Dynamic
Multi-Product Multi-Facility Supply Network Design

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Kurzfassung

Volatile Märkte, sich verkürzende Produktlebenszyklen und der globale Wettbewerb stellen die klassischen Lieferketten vor große Herausforderungen. Supply Chains müssen sich kurzfristig und dynamisch an die volatilen Marktanforderungen anpassen. Die volatilen Märkte werden immer weniger vorhersehbar. Die Supply Chains selbst müssen dynamischer werden, um die Marktvolatilität zu bewältigen. Daher wandelt sich das klassische Bild der stabilen Supply Chain in ein dynamisches Supply Network-Verständnis. Um diese neuen Anforderungen abzudecken, schlägt diese Arbeit das Dynamic Supply Network Design Problem (DSNDP) als zentrales Instrument in hierarchischen Planungssystemen vor. Zentrales Ziel der Arbeit ist es, einen Ansatz für das Design dynamischer Supply Networks unter gegebenen physischen Randbedingungen bereitzustellen. Um dieses Ziel zu erreichen, wird das Problem zunächst motiviert, charakterisiert und in Beziehung zum Stand der Technik der Supply Chain Planungsansätze gesetzt. Nachdem diese Grundlage geschaffen ist, wird das Problem formalisiert. Dazu werden alle Modellierungsannahmen formuliert. Auf dieser Grundlage werden drei aufeinander aufbauende Optimierungsmodelle für das DSNDP entwickelt, wobei ein Mixed Integer Linear Programming (MILP) Ansatz verwendet wird. Die Optimierungsmodelle entwerfen ein dynamisches Supply Network durch die Entwicklung eines Qualifizierungsplans für alle verfügbaren Ressourcen in jeder Periode des Planungshorizonts. Dieses dynamische Supply Network weist den verfügbaren kapazitiven Ressourcen die entsprechenden Qualifikationen zu, um die volatile Nachfrage dynamisch zu bedienen und die Gesamtkosten zu minimieren.

Dabei werden der tatsächliche Produktionsschwerpunkt jedes Produktionspartners (Produktmix-Abhängigkeit), die spezifischen Erfahrungen jedes Produktionspartners (Qualifizierungsabstufung), die Fähigkeit der Fabriken, ein Produktportfolio und nicht nur einzelne Produkte abzudecken (multitasking facility) sowie die Möglichkeit der Pre-Prozessierung berücksichtigt. Jedes Modell wird um eine dieser Hauptannahmen erweitert. Dies macht die Modelle immer realistischer jedoch auch komplexer. Einschränkungen in der Problemgröße motivieren die Arbeit zu einem zusätzlichen heuristischen Ansatz. Die vorgeschlagene Displacement Heuristik berücksichtigt die gleichen Annahmen, löst das Designproblem jedoch iterativ. Dadurch erreicht sie zwar niedrige Berechnungszeiten, verliert aber die Optimalitätsgarantie. Durch die geringen Rechenzeiten ist die Heuristik für realistische industrielle Problemstellungen geeignet. Die Displacement Heuristik führt zu Optimalitätslücken von 4 bis 6%, wie die Validierung gegen das Optimierungsmodell zeigt. Mit spezifischen Experimenten wird das Verhalten der Displacement-Heuristik in realistischen industriellen Problemstellungen evaluiert. Aus den Erkenntnissen dieser Auswertung lassen sich mehrere konkrete Vorschläge für die Gestaltung und das Management dynamischer Supply Networks ableiten. Da der Trend zu Volatilität und kürzeren Produktlebenszyklen anhält, ist zum Abschluss dieser Arbeit eine Motivation für weitere Forschungs- und Umsetzungsaktivitäten auf dem Gebiet der dynamischen Wertschöpfungsnetzgestaltung gegeben.

Abstract

Volatile markets, shortening product life cycles and global competition confront classical supply chains with major challenges. Supply chains are required to adapt dynamically on short notice to the volatile market requirements. As volatile markets are becoming less predictable the supply chains itself have to be more dynamic to cope with the market volatility. Hence, the classical image of the stable supply chain has to be converted to a dynamic supply network understanding. To cover these new requirements, this thesis proposes the Dynamic Supply Network Design Problem (DSNDP) as a central instrument in hierarchical planning systems. It is the central objective of the thesis to provide an approach for design of dynamic supply networks under given physical constraints. To fulfill this objective the problem is first motivated, characterized and set in relation to the state of the art supply chain planning approaches. After this basis is settled, the problem is formalized. All the modelling assumptions can be formulated. On this basis three consecutive optimization models for the DSNDP are developed, using a Mixed Integer Linear Programming (MILP) approach. The optimization models design the dynamic supply network by developing a qualification schedule for all available facilities in each period of the planning horizon. This dynamic supply network assigns the adequate qualifications to the available capacitated facilities, to dynamically serve the volatile demand minimizing the overall costs. It therefor considers the current production focus of each facility resource (product mix-dependency), the specific experiences of each facility resource (qualification differentiation), the ability of the facilities to cover a product portfolio, rather than only single products (multitasking facility) as well as the pre-processing option. Each model is extended by one of these main assumptions. That makes the models increasingly realistic but also more complex. Serious limitations in problem size are motivating the thesis for an additional heuristic approach. The proposed Displacement Heuristic considers the same assumptions, but solves the design problem iteratively. Thereby, it leads to extremely low computation times, but looses the optimality guarantee. With the low computation times, it is capable for realistic industrial problem settings. The Displacement Heuristic leads to a goodness of 4 to 6%, as the validation against the optimization model shows. Specific experiments evaluate the behaviour of the Displacement Heuristic in such realistic industrial problem settings. Concluding the insights of this evaluation, several concrete suggestions for design and management of dynamic supply networks can be derived. As the trend for volatility and shorter product life cycles is ongoing, the conclusion of this thesis provides a motivation for further research and implementation activities in the field of dynamic supply network design.

