.7 million euro. The increase in profit is higher than the total investment cost, which in reality is spread out over 30 years for kilns and 8 years for presses. The second scenario is to analyze if the demand has to be fully served, because the consequences of not serving demand cannot be accurately estimated. Switching to a fully served demand model does not influence the optimal solution nor the served demand of the model. The model does not serve a negligible amount of demand, when the redesign option to invest in kilns and presses is excluded. The third scenario contains a situation with a yearly demand increase of 20 percent and a situation with a yearly demand decrease of 20 percent. Only in the situation of demand increase the optimal solution changes, but the extra redesign decisions in the form of adding presses and kilns do not justify the increase of profit. The fourth scenario analyzes the influence of sourcing cost on the optimal FNR solution. Changing the sourcing costs of suppliers with a 10 percent increase and decrease, had the biggest impact on the production quantity of Purchase China, which is fully dependent on suppliers. The last scenario is possible duty rate changes after closing factory 5. Even doubling the current duty rates on products to North America does not influence the optimal FNR solution.

Recommendations

The analyses have resulted into 4 recommendations for RHIM. Firstly, perform the FNR decisions that are recommended at time period t = 0. This means that factory 5 has to be closed from the beginning. Moreover, from the beginning 3 presses and an MPG B kiln have to be added to factory 1. Furthermore, from the beginning an MPG A kiln and 6 presses have to be added to factory 2. Besides that, from start an MPG B kiln has to be added to factory 4. Every year the FNR model has to be runned to determine the best redesign decisions for that year. An important note is to yearly update the parameter data. Secondly, RHIM should not be too dependent on Purchase China in the future. When suppliers change the material sourcing costs, the influences are mostly visible in the production allocation of Purchase China. Thirdly, RHIM uses cost minimization for decision making because RHIM expected that every product demand is profitable. However, the thesis shows that if the FNR model is only allowed to close a factory, then the FNR model did not serve all demand. So, the company should take profit maximization into account for the decision making. Lastly, experts of RHIM think that the use of multi-level configurable BOMs deliver extra profit and accurateness and should be taken into account in yearly production allocations as well.

Preface

This report is my graduation project for the master Operations Management & Logistics at the Technical University of Eindhoven. This report would not have been established without the support of experts in the field of facility network optimization. That is why I want to thank the following experts:

First of all, I would like to thank my company supervisor ir. B. Kersten from RHI Magnesita. Ir. B. Kersten has a lot of knowledge about facility network optimization. In a short moment of time ir. B. Kersten is able to analyze the correctness of the decisions of a facility network model. Moreover, the position of ir. B. Kersten enabled me to have a broad and quick access to the necessary data for the project. Besides that, within the company I am supported extensively by multiple persons, which helped me to solve sub-problems that have led to solving the bigger picture. The opportunity to discuss problems with multiple persons made it possible to understand the problem and to put the pieces of the puzzle together.

Furthermore, I would like to thank my first supervisor dr. A. M. Florio from the Technical University of Eindhoven. Dr. A. M. Florio became my first supervisor halfway during my graduation project. Dr. A. M. Florio supported me and gave advise without limiting my research view. I would also like to thank my third supervisor dr. J. Kinable from the Technical University of Eindhoven. Dr. J. Kinable started the graduation process as my first supervisor. Unfortunately, dr. J. Kinable made a job transition, which changed his supervisor ranking. Dr. J. Kinable supported me during the master and halfway through the graduation project. Lastly, I would like to thank my second supervisor dr. V. Lurkin from the Technical University of Eindhoven. Dr. V. Lurkin supported me with feedback and guidance during the project.

Job van Gangelen

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List of Abbreviations

BOM = Bill Of Materials
CDMMFLP = capacitated, dynamic, multi-commodity, multi-echelon facility location problem
FLP = Facility Location Problem
FND = Facility Network Design
FNM = Facility Network Model
FNR = Facility Network Redesign
RHIM = RHI Magnesita

1 Introduction

This master thesis report starts with an introduction to get familiar with the research domain and the company in which the thesis is conducted. The report provides a strategic management study. The study aims to maximize the company's profit by performing a facility network redesign including multi-level configurable bill of materials (BOM). The thesis is performed at RHI Magnesita (RHIM) in Rotterdam (The Netherlands).

1.1 Company description and business context

Two years ago, RHI and Magnesita merged to become the global market leader in refractory products. Refractory products are defined as products that are used in high temperature industrial processes that have to withstand temperatures of 1200 degrees Celsius and beyond. The purpose of the product is to protect production equipment against mechanical, thermal and chemical stress. Examples of production equipment are furnaces and kilns. A refractory product should secure that materials are contained safely as the materials are melted, fired, shaped or burned (RHI Magnesita, 2019c). RHIM has more than 100 facilities around the world (figure 1). Furthermore, RHIM is focused on innovation to be the best refractory product supplier. Moreover, RHIM is known in the market for the broadest range of products and the best supply and quality security in the production market for steel, glass, cement and copper. The best supply and quality security can be partly arranged through the vertical integration of all the processes from mining to production and from installation to recycling of the products. Figure 2 is provided to give an overview of the manufacturing process of RHIM. The company has in total 14,000 employees that serve over 14,000 customers (RHI Magnesita, 2019a).

Figure 1: Locations of facilities around the world (RHI Magnesita, 2019c)

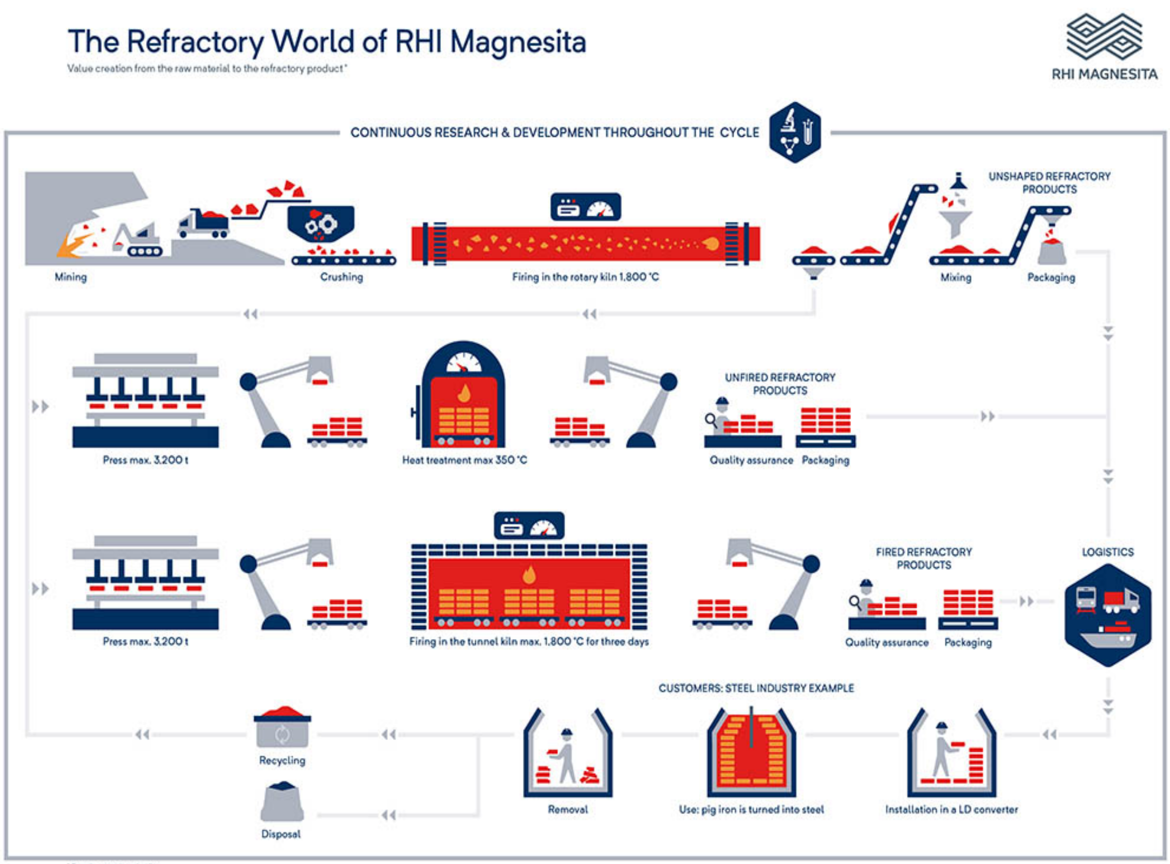

Figure 2: Manufacturing process of RHIM (RHI Magnesita, 2019b)

1.2 Problem identification

The problem RHIM is facing is the inability to optimize its complex facility network. RHIM has strong reasons to believe that their facility network can be optimized. Since the merge, the capacity of RHIM's production factories is too high for the obtained yearly global demand. The reason is that clients desire to have two suppliers for supply security. So, before the merge clients would have had RHI and Magnesita delivering the refractory goods, but to prevent problems the clients have searched for another supplier to assure supply security. The overcapacity of factories affects the profit of RHIM, because the factories have high fixed costs that could have been saved by a better facility network design (FND). Moreover, the demand volumes are growing in developing countries, but are almost flat in the Western hemisphere. The production network has to be adapted to better fit the demand of developing countries. Furthermore, variable costs of factories can decrease due to a higher efficiency as the production amount per factory is increasing. RHIM used to fix the problem partly by focusing demand on certain factories and mothballing some factories for an undefined period of time. The paused factories restart when the demand is high enough or another factory has long-term manufacturing problems. However, the thesis should aim to explore the FND of RHIM extensively to fully address the problem. The thesis should overview the entire supply chain on a long term base. It will identify which factory locations should remain, expand or close. Moreover, the allocation of each factory will be identified as well. The facility network redesign (FNR) options will be included simultaneously in the optimization of the supply chain because FNR needs extensive planning. For accurateness the problem focuses on the entire supply chain at detailed level of BOM. Yan et al. (2003) state a BOM as: "Generally, BOM can be described as a hierarchical product structure that specifies the quantity and lead time of each item, ingredient, or material needed to assemble, mix, or produce the end product" (p. 8). The BOM in context of RHIM specifies only the quantity of each material needed to mix, assemble or produce the end product.

1.3 BOM structure

This section explains why the BOM has a major influence on the FNR of RHIM. The customer demand is manufactured in the production factories of RHIM. The production factories include the following pieces of equipment; mixers, presses and kilns. The equipment in the production factories make use of multi-level configurable BOMs. Multi-level BOM means that at each equipment in a production factory a BOM can be chosen. Moreover, configurable BOM means that at each equipment can be chosen between multiple BOMs to produce a finished good, semi-finished good or mixture. The BOM structures can be separated into two variants. One variant is for the finished goods and includes three levels of configurable BOMs (figure 3). The other variant is for mixtures and includes only one level configurable BOMs (figure 4). The possible material flow for finished goods is explained in figure 3. The finished goods can be produced in multiple production factories. In a production factory the realization of the finished good is established by the sequence of three pieces of equipment. The sequence is mixer, press and kiln. If a production factory is assigned to produce a certain number of a finished good then at the kiln one or more BOMs have to be chosen. The choice at the kilns determines the necessary material flow from the presses. The presses have to produce the necessary material for the kilns and therefore need to choose one or more BOMs to realize the semi-finished good. The mixers need to deliver the necessary mixtures for the chosen BOMs at the presses. The mixers can choose one or more BOMs to produce the necessary mixtures. The materials that belong to the chosen BOM or BOMs have to be delivered by the suppliers and raw material plants (RMPs). The possible material flow for mixtures is shown in figure 4. In a production factory one or more BOMs can be chosen to make the mixture at the mixers. The necessary material for the BOM or BOMs can be delivered by suppliers and RMPs. The blue arrows in figure 3 and 4 are presenting unfinished material flow possibilities.

The possible material flow structures provide insight that products can be manufactured on multiple ways. The BOM choice and the inherent material flow have influence on used capacities of the equipment in the production factories. Each equipment in the production factory has different types that are able to make a certain group of mixtures/semi-finished products/finished products. So, the capacity of one equipment type can be fully addressed, but the finished product, semi-finished product or mixture can still be made by choosing a different BOM at an equipment in the production factory. This means that FNR decisions can change by taking the BOM choices into account. Lastly, the multi-level configurable BOMs determine the used materials. This is for RHIM very important because the material costs are 70 percent of the total cost and the supply of materials is limited.