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Contents

1 Introduction

"It is not the strongest of the species that survives,
nor the most intelligent that survives.
It is the one that is most adaptable to change."
[Charles Darwin, Evolutionary Biologist]

Markets tremendously changed in recent years. Globalization and higher market transparency increased the global competition and price pressure. In parallel, customer requirements for new, customized products increased. Shorter product life cycles and higher market volatility is the consequence. New fast moving markets replaced stable ones. The combination of both trends provides huge challenges for the industry. From one day to another the demand structure can change tremendously, if a new product was launched. Product innovations and demand trends are not able to be suitably forecasted. How should a supply chain, which is bound to physical constraints, cover these trends? Supply networks have to become more dynamic to market volatility and new products but also stay cost-efficient. In earlier years this challenge was covered with inventory stocks. The recent extent of volatility makes buffering economically impossible or at least inefficient. Supply chains themselves have to become more flexible networks to dynamically cover the current market requirements. This challenge can be formulated in the Dynamic Supply Network Design Problem (DSNDP). This thesis faces this challenge and provides two connected approaches to design dynamic supply networks, considering the physical constraints. The focus is on providing the necessary flexibility under minimization of overall supply network costs. The thesis starts with a detailed motivation and characterization of the problem.

1.1 Motivation

Modern supply chains resemble more a network than a linear chain. Multiple suppliers serve multiple customers. Supply chains must have a high product portfolio to deliver a multitude of customers. Why is there a significant change recognized from stable linear chain-like supplier customer relations to multi-facility multi-product supply networks?
The explanation may be found in three interconnected phenomena: Firstly, demand of single products is becoming more and more volatile due to global markets, higher market transparency and higher variety of products (substitutional or complementary). Thereby, secondly, product life cycles are shortening (cf. Chopra and Meindl (2007)[19]) and, thirdly, globalized markets are getting more dynamic.
On the other hand, production capacities are quite static with given procurement times. In semiconductor industry in former years long-term delivery contracts with OEMs of ten years or more guaranteed stability in the supply network. Capacities could be bought with clear conscience for stable utilization even with equipment procurement times of up to two years. Tremendously shortened product life cycles in the consumer industry as well as in the automotive industry made the semiconductor planning environment unstable. While the demand changes and product life cycles shorten, the physical production environment, especially equipment procurement times, remains static. Hence, much more volatile markets have to be served with the same static system. This makes a sophisticated planning layer necessary, which coordinates the mid-term demand with the static capacity. The necessity of optimal flexibilization of the supply networks throughout all involved facilities requires major research attention. This work will cover this highly relevant field with the aim to design dynamic supply networks

serving volatile markets.
Thereby the following research questions will be answered step by step:

1. How can a supply network be designed dynamically for the volatile markets?

2. How and where can the dynamic supply network design process be integrated to the conventional hierarchical planning system?

3. How can overall costs be minimized in a dynamic supply network?

4. How can realistic sizes of the Dynamic Supply Network Design Problem (DSNDP) be solved in acceptable time?

The research questions will be answered throughout the thesis. The answers will be concluded in the final chapter 7. To guide the reader through the thesis, first of all the structure will be described in section 1.2. Thereafter all necessary terms and definitions are clarified and the concrete problem setting for dynamic design of supply networks will be characterized in 2.

1.2 Structure of the Thesis

Motivated by the increasing market demand volatility, this thesis about design of dynamic multi-product, multi-facility supply networks is structured in the following way. Figure 1.1 outlines the structure of the thesis: Firstly, in chapter 2 the modern dynamic multi-product multi-facility supply network design problem is characterized. Subsequently, an extensive literature review in chapter 3 evaluates the state of the art of modelling the described supply network design problem. Thereby, the literature review is based on a broad overview of hierarchical planning approaches. To embed the Dynamic Supply Network Design Problem (DSNDP), the literature review dives down to the single hierarchical planning problems. On this basis, an overview of concrete approaches for the supply network design problem

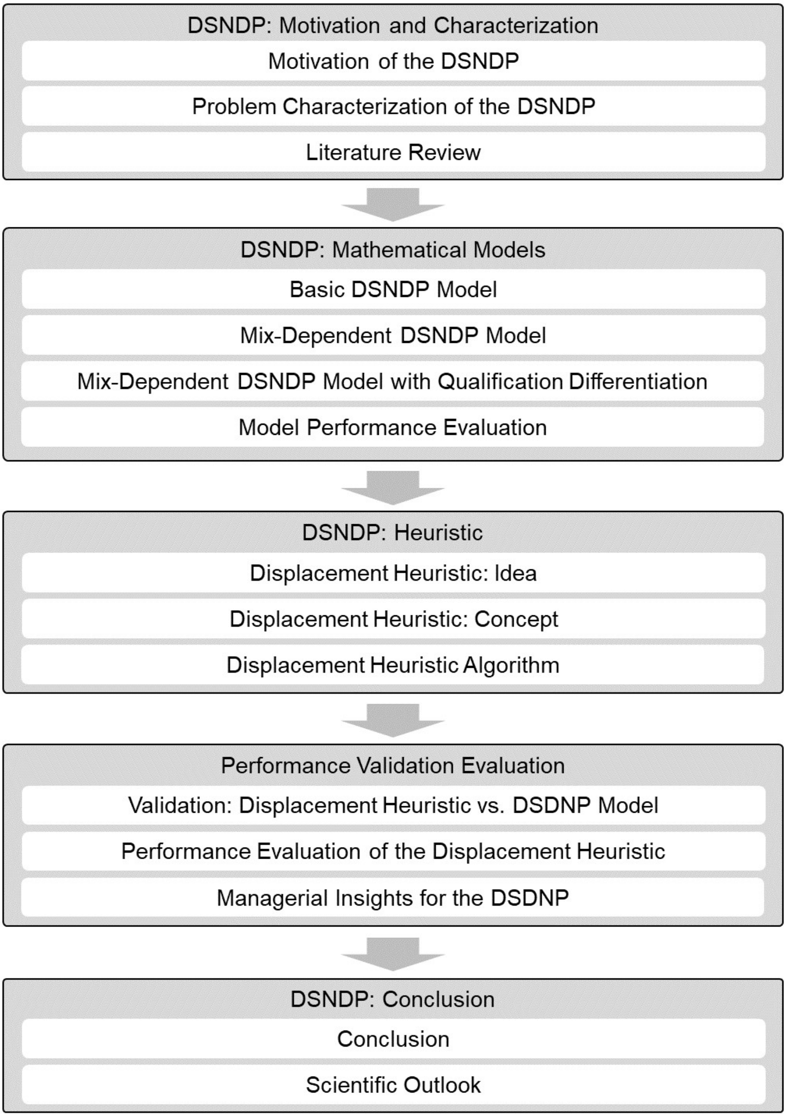


Figure 1.1: Structure of the Thesis

and closely related planning problems is provided. This analysis leads to the research gap to be closed by this thesis. Motivated by the problem characterization in chapter 2 and based on the state of the art evaluated in the literature review in chapter 3 the model premises are formulated in the Problem Formalization in chapter 4. This chapter is structured in several sections leading from a basic mathematical modelling approach in 4.1.3 to an extended mathematical model in 4.2.6 and with a second model extension to the final mathematical formulation of the optimization model in 4.3.3. The three modelling approaches are based on each other. For each modelling approach additional assumptions and pre-calculation routines are included to make it even more realistic. After formulating the model with all extensions, it will be implemented in a commercial mathematical solver. In the last section 4.4 of the Problem Formalization, the performance of the most advanced modelling approach is evaluated in different problem sizes. To speed up the model accepting loss of optimality in the subsequent chapter 5 a specific heuristic will be developed and implemented. In chapter 6 the performance of the heuristic will be validated against the optimal solution of the analytical optimization model, with focus on the deviation from the optimum and the computation time. Additionally, the performance of the heuristic is evaluated in specific supply network design experiments. The experiments specifically outline the modelling effects, borders and the practical impact. The performance evaluation closes with some managerial insights in section 6.3. In this final section, concrete managerial suggestions and advices are derived from the observations of the supply network design experiments. To close this thesis in the final chapter 7 critical conclusions are drawn and motivations for future research in the expanding field of dynamic supply network design are introduced.

2 Problem Characterization

As introduced in chapter 1 supply networks have to be designed dynamically to cope with the increasing volatility of market demands. The current chapter intends to characterize the DSNDP to answer the first research question how to design dynamic supply networks. Before the concrete design problem can be characterized, all necessary terms and definitions are introduced in the following section 2.1.