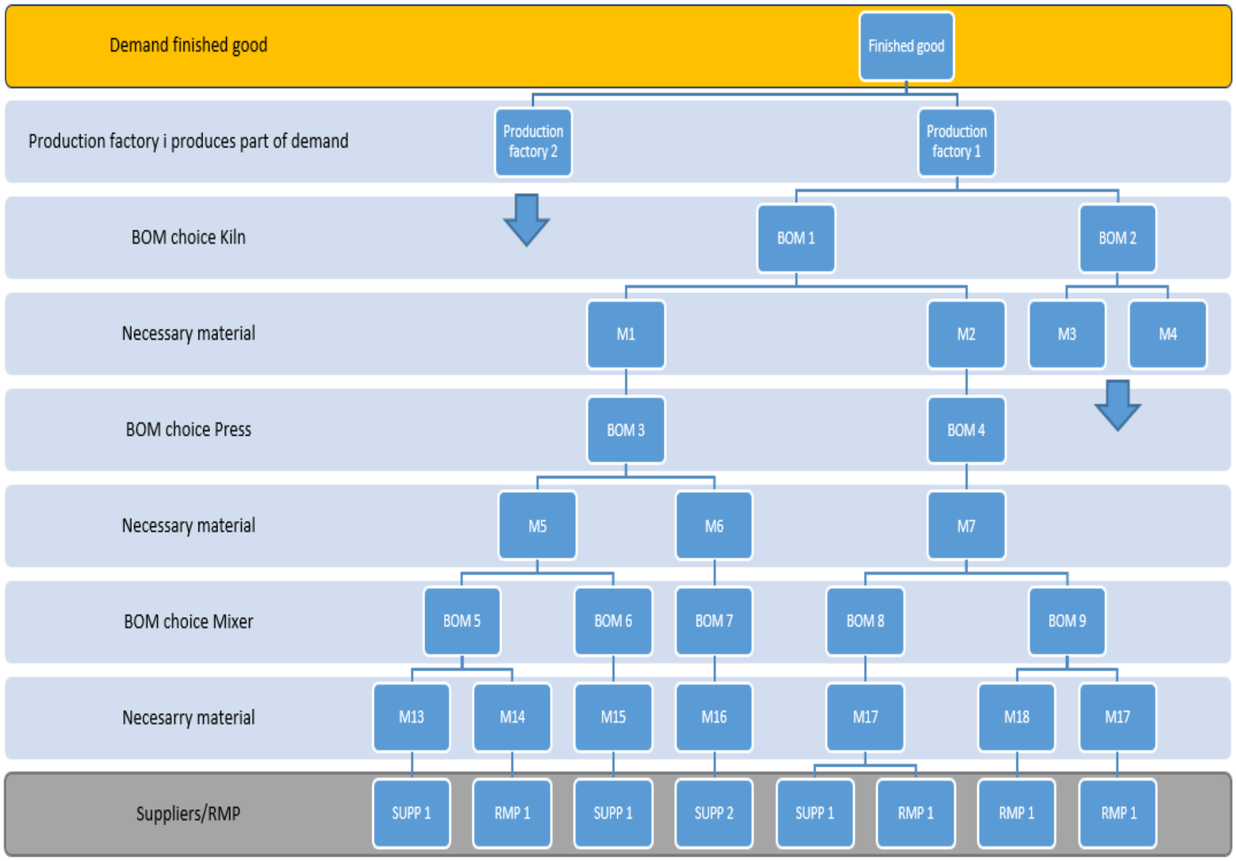

Figure 3: BOM structure for finished goods

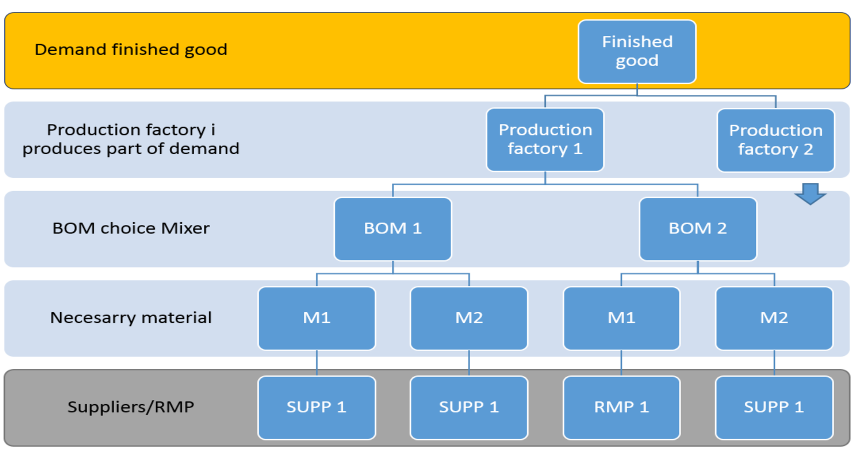

Figure 4: BOM structure for mixtures

1.4 Research goal

This research aims to assist industries that have multi-level configurable BOMs with their facility network design to maximize profit. The research is focused on strategic decisions. The research goal can be defined as:

To develop a mixed integer linear mathematical model that redesigns the facility network to maximize the profit taking the multi-level configurable BOMs into account. This model should find simultaneously the design of the facility network and the served demand to maximize the profit taking into account the facility redesign options, demand, product & supply chain characteristics and costs on a long-term view.

The model should help the management of the organization with the strategic decisions. The model can be valuable for the following strategic network decisions; the model provides information about how to redesign the facility network; the model provides the sales department with information about which demand should be served and from which location.

1.5 Scope of the research plus limitations

The scope of the research is determined by the problem description and the goal of the research. The scope of the research:

- **Multi-commodity**: RHIM sells more than 120,000 products, these products can be classified as finished goods, mixtures and raw materials. The sales of raw material is not included in the scope of the research because the sales of raw material has only influence on the capacity of the mixers. Besides that, the corporate policy is to only use excess capacity for the sales of raw materials and not to invest for the sales of raw material. The customer demand of mixtures is also not taken into account, because the capacity of mixers is not taken into account in the facility network model (FNM). The reason is that the capacity and investment cost of mixers is irrelevant in comparison to other equipment (table 1). The finished goods are assigned to a product group in combination with an application number. The structure of the product data is shown in figure 5. Every product can be aggregated to a product group (PG) and every product group can be aggregated to a main product group (MPG). The demand of finished goods of RHIM can be assigned to six MPGs, which are A, B, C, D, E and F. The capacities of factory kilns are indicated with these MPGs. On basis of the factory kilns the following division can be made: A/B, C/D and E/F. This thesis is focused on solving the A/B group, but the methodology to solve the FNR problem is the same for each MPG group. The A/B group is chosen to be solved, because this group's capacity is least influenced by the production of other MPG groups and the research has to be conducted in a limited time period. Only the kiln at factory 5 is able to produce MPG A and C in the same factory.

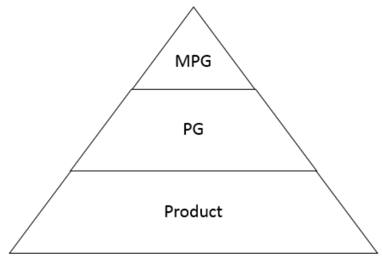

Figure 5: Product structure

Equipment	Capacity in ton	Investment in million euro
Mixer	1,000,000	0.5
Press	10,000	2-4
Kiln	35,000 - 100,000	2-12.5

Table 1: Extensions of equipment at a factory

- **Capacitated:** the production factories can be delivered by RMPs and suppliers. The RMPs have a capacity per MPG. The suppliers have an unlimited capacity. In the production factories the mixers have unlimited capacity. The presses have a limited capacity, but are not bounded to an MPG. Presses have certain pressing power that determines the production capacity of the press. If the press power is high then the press is able to produce multiple shapes at once. Moreover, a few products need a special shape, which cannot be performed by every press. However, in general presses are able to produce all products. That is why the model does not make a difference between presses. The kilns have a capacity and are bounded per MPG. There are two types of kilns. The first one is a temper kiln and the other one is a tunnel kiln. The tunnel kiln is firing products at 1400 to 1840 degrees Celsius and a temper kiln is firing the products at 250 to 350 degrees Celsius. The kiln in factory 5 is able to produce MPG A and C in the same kiln. The yearly planned used capacity for MPG C in factory 5 should be subtracted from the factory's capacity and the inherent fixed cost should be subtracted from the total fixed cost. Otherwise, it would not be possible to make an FNR for the A/B group. The yearly subtraction of capacity is possible due to a relatively constant demand of products.

- **Customer zones:** the demand of each customer is aggregated to 11 zones. The following zones are possible: India, Europe, CIS (Commonwealth of Independent States), China, Central America, Near and Middle East, Asia others, Africa, Turkey, South America and North America. The customer zones represent the demand of each product within a zone. The customers zone aggregation makes the FNM less complex, but also less accurate.

- **Multi-echelon:** RHIM has a fully integrated vertical supply chain. The facility network of RHIM includes the following entities; suppliers, mines, RMPs, production factories, warehouses and customers. At a mine is an RMP located to process the mined material. Suppliers and RMPs can deliver materials to the production factories. From the production factories the products are transported to customers across the world. A simplified version of the supply chain is visible in figure 6. The used echelons in the FNM are suppliers/RMPs, production factories and customer zones. The FNM does not include mines, because mines are only able to be located at areas with rich amount of materials in the ground. The warehouses are also missing in the FNR, because the network design of warehouses is a tactical decision in manufacturing industries. The reason is that warehouses do not have a direct influence on the manufacturing capacities of facilities, and warehouses are relatively cheap in comparison to production factories. Lastly, the model does not make use of fixed relations between certain suppliers/RMPs and production factories or certain production factories and customer zones. Moreover, Purchase China is included in the model, which is a supplier of finished goods that is treated in the model as a factory of RHIM. To be clear the factory does not belong to RHIM. Purchase China is given unlimited capacity, zero fixed cost and the conversion cost is as well zero. The other factories or purchase plants are not included in the model, because these factories/purchase plants are not able to produce MPG A or B products or only able to produce MPG A or B products that are not demanded.

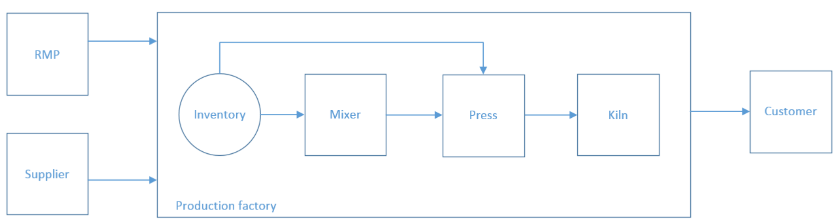

Figure 6: Simplified RHIM supply chain

- **Dynamic**: the FNR model makes use of time steps of one year. The time horizon of the model is 5 years, which is equal to the horizon of the business plan of RHIM. The business plan includes among other things the company strategy and investment plans. The business plan does not exceed 5 years, because new products and technologies make decisions for more than 5 years inaccurate. The model uses yearly time steps because the model assumes that the demand of every product is stable. The demand of every product is stable during the year except the demand of cement. The demand of cement has a peak at the end and beginning of the next year (Nov-Feb). The FNR model uses the products of MPG A and B, which does not include the product cement. So, the FNR model makes use of stable demand.

- **Facility network redesign options:** the model is capable of redesigning the facility network with the following options: closing a production factory or capacity expansion of presses and kilns. The FNM assumes that a production factory cannot be reopened in the planning horizon. This assumption is validated due to the short time horizon and high costs of closing and opening a facility. For the capacity expansion option is assumed that production factories can only expand the production capacities of products they can produce. So, investment in an extra press or different kiln will not generate possibilities to produce a bigger variety of products. This assumption is based on the fact that the production of each product requires specific knowledge, know-how and possible extra equipment to finalize the product.

- **Duties:** for international companies duties are an important aspect of network optimization. A different production allocation can increase or decrease the amount of paid duties. The duty fee is zero percent if a factory delivers within the customer zone it is located. The model assumes certain duty rates for transferring a product from the factory to another zone. In reality, the duties are varying between countries and per product. However, the use of customer zones does not make it possible to use duty rates per country.