2.1 Terms and Definitions

This section intends to define all necessary terms according to the specific purpose of this thesis. This thesis considers systems of multiple products and multiple resources. A **product** is the output of a transformation process (cf. Grabner (2017)[52]). A product can either serve customer demand or be an input for a further transformation process. In this context, a **final product** is a special kind of product, which satisfies demand of the end customer. It does not serve as input for further transformation. Whereas a **product component** represents an output of a transformation process, which again serves as an input for a further transformation process. Each final product follows a defined **work plan** . A work plan specifies the sequence of process operations. The definition for operation follows in the next sentences. Each final product may include several product components. Thereby, the work plan determines the product components, which are required for the final product in the end. The entire work plan for a final product can be split to the single **production stages**. Each production stage

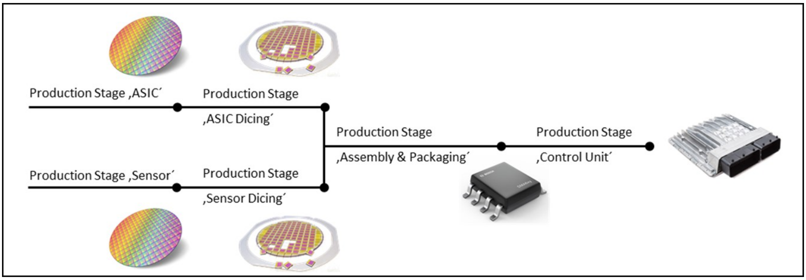


Figure 2.1: Semiconductor Work Plan [27] [26] [79] [25]

delivers a specific product component. If all necessary production stages along an entire work plan are executed, the particular final product is resulting, including all necessary product components. Figure 2.1 visualizes the concept referring to the simplified semiconductor work plan: Each production section consists of a defined section of operations. An **operation** represents a single production step as the highest level of granularity in a transformation process. It is performed on a machine. Operations can be differentiated in value adding and non-value adding operations. A value adding operation for example is a metallization step on a sputter machine in a semiconductor wafer fab. Whereas, a necessary but non-value adding step is an optical inspection for particles in a semiconductor wafer fab. Each operation has a requirement of specific machine capacity. This capacity requirement is expressed in time units and is called **process time**. Figure 2.2 visualizes the simplified production section "ASIC" [1] as a sequence of operations: Technologically, familiar products can be clustered to **product groups**. A product group contains several products. For example in semiconductor industry the product group "inertial sensors" contains sensor products for vehicle dynamics control as well as for navigation systems and many other applications (cf. Robert Bosch GmbH (2019) [51]). Each final

[1] ASIC: Application-Specific Integrated Circuit

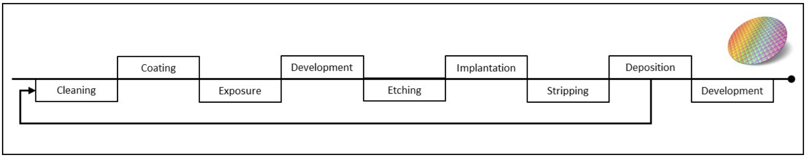


Figure 2.2: Simplified Production Stage ”ASIC”[27]

inertial sensor product contains at least one gyro sensor component, one acceleration sensor component and one integrated circuit component (ASIC) (cf. Tamura (2014) [116]). Each product is similar in its basic structure but differs in its specifications. Each product follows a **product life cycle**. This thesis follows the definition of Barlet and Twineham (2013) [10], where a product life cycle structures the limited life span of a product to specific stages. Thereby, the duration of each stage, and consequently of the product life cycle, mainly depends on the product, market and competition. To produce a product specific **resources** are required. The literature differentiates between natural, human and capital resources (cf. McConnell et al. (2009) [77]). This thesis limits the focus to capital resources, which represent all limited human made entities, which are required to produce products (cf. Samuelson and Nordhaus (2009) [106]). On a granular level, an operation requires time on a machine to be executed. On a broader level, a production stage requires time in a facility to be executed. A **machine** is the most granular resource unit considered in the system. A **facility** is a resource, containing a set of machines and representing a local entity, such as a wafer fab in the semiconductor industry. Each resource is limited and has a specific **capacity** (cf. Laguna and Marklund (2018) [70]). Producing a product affects the capacity of the involved resources. The overall capacity of the facility resource is determined by the sum of all machine resources involved. The capacity is measured in time units. According to Buitenhek et al. (2002) the capacity of a production machine is represented by its available time [15]. Consequently, the capacity of a production facility is defined by the sum of available time of all production machines involved. A facility in this thesis acts as an independent party in the system. The term facility is used equivalently to **production site** or **production location**. It can use the capacity of its machines for the production of different products. Whereas, a machine belongs to a facility and can not act independently. A facility is not dedicated to the production of one specific product. It can distribute its capacity and produce a variety of products at the same time. The set of products a facility is able to produce is called **product portfolio** or **product mix** (cf. Kahn and Morales (2001) [65]). A facility is independent in the choice of the product portfolio. The focus of production can change with qualification of different products. Nevertheless, there are some requirements to enable a facility to produce a product. Firstly, it requires free capacity. In addition, it has to undergo a **qualification** of the entire production stage. Every operation of the production stage has to be qualified at least on one of the machines. The thesis follows the understanding of Dinkelmann et al. (2014) [29], where the qualification builds the capabilities to perform a new operation. It enables the production resources to produce a product. For the dicing production stage in the semiconductor industry, every operation has to be qualified in a facility to perform the dicing production stage for a new product in a facility[2]. A qualification includes the necessary installation of hardware like saw blades or other machine components like handling units in the dicing machine. In parallel, potential software components may have to be installed. Furthermore, auxiliary material and consumable supply like cooling fluids have to be ensured. Additionally, the operation instructions have to be developed. The operation instruction describes what the machine and the workers have to do. It specifies process parameters and necessary machine configurations. In the dicing process, it specifies the kind of saw blade, the maximum degree of blade wear, the cutting speed, cutting posi-

[2] The dicing production stage cuts the wafer into the single dies. Therefor necessary hardware, software and control specification limits have to be defined in the qualification.

tions, cooling temperature, and further more. These parameters have to be tested and validated in advance on the single machine to avoid machine-specific process deviations. To keep track of the dicing process, specific test operations have to be developed to check the contamination with dust, the integrity of the cutting edges, and more. Furthermore, staff has to be trained for the handling of the product and the machine for the new operations. The training can be specified for technical and operational staff. Technical staff has to be trained to perform repair and maintenance tasks, operational workers have to be trained for the execution of the new operations. In addition to the single machine qualifications, automation and transportation routes and processes have to be installed in the facility. To summarize, depending on the complexity of the production stage and the number of operations involved, each qualification process can be more or less time consuming and expensive. If the qualification process is performed for each operation of a production stage, the facility is able to execute the production stage and produce the corresponding product. Thus, the facility has an active qualification state for this product for the current period. To maintain the qualification state, the performance of the machine has to be checked during the operation. If the operation has not been performed for one period, the quality requirement can not be guaranteed. Accordingly, the qualification state is deactivated automatically after one period, if the operation has not been performed. Both, the qualification itself and the maintenance of a qualification generate **qualification costs** and **qualification time**. The qualification as well as the qualification maintenence block the machine for a specific time and therefor reduce the capacity of the machine and consequently of the facility. Thus a qualification clearly differs from an **investment**. An investment extends the capacity of a resource and a qualification extends the capability of the resource. A qualification is inferior to an investment. It assumes the capacity of the resource as given. It enables the use of the capacity and determines the flexibility of the resource. Each capacity investment has a specific **procurement time**. Thus, a capacity investment is inert

and only becomes effective for the first time after this specific procurement time.
Performing a specific qualification on the new machine enables the facility to perform the corresponding operation and consequently take responsibility for a specific production stage in the **supply chain** for a final product. According to Skukla et al. (2011) [110] the supply chain is a chain of facilities, which transform raw materials to product components and then to final products to fulfill the customer demand. Muysinaliyev and Aktamov (2014) [85] differentiate between value chain and supply chain. Following their differentiation, this thesis exclusively focusses on supply chains. The supply chain of a final product covers all production stages of the work plan. Therefore, different facilities participate in the supply chain, taking responsibility for specific production stages. Each facility acts as a **production partner** in the supply chain. Thus, a production partner is a facility, which takes responsibility for at least one specific production stage in the entire work plan. It is part of the supply chain for the particular final product. As modern facilities are not dedicated to one product but might produce a product mix of several products, they are involved in other supply chains as well. Hence, they collaborate in a so-called **supply network**, serving different final products for different customers and markets (cf. Slack et al (2009) [114]). Referencing again the semiconductor industry, a wafer fab produces various ASICs for different applications. Thus, it serves various final products such as Electronic Control Units (ECU) or smart phones. Accordingly, it is a production partner in various supply chains and supplies various customers and markets. Consequently, it collaborates in a multi-dimensional dynamic supply network, including several supply chains.
Following the idea of Hax and Golovin (1977) [59] the entire supply network can be centrally coordinated with a so-called **Hierarchical Planning System**. A hierarchical planning system considers different **planning levels** with different planning decisions. The planning levels are differentiated according to their **planning horizon** and **planning buckets**. The planning

horizon determines the time scope, which is considered by the planning level. Depending on the planning horizon, a planning level can coordinate planning decisions with different scopes and impact. The planning buckets structure the planning horizon in periods and determine the granularity of the plan. Literature differentiates between small bucket and big bucket models. While small bucket models only allow one decision per period, big bucket models allow multiple decisions (cf. Quadt and Kuhn (2008) [97]).
As described in detail in section 3.1, hierarchical planning levels will be differentiated in **long-term planning**, **mid-term planning** and **short-term planning** (cf. Anthony (1965) [3]). In the long-term planning, the resources are specified and capacitated. In the mid-term planning, the production focus of the resources is coordinated with the resource qualifications. Thus, dynamic supply networks can be designed from static capacitated resources. In the short-term planning these dynamic supply networks are utilized (cf. Günther and Tempelmeier (2016) [54]). This thesis aims to design dynamic supply networks minimizing the overall supply network costs. The **overall costs** consist of production costs, qualification costs and holding costs. **Production costs** occur, when a production lot is produced. The production costs directly depend on the volume produced and can also be called variable costs of production (cf. Grant and Young (1996) [53]). **Holding costs** occur, when a production lot has to be stored. As already defined above, qualification costs occur, when the production resources are prepared for production of a specific product. According to Quadt and Kuhn (2008) [97] for capacitated lotsizing problems only qualification and holding costs are considered as decision-relevant. This definition of decision-relevant overall costs is also applied in this thesis for supply network design. In this thesis, the term overall costs only contains the decision-relevant costs (qualification costs and holding costs).
In addition to the referenced terms, this thesis introduces a set of new terms to close the targeted research gap. These are also introduced now in advance

of their use.