1.5.1 Uncertainties and limitations:

- **Customer zones:** the production factories of RHIM are not able to produce the same level of product quality. The product quality has influence on the lifetime of the product. The company prefers to deliver an order only by one or two factories, to prevent too early or late replacement of products. Due to the use of customer zones it is not possible to constrain the amount of delivering production factories. On the other side, this problem is more a tactical decision problem. After satisfying all demand in a customer zone, another model can be written to maximize the amount of served orders by single production factories.

- **Sales prices:** are given in euro per ton per product per customer zone. RHIM has to deal with a lot of Incoterms. The Incoterms determine the requirements, responsibleness for the transportation and tax payment. The Incoterms have influence on the selling price of a product. To generalize the model the Incoterms are not taken into account in the FNM. The model uses the weighted average price of a product per customer zone based on RHIM sales data from the year 2018/2019. The assumption is that the distribution of used Incoterms will be equal in the following time periods and the sales price of a product grows equally to the growth of the product cost. This means that the increased costs due to suppliers or raised energy bills are added to the sales prices of the product. This is uncertain, because the product prices are also dependent on the demand of the product in combination with selling prices of competitors.

- **Transportation cost:** is expressed as the price per ton for the transport from a production factory to a customer zone. The limitation is that the cost of transportation is similar for every product. Moreover, the transportation cost is not from door-to-door, but the cost is from the production factory to a customer zone. The transportation cost within the customer zone is not taken into account in the FNM. The cost of transportation within the customer zone is too complex to take into account. However, the transportation cost within the zone is low in comparison to the total transport cost and the Incoterms determine if it is paid by the customer or RHIM.

- **External influences and qualitative factors:** the FNR model does not take into account external influences and qualitative factors. The model has only included cost factors. However, factors as political environment, working culture and innovations or behavior of competitors are not implemented in the model. In the future RHIM can be heavily punished by governments for being a polluting industry. The amount of pollution taxes are different per country.

- **Capacities:** the suppliers have unlimited capacity in the model, which is a limitation. Furthermore, the capacity of mixers in production factories is not taken into account in the model. In reality mixers have a limited capacity and a certain amount of storage silos is necessary to produce a mixture. The equipment in the production factories can switch multiple times between BOMs, due to negligible switching times between BOMs. It is unclear if a production factory has enough silos or can place more silos to be able to switch endlessly between all the configurable BOMs. However, in general every production factory has an extensive number of silos.

1.6 Research question

The main research question is based on the problem description, systematic literature review, research goal and the other above mentioned sections:

What is the most profitable and robust FNR for RHIM taking the multi-level configurable BOMs into account?

In this research the term profit is defined as the sales price of a product for a certain customer zone minus the duty, sourcing, transportation, fixed and conversion cost. The FNR should be robust. With the aid of scenarios, the optimal FNR solution is tested on robustness and if necessary adapted.

1.6.1 Sub-research questions

The sub-research questions help to answer the main research question. The sub-research questions should be executed in the given sequence.

1. What scope and limitations should be taken into account in the FNR model of RHIM?

2. What is the mathematical model for the FNR of RHIM? How to implement the multi-level configurable BOM in the mathematical model?

3. What kind of data analyses should be conducted to check if the multi-level configurable BOM constraints can have influence on the FNR problem?

4. What scenarios have to be analyzed to check the quality of the optimal FNR solution? What is the influence of the scenarios on the FNR solution?

The last sub-research question is answering the research question.

5. What is the most profitable and robust FNR for RHIM taking the multi-level configurable BOMs into account?

2 Literature review

This chapter summarizes the highlights of the performed systematic literature review. The systematic literature review is focused on finding the theoretical basis of the research topic. This chapter starts with a general description of a FNR problem. Afterwards, a general description of BOM and the use of BOM in FNR problems is mentioned. Next, the suitable FNR problems are described, and a suitable FNR problem fits the scope of Section 1.5. Lastly, the possible objectives of FNPs are presented. The objective determines the results and should be linked to the problem description. Lastly, the literature gaps are explained, which emphasize the importance of conducting this research.

2.1 Facility network redesign problem

Min and Melachrinoudis (1999) summarize an FNR as a long-term view of the company and commitment to certain facilities. Moreover, Frantzeskakis and Luss (1999) conclude that an FNR model tries to design a network that serves existing and new demand in an optimal way. According to the research of Razmi et al. (2013) FNR is getting more important due to globalization. This research concludes that an FNR should take into account the current constraints, situations and properties to find the smoothest possible transition from the current state to the prospected optimum state. An FNR can result into savings in inventory, transportation, management costs and better capacity utilization rates. An FNR is interesting for merging companies, extending demand to new geographical areas, obsolete locations or demand changes (Thanh et al., 2008). In figure 7 a possible FNR solution is shown. Furthermore, Min and Melachrinoudis (1999) analyzed two ways of solving an FNR problem; the first tool are linear programming techniques; the second tool are scoring methods such as the analytic hierarchy process. A programming technique is preferred when no dominant solution exist. A programming technique is solving a linear problem with a solver. The scoring method is preferred for managers with a limited technical background and for small scale network problems with a lot of intangible factors. An intangible factor is subjective and difficult to take into account in a programming technique.

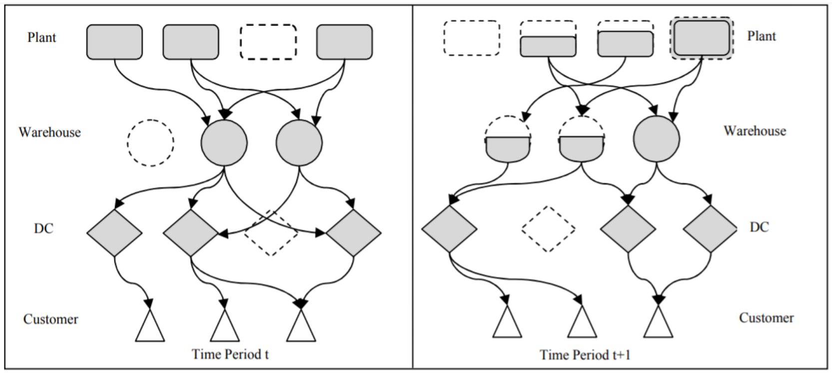

Figure 7: FNR (Behmardi and Lee, 2008)

2.2 Bill of materials

Yan et al. (2003) state a BOM as: "Generally, BOM can be described as a hierarchical product structure that specifies the quantity and lead time of each item, ingredient, or material needed to assemble, mix, or produce the end product" (p. 8). Vidal and Goetschalckx (1997) conclude that BOM is an important part of network optimization and should be investigated more. Moreover, the research of Schmidt and Wilhelm (2000) emphasize that the BOM choice of a layer has influence on the BOM choice in the predecessors. This research is related to FNPs and provides a technique to understand the structure of BOMs. This technique represents the BOM of a product with an assembly tree. Every layer of this assembly tree represents nodes that form together the BOM of the successor in the tree. The tree consists out of layers, predecessors and successors. The tree represents the sequence of components that have to be arranged to realize the final product (Schmidt and Wilhelm, 2000).

Yan et al. (2003) try to understand the influence of BOM choices in an FND to an extended level. Many interactions of BOM in a facility network can be explained with logical constraints. Yan et al. (2003) implement the following logical constraints: "if at least p of the proposed producers are open, then at least q of the candidate suppliers should be chosen" (p. 6) and "if product i will be produced in at least s of the proposed producers, then at least t of the candidate suppliers should be selected to supply the material m according to the BOM" (p.6). The logical constraints are translated into a BOM constraint, which is shown in figure 8. The constraint means that the suppliers have to deliver an amount of material m at producer k that should be bigger or equal than the total amount of material m that is necessary to fulfill the product production at factory k. This constraint is valid for every producer k and material m. The research of Wang et al. (2012) has taken the BOM into account for a well based material requirement planning. A multi-period model that includes BOM is capable of analyzing the capacity of vendors. The analysis can determine if a BOM should be chosen to fit with the supply capability of the network. The model of Wang et al. (2012) make use of a BOM constraint. The constraint ensures that the vendors are capable of delivering the materials.

$$\sum_{i,l} F_{ikl} R_{mi} \leqslant \sum_{j} G_{mjk} \quad \text{for} \quad \text{all} \quad k, m$$

Figure 8: Constraint for BOM (Yan et al., 2003)

2.3 Suitable facility network problems

Former researchers have solved capacitated, dynamic, multi-commodity, multi-echelon facility location problems (CDMMFLPs). A CDMMFLP in combination with BOM is only mentioned once in the literature. The model of Thanh et al. (2008) is closest related to the FNP of RHIM by including the possible capacity extension and BOM. This model is as well extended with a separation between hiring and buying facilities. In this extension is assumed that a hired facility can be closed at every time period and has only variable costs. In contrary, a bought facility cannot be closed in the time span of the model. The bought facilities have fixed and variable costs. The variable costs of the facilities are higher in the option of hiring a facility than buying a facility. The model's BOM inclusion represents only one BOM per product at one echelon. The model of Thanh et al. (2008) has as well the assumption that suppliers will give discount for larger orders. This assumption is modeled with a minimal and maximal utilization rate of facility capacity. The below mentioned researches are suitable FNPs, but did not include the BOM.

Wilhelm et al. (2013) modeled the CDMMFLP with the extension of possible downsizing and expanding capacity of a facility. The model extension of expanding and downsizing capacity of facilities provides more flexibility and less expensive options to serve the demand. Capacity flexibility is desired due to changing variables over time. Important changing cost variables are wages, crossing fees, local content rules or tariffs in countries around the world (Wilhelm et al., 2013). Flexibility is especially desired for facilities with expensive operations as cooling, heating, taxes, insurances or the security of processes or products. Facility capacity expansion can be less costly than opening new facilities due to already existing equipment, infrastructure, employers and/or government licenses for authorization.

Behmardi and Lee (2008) extended the CDMMFLP with the resources and time loss after a relocation of a facility or capacity and the option for reopening a facility. The cost of opening and reopening can be different for example due to facilities that are obnoxious or where environmental studies about impact are already conducted (Dias et al., 2007). Production capacities are not available during a facility or capacity relocation because it takes time to transfer capacity or a facility. Thanh et al. (2008) use a maximal rate of capacity utilization in the opening period of a facility after relocation.

Melo et al. (2006) have added inventory opportunities for goods, storage limitations and relocation of facilities and capacity to CDMMFLPs . Melo et al. (2006) have modeled a budget constraint instead of a maximum number of relocated facilities per time period. This budget constraint will ensure that the amount of opened, relocated and closed facilities is limited. A maximum vacating constraint is realistic because facility redesigns involve time and costs. Additionally, Melo et al. (2006) made the assumption that after a capacity transition the capacity cannot be changed in the next time periods. The assumption increases scalability of the problem size by limiting the amount of possible decision variables and provides stability for the facilities.

Miranda and Garrido (2008) extended the CDMMFLP by changing the capacity variable from deterministic to a stochastic variable. The research of Aghezzaf (2005) extended the CDMMFLP by changing the demand variable from deterministic to a stochastic variable. The extended models do not find the optimal solution with the minimum cost for a certain demand or capacity. However, each model searches for the solution that is the least expensive to adapt to any highly expected capacity or respectively market demand outcome. The demand and facility capacities are variables that can be uncertain in reality. Some markets are volatile and facilities can have breakdowns.

Hinojosa et al. (2000) have obtained the CDMMFLP solution via Lagrangian relaxation in combination with a heuristic. The goal of this method is to obtain a feasible solution of the initial problem via the lower bound solutions gained with the Lagrangian relaxation of the linear model. Moreover, Hinojosa et al. (2000) have added a constraint to the model that at least N facilities need to be open at time period T to prevent that facilities will be sold or closed to save cost in the last time period. In this model it is assumed that once a location is closed it cannot be opened again and an opened facility cannot be closed in the time span of the model. The authors have reasoned that customers get used to certain regularity with a specific facility, when this location is closed a certain market share can disappear.

2.4 Facility network problem objectives

The majority of the reviewed research papers are focused on the minimization of direct and indirect costs for allocating all the customers. However, according to Zhang (2001) is an FLM with a cost minimization objective not valuable. The obtained solution will be one-side oriented. The FLP objective determines the strength of the optimization solution. An FNP with a profit maximization objective can result in beneficial managerial insights. The constraint of ensuring that all demand will be served has to be dropped to strengthen the value of a profit maximization objective.