1. Combining the work plan and the process time, the **Linear Capacity Program** for every production stage can be generated. The Linear Capacity Program describes the capacity requirement of all products in the system as a linear program (LP). Using this definition, the Linear Capacity Program will be derived in detail in section 4.2.1.

2. As mentioned earlier, a facility resource can produce multiple products in parallel. This characteristic is essential in this thesis and is described by the novel term **multitasking facility**.

3. As resource qualifications play an essential role in this thesis, they are specified in detail. Firstly, a qualification is **mix-dependent**. The effort (costs and time) of the qualification depends on the product mix, which is already qualified. This characteristic is leaning on the concept of sequence-dependency in capacitated lotsizing models (cf. Quadt and Kuhn (2008) [97]). Details of this characteristic are derived in section 4.2.1.

4. The mix-dependency of two product mixes is determined by the so-called **relationship of products** or **relationship of product portfolios** in specific. The relationship of products (respectively product portfolios) quantifies the similarity of two products (respectively product portfolios).

5. Considering the concept of mix-dependency, qualification costs include two cost factors: The **basic cost** component and the **mix-dependent cost** component. These cost factors are discussed in section 4.2.5, when the qualification matrices are generated. For definition of the terms at this point, basic costs can be understood as a fix qualification cost factor. These basic costs represent product- and

mix-independent qualification effort like general cleaning procedures or general parameter test runs. The mix-dependent part of the qualification effort is influenced by the complexity and diversity of the product to be qualified to the previously qualified product mix. If a new product closely resembles the already qualified products, the mix-dependent cost factor is lower as if it is completely different. The mix-dependent cost component can be understood as the variable part of the qualification costs. Equivalently to the basic and mix-dependent qualification cost concept the basic and mix-dependent qualification times can be defined.

6. Additionally, the effort of a product qualification depends on the history of the resource. The thesis differentiates between **initial qualification**, **re-qualification** and **qualification maintenance**. An initial qualification is necessary, if the product has never been qualified on the particular resource. The re-qualification is necessary, if the product has already been qualified in the past. The qualification maintenance is necessary, if the product has an active qualification state in the previous period, which can be taken over to the current period. Therefore, the corresponding **initial qualification costs** and **initial qualification time** represent the effort for the initial qualification. Equivalently, the **re-qualification costs** and **re-qualification time** represent the effort for a re-qualification and the **qualification maintenance costs** and **qualification maintenance time** represent the effort for the qualification maintenance. This concept is called **qualification differentiation** and will be derived in detail in section 4.3.1.

These novel terms are motivated and derived in detail on this basis throughout the thesis. Finally, some general terms have to be introduced to provide a precise differentiation of the terminology.
The term **classical** is used for conventional assumptions and approaches like

linear supply chains instead of modern multi-dimensional supply networks. In the end of the thesis, the results are analyzed in specific **experiments**. Each experiment aims for a specific modelling effect. The experiments are clustered in **scenarios**, where the parameters of the experiment are varied. Further, it is necessary to differentiate the terms **evaluation** and **validation**. An evaluation is used to understand the behavior of a model in the thesis. A validation is used to assess the quality of heuristical solutions compared to the optimum.
These main terms provide an understanding throughout the thesis. In the subsequent section 2.2 the practical planning problem, tackled in this thesis, is characterized, using these definitions.

2.2 Characterization of the Dynamic Supply Network Design Problem

As introduced in chapter 1, supply networks have to be designed dynamically to cope with the increasing volatility of the markets. The current chapter intends to characterize the DSNDP to answer the first research question, how to design dynamic supply networks. This thesis aims to coordinate suitable resource qualification policies to bridge the static capacities to the volatile market requirements. The idea is to systematically adapt the capabilities of the given resources to the market requirements. Therefore, it is assumed that production sites as well as their capacities are given, but their capabilities can be changed with a qualification process. Of course, this flexibilization is assumed to generate additional qualification costs. If the dynamic qualification of resources on the mid-term level is still not able to cover the entire demand volatility, there exists the additional option for pre-production. The DSNDP tackles the tradeoff of just-in-time production with numerous qualifications versus block production with less qualifications but huge holding costs. It provides the options to fulfill the demand either from direct production in a facility or from the stock from previous periods. The DSNDP evaluates whether the gained reduction of holding costs outweighs the additional qualification costs or vice versa. Consequently, only cost-efficient qualifications are scheduled. Hence, only the efficient facilities are qualified to fulfill the demand of the specific products for one or more periods. This objective guarantees that the capacitated facilities build cost-efficient dynamic supply networks, which may change dynamically throughout the periods.

Altogether, the discussed DSNDP takes the facilities and capacities as well as products and demand (demand forecasts) as given and decides accordingly, which facility will satisfy, which product demand. Thereby, the capabilities of the capacitated facilities are kept flexible and qualification costs steer the qualification decisions.

Minimizing the overall costs, the DSNDP will qualify as many products as necessary but as few as possible in each facility. In this way in each period, the dynamic supply network will be adapted to efficiently fulfill the current demand.

In principle, with enough financial expenditures each facility could be qualified for each product needed. Decisions always will turn to the resource with lowest qualification effort. As a mid-term planning problem, the DSNDP is going to be incorporated in the state of the art hierarchical planning systems described for example by Tempelmeier (2017) [118]. For this purpose the subsequent chapter 3 will review the state of the art hierarchical planning systems and the involved planning problems.

3 Literature Review

The DSNDP has to be embedded in an hierarchical planning system. Therefor, it is essential to generate a state of the art overview of hierarchical planning systems as a first part of the literature review. This prepares the answer for the second research question, how to integrate the DSNDP to the hierarchical planning system. With this background, specific spotlights are set on the supply network design problem itself as well as on related problem formulations, such as location planning. This top down review will underline the research gap of this work.

3.1 Hierarchical Supply Chain Planning

Various approaches are proposed from the literature, to efficiently coordinate and synchronize the complex planning processes of huge global supply chains. Mainly two different strategies for production planning in supply chains can be differentiated:

1. Monolithic production planning approaches
2. Hierarchical production planning approaches

In monolithic production planning approaches all decisions are tried to be included within one planning model. This generally is on the one hand very computation-intensive and on the other hand suffers from a lack of detailed information at the right time (Vogel et al. (2017) [120]). Monolithic planning approaches may for sure have advantages concerning synchrony in simple supply chains with limited coordination effort. But as supply chains become more complex with shorter product life cycles, data availability can no longer be guaranteed and heterogenous physical structures are emerging. This provides obstacles for the monolithic approach. In the industrial context a monolithic planning approach will no more be feasible as different responsible parties decide in different points in time about different planning horizons and share only information required to avoid information overflow (cf. Schneeweiss (2003) [109]). Already in 1975, Hax and Meal (1975) reject an integrated monolithic planning system, due to prevention of management involvement at the specific stages of the decision-making process, even if it was possible to execute [58]. Sttladtler and Fleischmann (2012) state that the monolithic approach will never be suitably solvable nor satisfy the management requirements [115]. To cover these challenges Hax and Meal in 1975 came up with an hierarchical approach, which showed the hierarchical advantages [58]. The planning processes are graded to different hierarchical planning levels [58]. According to Dempster et al. (1981) [24] every planning level involves planning decisions on a specific aggregation level. On each level, specific suitable planning models coordinate the considered planning problems for a given planning horizon with the adequate planning granularity. The models therefor only require the necessary and available information and forward the planning decisions to the subsequent level as constraints. (cf. Vogel et al. (2017) [120], Rohde (2004) [105], Fleischmann and Meyr (2003) [41], Askin et al. (1992) [4], Dempster et al. (1981) [24], Hax and Meal (1975)[58]). Supply chains with increasing complexity in challenging global markets require such staggered planning approaches in different hierarchical levels with different scopes and planning horizons (cf. Schneeweiss (2003))[109], Tempelmeier (2017) [118]). The hierarchical planning approach is attractive because it does not have to be monolitically performed as a whole but each level can be performed independently. To coordinate one specific planning problem (ceteris paribus) in the hierarchical approach, not the entire planning system has to be executed. This avoids additional calculation effort and helps concentrating on

the decision of interest (Vogel et al. (2017) [120], Sawik (2009) [107]). A long-term plan which covers the entire supply chain on the most granular level is neither needed nor possible (Vogel et al. [120], Askin et al. (1992) [4]). Due to these reasons this work only considers hierarchical planning systems.
Fleischmann and Meyr (2003) summarized the following four characteristics of hierarchical planning systems [41]:

1. Longer planning horizons lead to higher uncertainty
2. Shorter planning horizons need higher planning frequencies
3. Every hierarchical level can be aggregated in different dimensions (e.g. time, products, resources, operations)
4. Planning levels map the hierarchical structure of the company and the importance of the decisions of every level varies, depending on the power of the decision maker.