The research of Zhang (2001) provides a multi-objective model that takes profit maximization and competition into account. This model determines the price of the product and the location of the facilities to achieve the maximum profit. This determination is based on reservation prices. A reservation price is the maximal price a customer is willing to pay, otherwise the customer will go to another supplier. A multi-objective model delivers more flexibility and can be more representative for reality (Farahani et al., 2010).

The research of Brimberg and ReVelle (1998) provides interesting managerial insight with a bi-criterion model. The multi-level objective is a combination of maximizing profit and the served demand. The interesting managerial insights will arise through the assumption that not all demand have to be served. Myung et al. (1997) conclude that profit maximization is the same as a cost minimization as the demand has to be fully fulfilled. Besides that, the multi-objective will deliver efficient solutions. Efficient solutions are solutions that are Pareto efficient. Multiple Pareto efficient solutions can exist. A decision maker will choose the preferred solution from the efficient solutions.

2.5 Research gaps

The literature review showed that an FNP in combination with BOM is not a widely investigated topic. However, the literature emphasized that the BOM should be involved in FNPs, because the BOM influences the material requirement planning. The importance of including BOMs for strategic management increases for production industries. Production industries that have multi-level configurable BOMs can influence their material requirement planning in such a way that FNR decisions can be changed. To conclude, the effects of multi-level configurable BOMs in an FNP are interesting and should be more investigated.

3 Data analyses

The data contains 5 factories and Purchase China. The factories are numbered 1 to 5 instead of location names. The reason is that the locations of the factories in combination with a potential closing can be interesting for competitors and misleading for employees of RHIM. The below mentioned products are described with an X and a number. In total are six products mentioned in this chapter which are 'X 1', 'X 2', 'X 3', 'X 4', 'X 5' and 'X 6' .

An important part of the data analyses is to check if all the material flow options are possible. This chapter analyzes step-wise the material flow possibilities. Firstly, is it possible to produce each demanded product at a factory? All the demanded products can be produced in at least one of the included factories. In table 2 is shown which 6 products can be produced in only one factory. It is important to minimize the number of products that can be produced in only one factory. Otherwise, a model that has to serve all demand is not able to close any factory. The products 'X 5' and 'X 6' can only be delivered by Purchase China. This is not a problem for the allocation of demand, because Purchase China is a supplier. In the model Purchase China is treated as a factory with zero fixed costs. A factory with zero fixed costs will never be closed in an FNR model. Moreover, these products have as well a low demand and the model is not obligated to serve all demand. The other four products of table 2 are made in a factory that can be closed. This demand will not be served if the factory closes. However, after running the model the unserved demand can be analyzed to check if it can be assigned to another factory with minor adaptions in the production line.

Secondly, the BOM analyses at the kilns of the included factories. After analyzing the input data, factory 5 is able to produce 3 products from which the factory's kiln does not have a BOM for production. Factory 2 and Purchase China are able to produce all 3 products. However, factory 2 is the only factory owned by RHIM that is able to produce all 3 products. That is why factory 5 is able to use the BOMs of factory 2 for these products. Now, all factories have at least one BOM at the kilns to produce all the applicable products. Applicable products are products that are able to be produced in a factory. Purchase China is modeled as a factory with infinite capacity. The model makes use of the assumption that at Purchase China the BOM of a product exists out of the product itself with a ratio of one. This step is repeated for the press and mixture phase.

Thirdly, the BOM analyses for the presses at the factories. Factory presses that do not have BOMs for the necessary material at the kilns are filled up with a BOM for the same material of a comparable factory. Not every material from the BOM at the kilns has to be processed in the presses and mixtures. The data set does not contain a BOM for these material in any of the factories. These products can be seen as products that facilitate the process of making a finished good at the kiln. That is why there is assumed that if the BOM of a material does not exist, the BOM exists out of the material itself with a ratio of one. The material can be sourced in the next phase. This is only applicable to two materials. So, this will affect the capacity of the presses negatively, but not in an amount which is worth mentioning.

Fourthly, the BOM analyses of the mixers at the factories. The required material for the presses at the factory can be delivered by mixers or directly by suppliers. The data input has to include at least one BOM or supplier that is able to deliver the necessary material at the presses. Missing BOMs at the mixers are filled up with BOMs of similar factories. A similar factory is a factory that is located the nearest to the missing BOM factory. If no factory has a BOM for the necessary material and there is no supplier able to deliver the material, then the material sourcing cost of a supplier to a nearby factory is used as sourcing cost.

Lastly, the necessary material for the BOMs of the mixers at each factory need to be delivered by at least one supplier. If no supplier is able to deliver the material, then the material sourcing cost of a supplier to a nearby factory is used. Moreover, the sourcing costs are checked on low and unrealistic numbers. The sourcing costs below 2 euro are deleted, which are 50 material sourcing costs. After the removal the lowest material sourcing cost value is 27.5 euro, which is low but can be reasonable. The material flow possibilities are checked again and the removal of 1 item leads to a material flow error. That is why the material sourcing cost of material RMS to factory 5 is added with a value similar to the RMS sourcing cost to a nearby factory.

Factory	**Product**	**Demand in ton**
Factory 4	'X 1'	3.85
Factory 4	'X 2'	10.44
Factory 4	'X 3'	537.96
Factory 4	'X 4'	98.91
Purchase China	'X 5'	0.0089
Purchase China	'X 6'	1.92

Table 2: Products that can be produced at one factory

4 Mathematical model formulation

The mathematical model is a capacitated, dynamic, multi-echelon, multi-commodity FNR model. The mathematical model is the first FNR model that includes multi-level configurable BOMs. The mathematical model is able to solve all three MPG divisions at once or separately. The objective of the model maximizes the profit by optimizing the facility network design and the served demand. The below mentioned sets are fixed and known from the start of the model.

$$\begin{aligned}
\mathsf{S} &= \text{ set of suppliers}\\
\mathsf{F} &= \text{ set of factories}\\
\mathsf{C} &= \text{ set of customers}\\
\mathsf{P} &= \text{ set of products}\\
\mathsf{B} &= \text{ set of BOMs}\\
\mathsf{L} &= \text{ set of group of products}\\
\mathsf{T} &= \text{ set of time periods}
\end{aligned}$$

The set of suppliers contains the suppliers and RMPs of RHIM. The set of factories contains the production factories of RHIM. The set of customers contains the customer zones. The set of products exists in case of RHIM out of finished goods belonging to MPG A or B. The set of group of products has to be used for capacities of equipment. Multiple different products can be produced on one machine. The group of products that can be produced on one equipment type is indexed with $\mathsf{l} \in \mathsf{L}$. The set of time periods contains 5 time periods. The time horizon is 5 years with annual steps, which is comparable to the business plan structure of the company.

4.1 List of parameters

$$
\begin{aligned}
\mathsf{Price}_{pc} &= \text{sales price of product p per kg for customer c}\\
\mathsf{DEM}^{t}_{pc} &= \text{demand of product p in kg from customer c at time period t}\\
\mathsf{D}_{fc} &= \text{duty rate on demand of customer c delivered by factory f}\\
\mathsf{CS}^{t}_{sl} &= \text{capacity of supplier s for group of products l at time period t}\\
\mathsf{FC}_{f} &= \text{fixed cost of factory f per time period}\\
\mathsf{Q}_{fpbm} &= \text{quantity of material m to make 1 kg of product p with BOM b in factory f}\\
\mathsf{TC}_{fc} &= \text{transportation cost from factory f to customer c per kg of a product}\\
\mathsf{VC}_{fp} &= \text{variable cost of manufacturing 1 kg of product p at factory f}\\
\mathsf{SC}_{sfm} &= \text{sourcing cost of 1 kg of material m for factory f from supplier s}\\
\mathsf{CC}_{f} &= \text{cost of closing factory f}\\
\mathsf{BOM}_{fpb} &= \text{parameter which has the value 1 if factory f is able to produce product p with}\\
&\ \text{BOM b, else the value is 0}\\
\mathsf{CP}_{f} &= \text{capacity of press at factory f per time period}\\
\mathsf{CK}_{fl} &= \text{capacity of kiln at factory f for group of products l per time period}\\
\mathsf{CNP}_{f} &= \text{capacity of new press at factory f per time period}\\
\mathsf{CNK}_{fl} &= \text{capacity of new kiln at factory f for group of products l per time period}\\
\mathsf{FCK}_{fl} &= \text{fixed cost for new kiln for group of products l at factory f per time period}\\
\mathsf{FCP}_{f} &= \text{fixed cost for new press at factory f per time period}
\end{aligned}
$$

The above-mentioned parameters are deterministic because the uncertainty in the market of RHIM is low. A single factory of RHIM is not able to produce every product. Moreover, a factory can produce a product by choosing from a set of BOMs, but another factory is able to produce the same product by choosing from a different set of BOMs. The differences between factories are due to different equipment, knowledge, know-how and different product requirements. The parameter BOM_{fpb} ensures that the required product qualities are validated during the production. This parameter ensures as well that a new kiln or press in a factory cannot result in the production of products that could not be preformed before. The parameters FCK_{fl} and FCP_{f} are the depreciation cost in combination with other fixed costs for new kilns and presses. The total investment for kilns is divided over 30 years and for presses over 8 years. The depreciation is stretched over more years than the time horizon of the model. That is why the optimal FNR solution has to be analyzed to check if the redesign decisions are delivering enough profit to be executed.

4.2 List of variables

PF^t_{fpc} = fraction (regarding to $\text{DEM}^t{}_{pc}$) of product p delivered to customer c from factory f at time period t

K^t_{fpb} = production amount kiln of factory f of product p with BOM b at time period t

P^t_{fmb} = production amount press of factory f for product m with BOM f at time period t

M^t_{fmb} = production amount mixer of factory f for product m with BOM b at time period t

SP^t_{sfm} = amount of product m delivered to the presses at factory f by supplier s at time period t

DS^t_{sfm} = amount of product m delivered to the mixers at factory f by supplier s at time period t

FO^t_{f} = a decision variable that determines if a factory f at time period t is open denoted by 1, or closed denoted by 0

IP^t_{f} = number of invested presses at factory f at time period t

IK^t_{fl} = number of invested kilns at factory f for group of products l at time period t

The variables IP^t_f and IK^t_{fl} are integer variables, because it is not possible to place half a kiln or press in a factory. Moreover, a new kiln or press at a factory cannot be removed in the time horizon of the model. A factory cannot be closed after investing in new kilns or presses. RHIM is not bounded to perform FNR decisions in the first time period. RHIM does not experience much consequences of executing yearly FNR decisions.

Objective:

$$\max \quad \sum_{t\in T}\sum_{p\in P}\sum_{f\in F}\sum_{c\in C}(1-D_{fc})\text{Price}_{pc}\text{DEM}^t_{pc}\text{PF}^t_{fpc} - \sum_{t\in T}\sum_{p\in P}\sum_{f\in F}\sum_{c\in C}\text{TC}_{fc}\text{DEM}^t_{pc}\text{PF}^t_{fpc}$$

$$-\sum_{t\in T}\sum_{p\in P}\sum_{f\in F}\sum_{c\in C}\text{VC}_{fp}\text{DEM}^t_{pc}\text{PF}^t_{fpc} - \sum_{t\in T}\sum_{s\in S}\sum_{f\in F}\sum_{m\in P}\text{SC}_{sfm}(\text{DS}^t_{sfm}+\text{SP}^t_{sfm})$$

$$-\sum_{t\in T}\sum_{f\in F}\sum_{l\in L}\text{FCK}_{fl}\text{IK}^t_{fl} - \sum_{t\in T}\sum_{f\in F}\text{FCP}_f\text{IP}^t_f$$

$$-\sum_{t\in T}\sum_{f\in F}\text{FC}_f\text{FO}^t_f - \sum_{f\in F}\text{CC}_f(1-\text{FO}^T_f)$$

s.t.

$$\sum_{f\in F}\text{PF}^t_{fpc} \leqslant 1 \qquad \forall t\in T \quad \forall p\in P \quad \forall c\in C \tag{4.1}$$

$$\sum_{m\in P}\sum_{b\in B}\text{P}^t_{fmb} \leqslant \text{CP}_f\text{FO}^t_f + \text{CNP}_f\text{IP}^t_f \qquad \forall t\in T \quad \forall f\in F \tag{4.2}$$

$$\sum_{p\in l}\sum_{b\in B}\text{K}^t_{fpb} \leqslant \text{CK}_{fl}\text{FO}^t_f + \text{CNK}_{fl}\text{IK}^t_{fl} \qquad \forall t\in T \quad \forall f\in F \quad \forall l\in L \tag{4.3}$$

$$\sum_{b\in B}\text{BOM}_{fpb}\text{K}^t_{fpb} \geqslant \sum_{c\in C}\text{DEM}^t_{pc}\text{PF}^t_{fpc} \qquad \forall t\in T \quad \forall f\in F \quad \forall p\in P \tag{4.4}$$

$$\sum_{o\in B}\text{BOM}_{fmo}\text{P}^t_{fmo} \geqslant \sum_{p\in P}\sum_{b\in B}\text{Q}_{fpbm}\text{K}^t_{fpb} \qquad \forall t\in T \quad \forall f\in F \quad \forall m\in P \tag{4.5}$$

$$\sum_{o\in B}\text{BOM}_{fmo}\text{M}^t_{fmo} + \sum_{s\in S}\text{SP}^t_{sfm} \geqslant \sum_{p\in P}\sum_{b\in B}\text{Q}_{fpbm}\text{P}^t_{fpb} \qquad \forall t\in T \quad \forall f\in F \quad \forall m\in P \tag{4.6}$$

$$\sum_{s\in S}\text{DS}^t_{sfm} \geqslant \sum_{p\in P}\sum_{b\in B}\text{Q}_{fpbm}\text{M}^t_{fpb} \qquad \forall t\in T \quad \forall f\in F \quad \forall m\in P \tag{4.7}$$

$$\sum_{m\in l}\sum_{f\in F}(\text{DS}^t_{sfm}+\text{SP}^t_{sfm}) \leqslant \text{CS}^t_{sl} \qquad \forall t\in T \quad \forall s\in S \quad \forall l\in L \tag{4.8}$$

$$\text{FO}^0_f = 1 \qquad \forall f\in F \tag{4.9}$$

$$\text{FO}^t_f \geqslant \text{FO}^{t+1}_f \qquad \forall t\in T \quad \forall f\in F \tag{4.10}$$

$$\text{IK}^t_{fl} \leqslant \text{IK}^{t+1}_{fl} \qquad \forall t\in T \quad \forall f\in F \quad \forall l\in L \tag{4.11}$$

$$\text{IP}^t_f \leqslant \text{IP}^{t+1}_f \qquad \forall t\in T \quad \forall f\in F \tag{4.12}$$

$$\sum_{l\in L}\text{IK}^t_{fl} \leqslant 2\,\text{FO}^t_f \qquad \forall t\in T \quad \forall f\in F \tag{4.13}$$

$$\text{IK}^t_{fl} \in \mathbb{Z} \qquad \forall t\in T \quad \forall f\in F \quad \forall l\in L \tag{4.14}$$

$$\text{IP}^t_f \in \mathbb{Z} \quad \text{and} \quad \mathbb{Z}\in[0,6] \qquad \forall t\in T \quad \forall f\in F \tag{4.15}$$

$$1 \geqslant \text{PF}^t_{fpc} \geqslant 0 \qquad \forall t\in T \quad \forall f\in F \quad \forall p\in P \quad \forall c\in C \tag{4.16}$$

$$\text{K}^t_{fpb} \geqslant 0 \qquad \forall t\in T \quad \forall f\in F \quad \forall p\in P \quad \forall b\in B \tag{4.17}$$

$$\text{P}^t_{fmb} \geqslant 0, \quad \text{M}^t_{fmb} \geqslant 0 \qquad \forall t\in T \quad \forall f\in F \quad \forall m\in P \quad \forall b\in B \tag{4.18}$$

$$\text{FO}^t_f \in \{0,1\} \qquad \forall t\in T \quad \forall f\in F \tag{4.19}$$

4.3 Objective and constraint explanation

The objective is to maximize the profit by subtracting transportation, sourcing, conversion, investment (expressed in depreciation of new presses and kilns per year), duties, fixed and closing cost from the revenue that follows from the served demand. The closing cost part of the objective contains only time period T which means that the total closing cost is calculated once in the last time period. Constraint 4.1 means that you cannot produce more than the demand. Constraint 4.2 means that the capacity of the original presses of factory f plus the added capacity have to be bigger or equal than what is produced in those presses. Constraint 4.3 means that the capacity of the original kilns of factory f plus the added capacity have to be bigger or equal than what is produced in the kilns at that factory. Constraint 4.4 means that the kilns of factory f need to produce at least the amount of each product that the factory delivers to its customers. Constraint 4.5 means that the presses of factory f need to produce at least the amount of semi-finished goods that the kilns at factory f need. Constraint 4.6 means that the mixers at factory f plus the suppliers need to produce/deliver at least the amount of material the presses need. Constraint 4.7 means that the suppliers need to deliver at least the necessary amount of material the mixers of factory f need. Constraint 4.8 means that the total amount a supplier delivers should be lower or equal than capacity of a supplier. Constraint 4.9 means that every factory f is open at the start of the model. Constraint 4.10 means that once a production factory closes it cannot be reopened. Constraint 4.11 means that once an additional kiln is placed at a factory it cannot be removed. Constraint 4.12 means that once an additional press is placed at a factory it cannot be removed. Constraint 4.13 prevents that a closed factory still can produce products by adding new presses and kilns. Moreover, this constraint ensures that a factory can place a maximum of two extra kilns. A maximum of two kilns is due to the size of the kilns. Constraint 4.14 means that the variable IK_{fl}^{t} is an integer. Constraint 4.15 means that the amount of added presses to a factory is an integer value and has a maximum of 6. The maximum number is based on the fact that a kiln uses a maximum of 3 presses per kiln. Constraint 4.16 limits the variable PF_{fpc}^{t} between zero and one because in the model the factories cannot deliver less than zero products or more than the demand. Constraint 4.17 means that variable K_{fpb}^{t} is non-negative. Constraint 4.18 means that the variables P_{fmb}^{t} and M_{fmb}^{t} are non-negative. Constraint 4.19 means that the variable FO_{f}^{t} is a binary integer variable.

Side note: The investment constraint is not modeled because the maximum investment of RHIM is estimated on 100-200 million euro per year. The chance of meeting the maximum investment is unlikely if you compare it to the costs of the network redesign options.

5 Results

An important aspect of FNR optimization is to have an expectation of the results. The expectation for the FNR model is that at least one of the factories has to be closed, due to the overcapacity of the factories in comparison to the demand. The factories are located in North America, Europe and China. The demand growth expectations are that the Asian market is increasing and the rest is more or less constantly growing with 1-2 percent. RHIM has three locations based in Europe. It would be logical to close one of the locations in Europe to have factories close to each customer zone. On the other side, the fixed costs in factory 5 are at least three times the fixed costs of the other factories. It would make sense that the savings of variable, transportation, duty and sourcing are not comparable to the major fixed costs.

The model is checked extensively with small data sets to be able to implement the production allocation of MPG A and B. The production allocation and BOM choices for the entire data set are too complex to check manually. That is why the FNR solution is analyzed by partly integration of variables into the objective. The constraints and variables in the objective are implemented separately to check if the maximum profit decreases or at least remains equal. Moreover, at each implementation the results are checked on being logical. Duties and transportation costs have an important role in the solution of the model. A strong visible allocation within the customer zone of a factory should be visible. The visibility of the allocation within the customer zone of the factory will weaken if the amount of constraints and cost element in the objective are added.

The FNR model has a computation time of 82.76 seconds. The optimal solution recommends to close factory 5. The current MPG C production at factory 5 can easily be reallocated to other factories. The extra allocation costs are negligible in comparison to the profit change of 96.5 million euro. Figure 9 is a representation of allocation of demand in the optimal solution. The figure shows that factory 5 does not serve any demand. Figure 9 does not show which quantity is transported from each factory to each customer zone. That is why figure 10 gives another presentation of the allocation of demand. In figure 10, 'Optimized baseline' means the optimal solution without allowing redesign decisions and 'Optimized network' means the optimal solution with the redesign decisions. The investment decisions in the optimal solution are that at t = 0 factory 1 invests in 3 presses and in t = 3 one press more. Moreover, factory 2 invests in 6 presses from t = 0. These factories are apparently able to produce at a low cost. Furthermore, factory 1 invests in a kiln for MPG B at time period t = 0. Factory 2 invests in a kiln for MPG A at time period t = 0. Factory 4 invests in a kiln for MPG B at time period t = 0. The FNR solution quality is checked by capacity utilization rates of presses, kilns and RMPs. After the network redesign the production flexibility is still high. Factory 3 has in every time period at least 78.1 percent of free capacity at the presses and at the kilns for the production of MPG A and B products. Moreover, Purchase China is able to produce as well more products of MPG A or B.

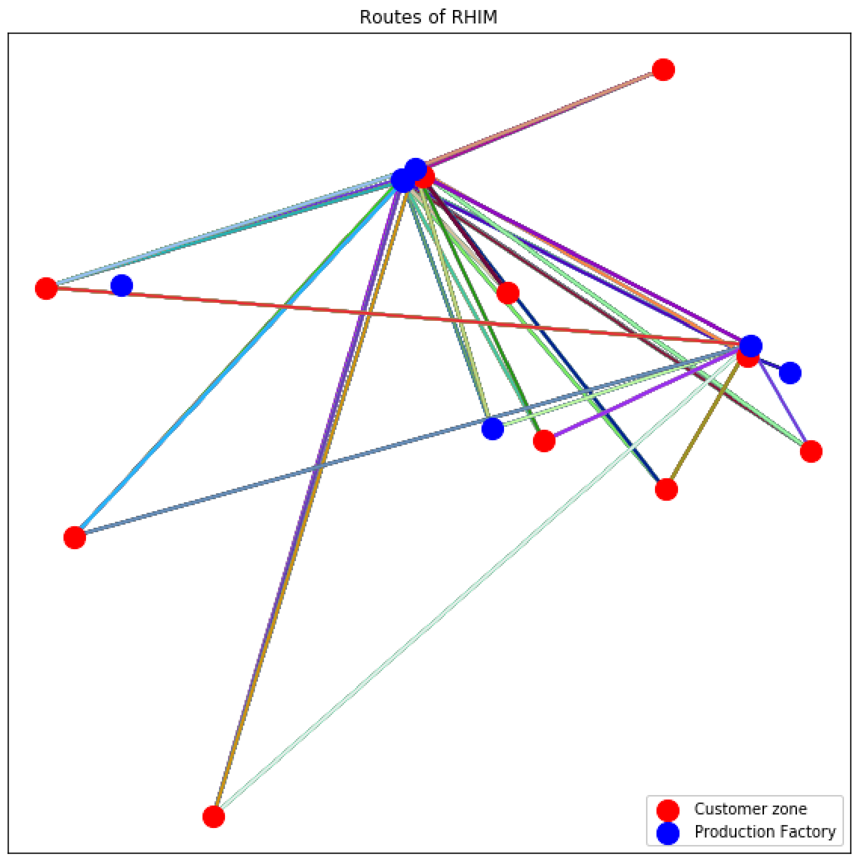

Figure 9: Allocation of demand

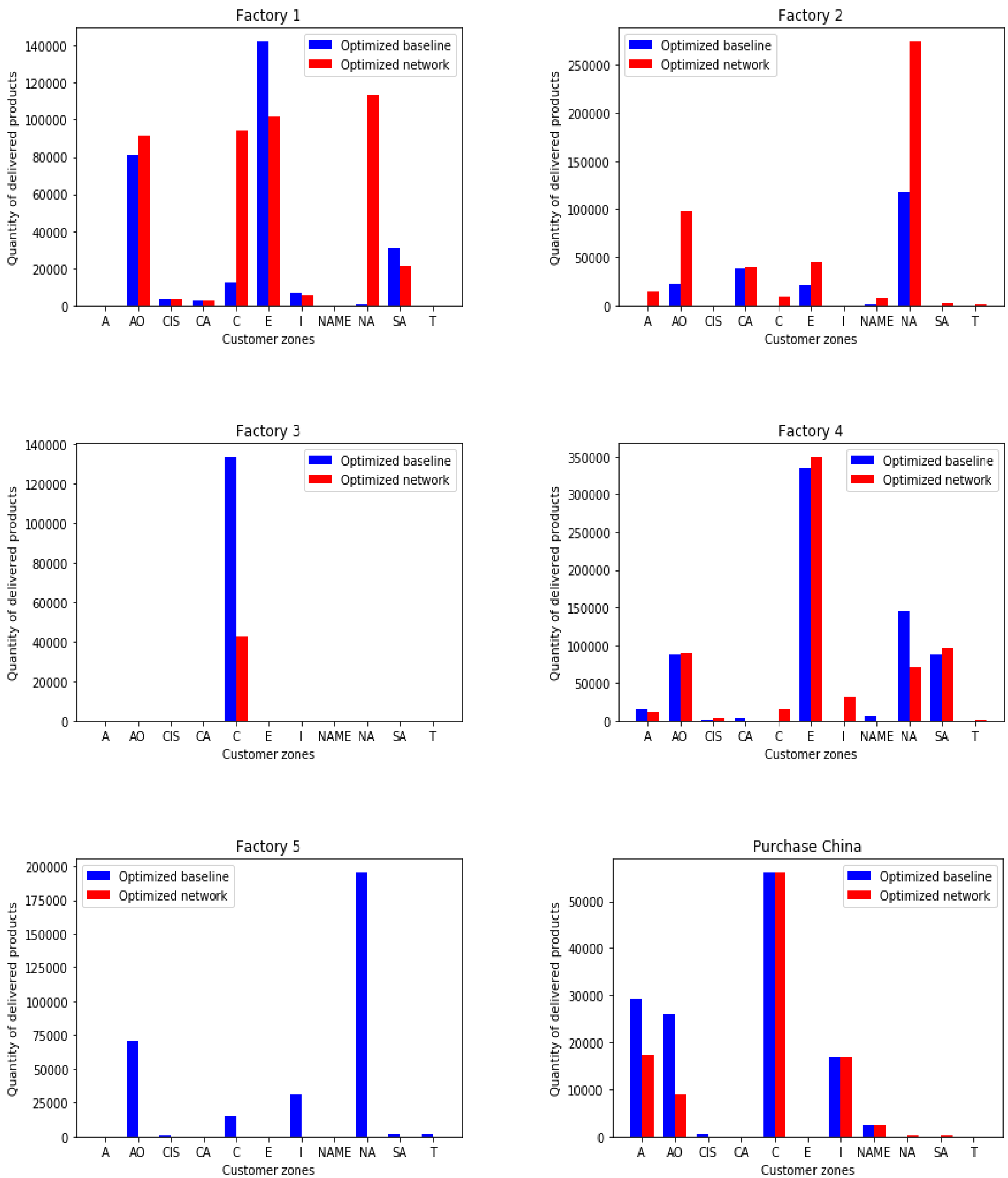

Figure 10: Allocation of products per customer zone per factory (A = Africa, AO = Asia Others, CIS = CIS, CA = Central America, C = China, E = Europe, I= India, NAME = Near and Middle East, NA = North America, SA = South America, T = Turkey)

Figure 11 shows the costs of the optimized baseline and optimized network. Most of the savings of the optimized network occur at the fixed cost (FC). The costs of the network redesign are visible with the closing cost (CC) and investment cost (IC). The duty cost increases due to the optimized network, which is logical because the demand in North America cannot be supplied by factory 5 anymore. Due to the investments in presses and kilns is the network able to decrease the variable cost (VC) and the sourcing cost (SC). This is promising, because the closing of factory 5 increases the variable and sourcing cost in this model.

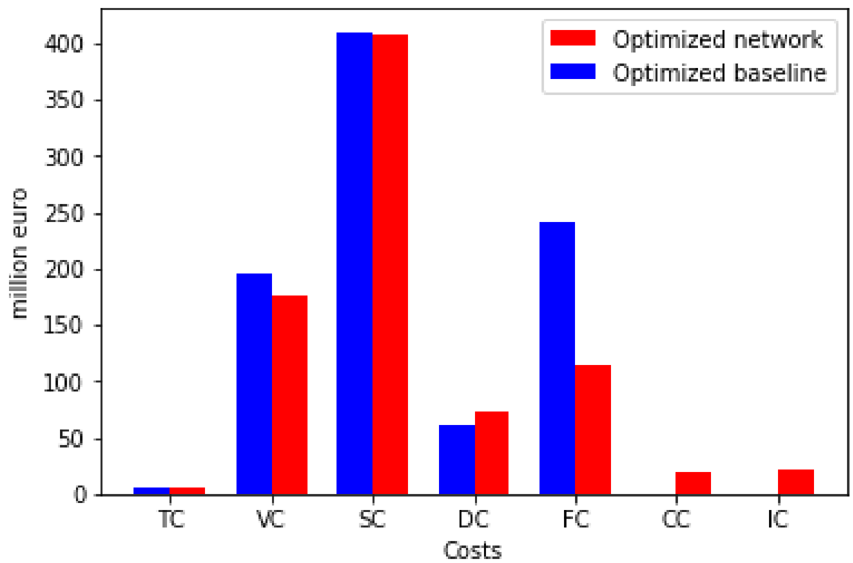

Figure 11: Cost differences between the optimized network and the optimized baseline (TC = transportation cost, VC = variable cost, SC = sourcing cost, DC = duty cost, FC = fixed cost, CC = closing cost and IC = investment cost (expressed in depreciation))

The suppliers and RMPs that deliver materials to the factories are analyzed. Most factories are delivered by suppliers or nearby RMPs. These material flows are logical, because the material sourcing cost differences between RMPS are mostly influenced by transportation costs. However, factory 4 is partly delivered by an RMP (RMP 072) which is not closely located (Figure 12). The mentioned RMP is closely located to factory 5. So, it is unknown if the RMP remains open without having a factory closely located. In the worst case scenario, the delivery of material is replaced by another RMP, which increases the average material sourcing cost with 14 percent. Besides that, the utilization rates of the RMPs are not crossing the 25 percent. RMPs have to deliver other not in this model included factories as well to produce all the products of RHIM. A bottleneck can occur after allocating the other product productions. However, chances of large problems because of bottlenecks at the RMPs are small. The factory will use in most cases the RMP that is closest located to the factory. The RMPs and factories are spread out over the world.

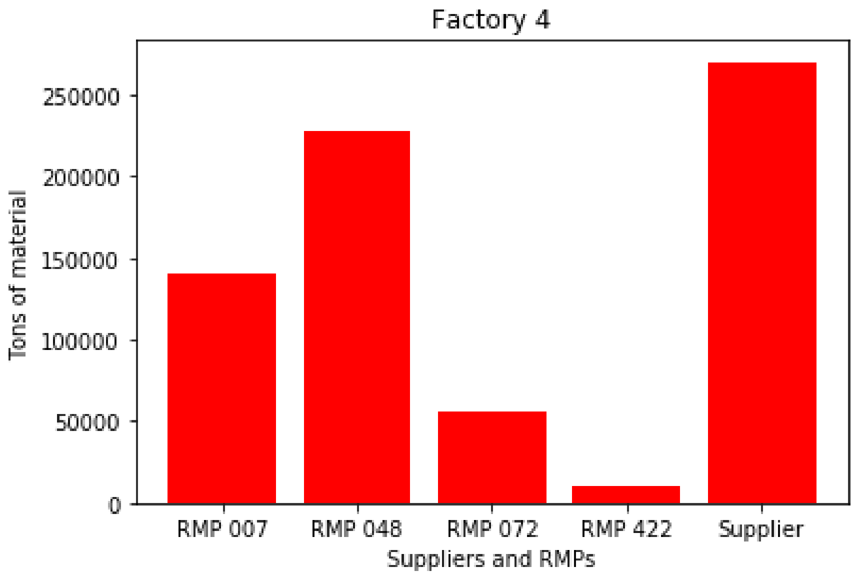

Figure 12: Factory 4 is served by RMPs and suppliers

6 Validation of the results

The FNR model is able to design the optimal network for the given parameters. The parameters are based on current data and predictions of experts of RHIM. However, the future is hard to predict. That is why analyses are conducted to test if the optimal FNR decisions do not change if the parameters are slightly changing. The parameters of the model can be divided into two groups. Group one are parameters that have low variation and group two exists out of parameters with a higher level of variation. Group one contains the following parameters: capacities of RMPs and factories, sourcing costs of RMPs, transportation costs, BOM structures and the variety of demand. Group two contains the following parameters: sourcing costs of suppliers, demand and duty rates for products. The following scenarios are analyzed:

- **Optimal solution without allowing FNR options:** The optimal solution of an FNR model can be to close a factory or to invest in an extra kiln or press. However, a slight increase in profit does not justify the loss of production flexibility or amount of work for executing the FNR options. Moreover, the closing of a factory or installation of extra presses or kilns is time consuming. Lastly, not all qualitative and quantitative factors are taken into account in the model. That is why there has to be tested if every FNR option is increasing the profit enough.

- **Full demand delivery vs. no full demand delivery:** One of the qualities of RHIM is to be able to deliver a broad range of products. The broad range of products can be diminished if the model is allowed to not serve all demand. Moreover, some customers can have motives to switch from supplier if one of their demanded products cannot be delivered by RHIM anymore. That is why the FNR decisions and the inherent profit have to be compared for a scenario of fully serving the demand and a scenario without having the obligation to serve all the demand.

- **Increase and decrease in demand:** The future demand can differ from the expectations due to external factors. That is why the FNR model is tested in two situations. In scenario 1, the entire demand is increased with 10 percent. In scenario 2, the entire demand is decreased with 10 percent. There is assumed that every product is equally volatile for demand changes.

- **Increased cost suppliers:** The RMPs are able to keep the raw material sourcing cost stable for the time horizon of the model. The sourcing cost of suppliers can increase or decrease due to global demand or the total offer of raw material. The FNR model is tested for some situations with increases and decreases of material sourcing cost of suppliers.

- **Increase of duty rates:** The United States has tried to influence the refractory market in the past. The FNR decisions need to be tested on possible increased import duties. The modeled scenario is that the United States installs more duties on products that are produced outside the United States. Two sub scenarios of import duty increases are modeled. First sub scenario is increasing the current import duties with 0 to 100 percent. The second sub scenario is that the import duties of the United States are 20 percent for all products regardless of the exporting country. The FNR model makes use of customer zones, which means that the import duty rates in the United States function as the import duty rates of North America. The United States wants to protect their steel production market. Other countries are also using duties to protect their own production markets. However, other countries will most likely protect different production markets, as high-tech products or food. So, the increase of duties in other customer zones for MPG A and B products is not modeled.

7 Scenarios

The below mentioned scenarios are helping to test the robustness of the optimal solution of the FNR model. The increase in profit should be high enough in most of the scenarios to perform the FNR decisions. The scenarios are helping to analyze the effects of the suggested FNR decisions in the future.

7.1 Solution without allowing FNR options

The profit increases with 96.5 million euro by including redesign options in a full served demand model. However, the FNR decisions have to be implemented partly to analyze the increased profit due to each redesign option. In a full served demand model the profit increases with 43.8 million euro by only including the option to close factories. Moreover, the profit increases with 52.7 million euro by only including the option to invest in kilns and presses in a full served demand model. The financial differences between the two analyzed sub scenarios are worth to mention. The FNR model should include the redesign options to close factories and invest in presses and kilns. The redesign options generate more value than the costs of the investments.

7.2 Full demand delivery vs. no full demand delivery

The first sub scenario analyzes the served demand of the FNR model excluding the redesign options. The FNR model chooses to deliver all demand. The second sub scenario analyzes the served demand of the FNR model including redesign options. The FNR model chooses again to deliver all demand. The third sub scenario analyzes the served demand of the FNR model with only including the redesign decision to close factories. The FNR model will not serve around 37901.5 ton of products and the model closes factory 5. The FNR model saves 1.6 million euro when it does not serve all the demand. The savings are mainly made in the duty and sourcing cost. However, what are the consequences of not serving all demand? In practical problems penalty costs are used to model the consequences of not serving demand in an FNR model. The FNR model of RHIM does not make use of penalty costs. Instead of penalty costs the profit is analyzed by serving different percentages of demand. Figure 13 shows that the profit increases linearly when the percentage of minimum served demand decreases. This means that the figure does not include a turning point and the FNR decisions of the optimal solution are not influenced by the percentage of served demand. A more precise analysis of the unserved demand reveals that only the demand of three products in customer zones India and/or Near and Middle East are not served in all five years. That is why there is chosen to model the FNR problem with serving all demand in the following scenarios.

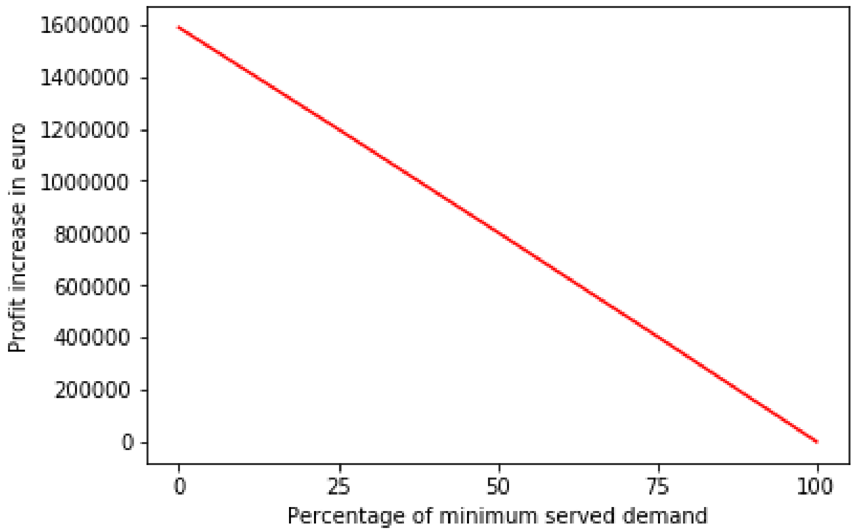

Figure 13: Profit increase due to not serving all demand

7.3 Increase and decrease in demand

In the first sub scenario the demand of every product is decreased with 20 percent for 5 years. The chances of a market volume decrease of 20 percent are low, because the refractory product demand is relatively stable. The optimal FNR solution is equal to the redesign solution of chapter 5. The profit increases with 84,0 million euros by implementing the optimal redesign decisions. The amount of profit is still large enough to justify the FNR decisions.

In the second sub scenario the demand of every product is increased with 20 percent for 5 years. The profit in the optimal solution is 9.65 million euro higher than in case of using the FNR decisions of chapter 5. The FNR decisions of the optimal solution include the redesign decisions of chapter 5 plus more presses and kilns. The difference is 3 more kilns and 6 more presses during the time periods. The increase in profit does not justify the extra investment decisions because the depreciation has to be paid for a longer period than the duration of the model.

To conclude, the optimal FNR decisions of chapter 5 are stable when the demand forecast changes. The FNR does not have to be changed if the total demand variation is lower than 20 percent. Purchase China has a lot of capacity and is not much more expensive than the factories of RHIM. That is why the extra FNR decisions due to demand changes are not justifiable with the increase in profit. The production of demand at Purchase China is comparable to the capacity of factory 3. So, RHIM is not very dependent of Purchase China, which is in real life a supplier.

7.4 Increased cost suppliers

The FNR model of chapter 5 assumes that the sales prices of products and material sourcing costs are stable. However, in reality the product prices change in parallel with the sourcing costs. In the past, the sourcing costs for suppliers had once a variance of 40 percent during a year. In discussion with an expert of the company, the estimated appropriate sourcing cost variance taking the fixed sales price assumption into account is 10 percent per year. First, the model computes the optimal solution with a decrease in sourcing cost of suppliers with 10 percent. The model invests in 1 press less at factory 1 at time period t = 3 in comparison to the optimal solution of chapter 5. This results in a profit difference that is less than 750,000 euro. The investment differences are small and the investment in the extra press has to be done at time period t = 3. The optimal solution has to be analyzed yearly with updated parameters. FNR solution differences are the most problematic at time period t = 0. The profit of the optimal solution in comparison to the solution of chapter 5 is 19.5 million euro. The increased profit due to lower sourcing cost is way bigger than the investment differences. The company can adapt easily to the new situation if the first two periods have a decrease of 10 percent in supplier costs. The changes in the production allocation are logical. There are 3 relevant differences that occur after the sourcing cost decrease. Firstly, factory 1 produces less products in total. Secondly, factory 3 produces more products for especially China, which material sourcing increase is clearly visible in figure 14. Thirdly, Purchase China produces more for customer zones China and Asia Others, which is clearly visible in figure 15. Purchase China is fully dependent of suppliers sourcing costs. The other factories are also dependent on RMPs.

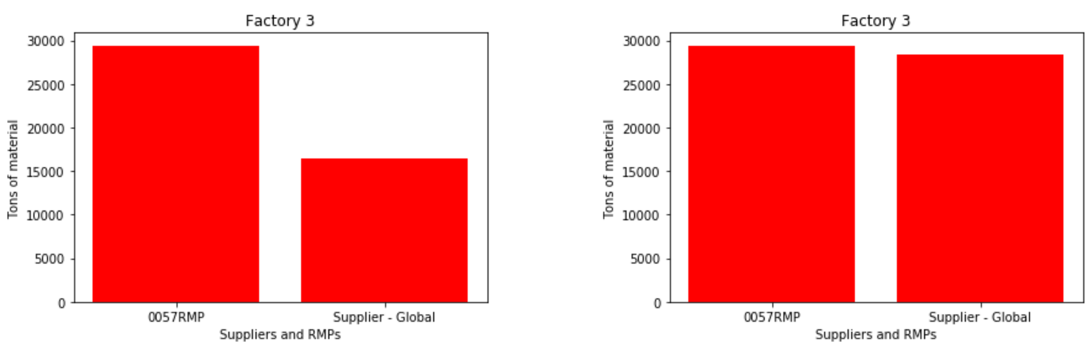

Figure 14: Increase in material sourcing as the sourcing cost of suppliers drops

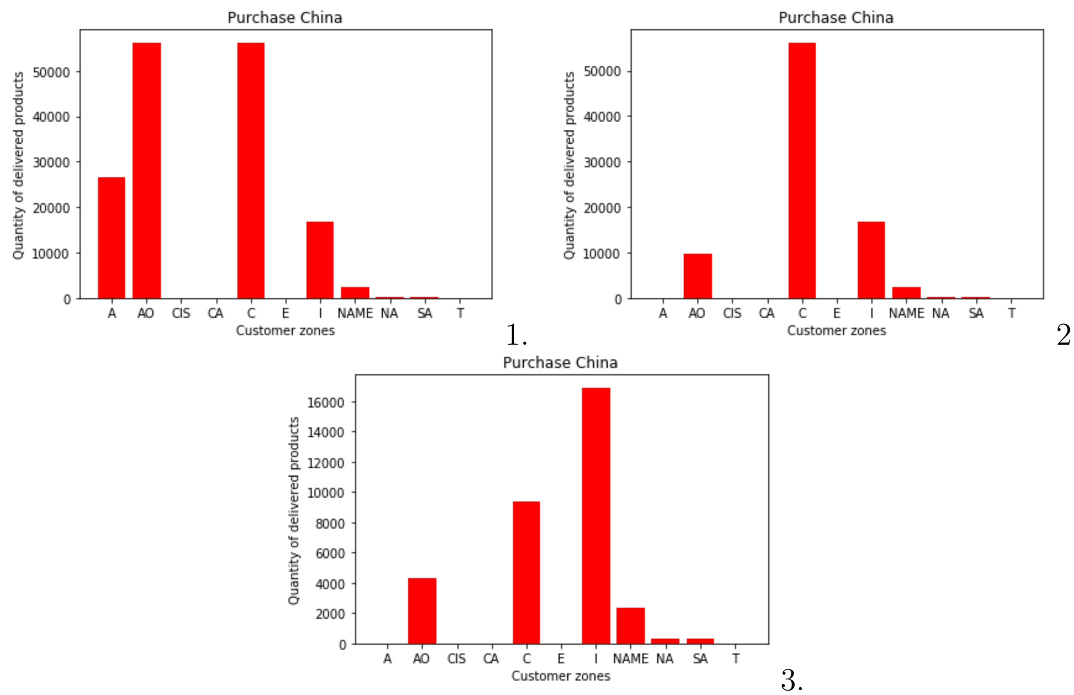

Figure 15: Allocation of products for Purchase China in case of 10 percent decrease of sourcing costs (1.), original sourcing costs (2.) and increase of 10 percent in sourcing costs (3.)

The increase of 10 percent in sourcing cost of suppliers has more influence on the FNR decisions. The investment differences are visible from t = 0, which is an extra press at factory 1 and another press is added at time period t = 4. Moreover, at factory 1 is invested in an MPG B kiln at time period t = 3. The other FNR decisions remain equal to the optimal FNR solution of chapter 5. The new FNR decisions have effect on production allocation. First of all, RMPs deliver more material to factory 1 and the production of factory 1 increases. Secondly, the production of Purchase China decreases. The effects of the new FNR solution are expected after a sourcing cost increase of suppliers. The investment decisions do not differ much from the original optimal solution. The model has three years left to decide to invest in an extra kiln. The investment in an extra press at t = 0 will not change the profit tremendously. Moreover, the expectations of next year are the most precise ones and a change of sourcing cost is not expected. That is why the recommendations of the optimal solution of chapter 5 are still valid.

The robustness of the investment decisions has to be the most accurate for closing a factory, then investment in kilns and lastly the presses. The sequence is based on the easiness of changeability of the investment decisions. The closing of a factory is by far the most difficult one to change. In the discussed scenarios the changes were visible in the press and kiln investments. An extra scenario is analyzed to check if the closing of factory 5 is still valid if the sourcing cost decreases or increases with 50 percent for 5 years. The optimal redesign decisions only changes for the investment in kilns and presses. The closing of factory 5 remains valid. So, the most difficult recommendation is also the most robust one.

7.5 Increase of import duty rates in North America

The current import duties of North America are 3 percent for the European factories and 13 or 16 percent for the Chinese factories. Figure 16 shows the profit versus the import duties of North America. Figure 16 shows that the profit decreases slowly as the import duties increase. The production allocation changes more, the European factories serve more demand of North America if the import duties increase. The reason is that the import duties increase with a certain percentage. The duties for European factories to export to North America increase only up to six percent, after a 100 percent increase of the current import duties. This is still a lower duty rate than the initial duty rate for factories from China. That is why in the second scenario the duty rates in North America increase to 20 percent for every factory. The FNR model still recommends the redesign decisions of chapter 5. The optimal FNR solution increases the profit with 37.4 million euro even when the import duty rate of North America is 20 percent.

In reality, the import duties are lower than the used import duties in the FNR model. The reason is that FNR model makes use of customer zones. This means that in practice the total paid duties will be lower. The sensitivity analysis for duty rates shows that the optimal FNR solution remains valid if the duty rates in North America increase. To conclude the FNR solution of chapter 5 is optimal for the most likely duty changes.

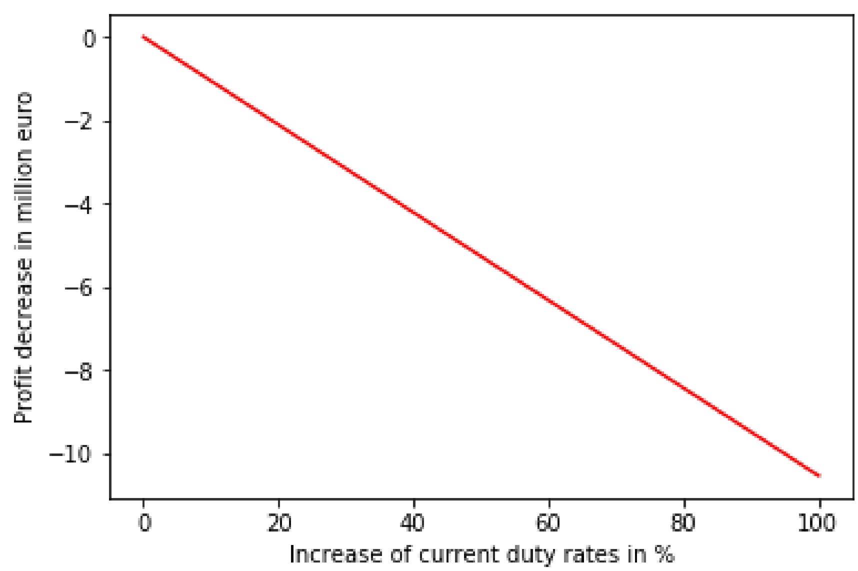

Figure 16: Change of objective due to increasing import duties

8 Configurable BOMs

The FNR model makes use of multi-level configurable BOMs. The effects of multi-level BOMs are visible with the profit increase due to the investment options in kilns and presses. However, the effects of configurable BOMs are less visible. Choosing the cheapest BOM sequence in an FNR with multi-level configurable BOMs is complex. The necessary material at the lowest BOM level can be sourced at different RMPs and suppliers that have different prices for each factory. The configurable BOMs should be implemented in the FNR to be able to get the cheapest and most detailed material requirement planning.

The importance of configurable BOMs is not easily visible in this thesis, because the FNR model is solved for a select group of factories. The RMPs have capacity constraints in the model, but in reality the RMPs need to deliver to all the factories and not only the selected group for MPG A and B production. In the current model the cheapest possible BOM will be chosen for the production of every product. However, if the capacity at the RMPs for certain raw materials are running out, the model has to rethink about which BOM to choose. There are different costs associated with the BOMs. Choosing different BOMs can deliver different FNRs. Besides that, the model of RHIM has three levels of configurable BOMs. The levels expressed in equipment are: mixers, presses and kilns. Only the kiln exists out of two types. The importance of multi-level configurable BOMs increases if more levels have different types. In this case the choice of BOM would have a bigger effect on the FNR decisions for the optimal solution.

Two situations are shown to emphasize that configurable BOMs can have more influence on the FNR solution. The first situation, the BOM choices at the mixers in the optimal solution of chapter 5 are not allowed to be chosen anymore. Unless the mixers have no alternative BOM for a certain material. The FNR model is runned again and the profit decreases with 6.2 million euro by forcing the FNR to make a different BOM choice at the mixers. In the second situation the capacity of RMPs is divided by 100 to model the influence on FNR decisions. The new FNR optimal solution is compared with the optimal solution presented in chapter 5. The new optimal solution does not open an extra press at factory 1 at time period t = 3. The differences are not major, but the differences in redesign decisions increase when the difference between the sourcing costs increases or if the difference between BOMs increases.

9 Conclusion and discussion

9.1 Conclusion

This project is a strategic management study to maximize the profit of FNR problems. In the conclusion the main research question is answered and recommendations for RHIM are given. The research question:

What is the most profitable and robust FNR for RHIM taking the multi-level configurable BOMs into account?

The most profitable FNR for RHIM includes the following decisions in the upcoming five years. Firstly, factory 5 has to be closed from the beginning of the model. Secondly, from the beginning 3 presses and an MPG B kiln have to be added to factory 1 and in the third year an extra press has to be added. Thirdly, from the beginning an MPG A kiln and 6 presses have to be added to factory 2. Fourthly, from start onwards an MPG B kiln has to be added to factory 4.

After the network redesign the production flexibility is still high. Factory 3 has in every time period at least 78.1 percent of free capacity at the presses and at the kilns for the production of MPG A and B products. Moreover, Purchase China is able to produce as well more products of MPG A and B. However, too much dependency on suppliers is not preferred. The current model makes use of an RMP nearby factory 5. It is not clear if the closing of factory 5 has influence on the position of this RMP. However, the model is able to switch the material flow from this RMP for a sourcing cost increase of 14 percent. The current MPG C production at factory 5 can easily be reallocated to other factories. The extra allocation costs are negligible in comparison to the profit changes.

The mentioned FNR decisions deliver the optimal profit for the given parameters. However, to conclude on the robustness of the optimal solution, several scenarios are tested that can have an influence. The first scenario is analyzing the model with and without FNR options. The redesign decision of closing facilities delivers 43.8 million euro and the investment decision in kilns and presses delivers 52.7 million euro. The increase in profit is higher than the total investment cost, which in reality is spread out over 30 years for kilns and 8 years for presses. The second scenario is to analyze if the demand has to be fully served, because the consequences of not serving demand cannot be accurately estimated. Switching to a fully served demand model does not influence the optimal solution nor the served demand of the model. The model does not serve a negligible amount of demand, when the redesign option to invest in kilns and presses is excluded. The refractory market is a stable market, but the future expectations of parameters can be incorrect. That is why the third scenario exists out of a situation with a yearly demand increase of 20 percent and a situation with a yearly demand decrease of 20 percent. In the situation of demand increase the original optimal solution remains valid, because the extra redesign decisions in the form of adding presses and kilns do not justify the increase of profit. In the scenario with 20 percent decrease of demand the new optimal redesign decisions are equal to the original redesign decisions. So, demand variations of 20 percent do no influence the redesign decisions. The fourth scenario analyzes the influence of sourcing cost on the optimal FNR solution. The model makes use of suppliers and RMPs that deliver to the factories. The RMPs have stable sourcing costs for the factories. The suppliers can change their prices during the years. Changing the sourcing costs of suppliers with a 10 percent increase and decrease had the biggest impact on the production quantity of Purchase China, which is fully dependent on suppliers. The difference between the original optimal solution and the scenario of the increased sourcing costs is only 1 press from time period t = 3. The model needs to be the most accurate for the near future because only the decisions at time period t = 0 have to be made. The redesign decisions in the increased and decreased material sourcing costs situation are not justifiable with the increased profit and low chance of occurring. The last scenario is possible duty rate changes after closing factory 5. Even doubling the current duty rates on products to North America does not influence the optimal FNR solution. The practical recommendations are based on interesting findings and FNR decisions at time period t = 0.

Practical recommendations

- Perform the FNR decisions that are recommended at time period t = 0. Firstly, factory 5 has to be closed from the beginning of the model. Secondly, from the beginning 3 presses and an MPG B kiln have to be added to factory 1. Thirdly, from the beginning an MPG A kiln and 6 presses have to be added to factory 2. Fourthly, from start an MPG B kiln has to be added to factory 4.
- Every year the FNR model has to be runned to determine the best redesign decisions for that year. An important note is to update the parameter data yearly.
- RHIM should not be too dependent on Purchase China in the future. When suppliers change the material sourcing costs, the influences are mostly visible in the production allocation of Purchase China.
- RHIM should take profit maximization into account for the corporate decision making instead of cost minimization. This thesis showed that in certain situations not all demand deliver a profit.
- Experts of RHIM think that the multi-level configurable BOMs should be taken into account in other business decisions such as the yearly production allocation.

9.2 Discussion

9.2.1 Academic relevance

The literature review showed that multi-level configurable BOMs in FNPs are not investigated. However, the literature review emphasized the importance of including BOMs in FNR problems. The inclusion is necessary for the material planning and increases accurateness of the solution.

This is the first research paper that has included multi-level configurable BOMs in a FNR model. Production industries that have multi-level configurable BOMs can influence their material requirement planning in such a way that FNR decisions can be changed. The following thesis results show the value of including multi-level configurable BOMs in FNR problems. Firstly, the inclusion of multi-level configurable BOMs increases the quality of the solution because it is not possible to know at each level which BOM has the lowest costs beforehand. Choosing the cheapest BOM at the levels is not possible manually. The increase of detail has an influence on the accurateness of the material flow, profit and the FNR decisions. Especially, if the material flow of the organization is capacitated and capacity extension decisions can be made. Secondly, the inclusion of multi-level BOMs increases the amount of FNR options, which increases the flexibility of the network. At different BOM levels decisions can be made to adapt the production capacity instead of only closing a facility. Thirdly, the inclusion of multi-level configurable BOMs results in a higher profit. The facility network is able to focus the production on the cheapest locations due to accurate material planning and capacity extensions at different levels. Fourthly, the inclusion of multi-level configurable BOMs has influence on the FNR decisions, which can deliver again extra profit. The factories are able to cope with maximum capacities of suppliers and equipment because they are able to chose a different BOM which can prevent an extension of a facility.

To conclude, this thesis is a valuable addition to the current literature. Production industries with multi-level configurable BOMs that want to redesign their facility network should take the results of this thesis into account. The inclusion of multi-level configurable BOMs delivers a lot of advantages that otherwise would be missed.

9.2.2 Limitations

The accurateness of the provided solution could be increased if all the products and factories were included. The reason is that the solved FNR problem includes factory 5, which can produce products from MPG C. The current MPG C production of factory 5 is reallocated, but this is not comparable to solving the total product range at once. Besides that, solving the FNR problem for all products can result in bottlenecks at the RMPs and can change the allocation of production. Partly solving the problem could result in a local optimum.

The FNR model makes use of duty rates per customer zone. In reality, the duty rates are determined per country and can be different within a customer zone. However, the model assumes the highest duty rate within the customer zone as the general duty rate. A more precise calculation of the duty rates per customer zone or a data set that allocates the demand per country would be better.

The completeness of the BOMs per product per factory are difficult to check. In the model every product has at least one BOM. However, it is not known if every possible BOM is included in the list of configurable BOMs. In each factory a certain set of products can be produced. The products can be grouped to product groups, each product group has a set of BOMs per factory. The disadvantage is that if one product within the product group can be made with a cheap BOM, then the other products can also be made with this cheaper BOM. This could be improved by having configurable BOMs per product per factory instead of configurable BOMs per product group per factory.

9.2.3 Future research

The scalability of multi-level configurable BOMs in the decision making of FNR could be analyzed and improved. The inclusion of multi-level configurable BOMs means that more decision variables are added to the problem. More decision variables increase the complexity of the problem, which means a longer computation time. Future research could investigate what problem sizes deliver solutions in acceptable computation times and what kind of methods can be used to decrease the computation time to solve the problem.

Moreover, future research can be focused on finding more advantages of configurable BOMs. One way can be to solve the FNR model with the entire set of products of RHIM. Furthermore, in future research a sensitivity analysis can be conducted on factors of multi-level configurable BOMs. The analysis can investigate the effects of having multi-level BOMs with different amount of layers. It is possible that after a certain amount of layers the FNR is not influenced anymore. Besides that, a sensitivity analysis can investigate what differences in configurable BOMs have influence on FNR. Differences in configurable BOMs can be the amount of configurable BOMs per product or material differences between BOMs for a product. This can result in an accurate approach for deciding per FNR problem to include multi-level configurable BOMs or to leave it behind.

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Appendix

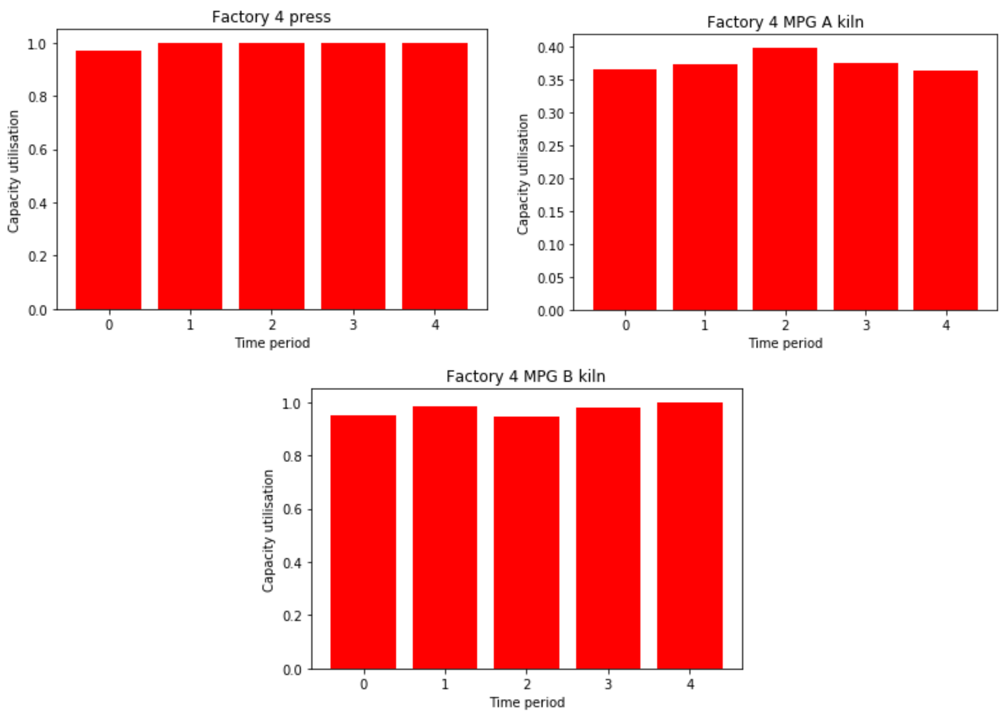

Figure 17: Utilization rates of capacity at factory 4