There are multiple planning approaches existing, which take into account all of these characteristics, while others only partially incorporate these characteristics (Vogel et al. (2017) [120]).
Most hierarchical planning literature agrees that the staggered planning process in each planning level only takes one variable decision and ceteris paribus takes the environment as given constraints (cf. Fleischmann and Meyr (2003) [41]). Although the concrete design of real planning problems varies according to the industrial requirements, the general structure of the hierarchical planning system is similar throughout the industrial domains (cf. Vogel et al. (2017) [120], Askin et al. (1992) [4]). As introduced in section 2.1 Anthony (1965) [3] categorizes the general hierarchical planning structure in three commonly accepted planning horizons: The **long-term planning** with a planning horizon of more than 24 months covers strategic resource investment planning problems, the **mid-term planning** with a

planning horizon of 6 to 24 months covers tactical qualification planning decisions with the aim to efficiently use the given resources and the **short term planning** with a planning horizon of a few days to 3 months specifies the concrete planning instructions for the intermediate execution. On this basis Günther and Tempelmeier (2016) differentiate the following four hierarchical planning levels with decreasing planning horizon and decreasing size of time buckets: **Aggregate planning**, **master planning**, **lotsizing**, **fine planning** [54]. Beyond these generic classifications each hierarchical planning approach has certain similarities and differences. To better structure the different approaches from literature and show similarities and differences the following evaluation criteria (C.1 - C.9) are introduced here:

1. C.1: Uncertainty considered
2. C.2: Planning horizons decreasing
3. C.3: Planning granularity increasing
4. C.4: Time buckets decreasing
5. C.5: Rolling planning horizons assumed
6. C.6: Aggregate planning concentrating on entire supply chain
7. C.7: Master planning concentrating on single production stage
8. C.8: Aggregate decision is constraint for subsequent decision
9. C.9: Parallel resources considered

The first three criteria (C.1 - C.3) are captured from the literature review of Fleischmann and Meyr (2003) [41]. Additionally, two criteria (C.4 - C.5) are added according to the literature review from Vogel et al. (2017) [120]. The remaining criteria (C.6 - C.9) are added in this work. The following table 3.1 uses these criteria to evaluate major hierarchical planning approaches from literature. If the criterion is fulfilled by a specific contribution, this

is indicated by a ”*y*”, while an ”*n*”, indicates if its not fulfilled. An ”*o*”, indicates whether there is no focus on this criterion or it is not mentioned explicitly in the respective contribution.
Following this overview the hierarchical planning history can be understood. Hax and Meal [58], Hax and Golivin (1977) [59] as well as Bitran et al. (1981) [12] are major pioneers in hierarchical planning systems. All three pioneer groups of authors are linked to the Massachusetts Institute of Technology (MIT) so that the hierarchical production planning theory often also is called MIT-theory [108]. Hax and Meal (1975) for the first time mention the existence of an aggregate coordination effort between different production plants. The coordination effort has to be managed prior to the detailed scheduling problem. Thereby, as mentioned earlier the decision about the aggregate coordination problem serves as a constraint for the detailed scheduling problem (cf. Hax and Meal (1975)[58], Vogel et al. (2017) [120], Askin et al. (1992) [4], Rohde (2004) [105]). Hax and Golovin (1977) on this basis present an extended approach, where detailed planning levels provide beneficial detailed information in a feedback loop, back to the aggregate planning level [59]. Bitran, Haas and Hax (1981) compare different disaggregation strategies with real life data. Thereby, they set special attention to problems of infeasibility as well as to the treatment of high setup costs [12]. Although multiple approaches already existed in the early years the hierarchical planning theory still suffered from the lack of industrial acceptance [82]. According to Meybodi and Foote (1995), this motivated a number of practical studies reporting the cost saving potential of hierarchical planning approaches in different industries [82].
During time different hierarchical planning systems developed with different structure and planning levels (cf. Gabbay [46], Oliff and Burch (1985) [89], Liberatore and Miller (1985) [75], Borison et al. (1984)[13], Axsäter and Jönsson (1984) [6], Leong et al. (1989) [74], Bowers and Jawis (1992) [14], Zäpfel (1996) [126], McKay et al. (1995)[78], Herrmann et al. (1994) [60]) Most systems incorporate two hierarchical planning levels - Aggre-

Table 3.1: Review of Hierarchical Planning Literature with assessment of Criteria 1-9

Contribution	C.1	C.2	C.3	C.4	C.5	C.6	C.7	C.8	C.9
Hax and Meal (1975) [58]	y	y	y	y	n[a]	y	y	y	y
Hax and Golovin (1977) [59]	y	y	y	y	o[b]	n	y	y	o[c]
Bitran et al. (1981) [12]	y	o	y	o	y	n	y	y	n
Axsäter and Jönsson (1984) [6]	y	n	y	y	n	n	y	o	y
Chung and Krajewski (1987) [21]	y	y	y	y	y	n	y	n	o
Herrmann et al. (1994) [60]	n	y	y	y	y	n	y	y	y
Meybodi and Foote (1995) [82]	y	y	y	o	y	n	y	y	n
Zäpfel (1996) [126]	y	y	y	o	y	n	y	y	o
Qiu et al. (2001) [96]	y	n	y	n	y	n	y	y	o
Gebhard and Kuhn (2008) [50]	y	y	y	y	y	n	y	y	n
Rohde (2004) [105]	y	y	y	y	y	n	y	y	n
Aghezzaf et al. (2011) [1]	y	y	n	y	y	n	y	y	n
Ortiz-Araya, Albornoz (2012) [91]	y	y	y	n	y	n	y	y	n
Kröger (2014) [69]	y	y	y	y	y	n	y	y	n
Stadtler and Fleischmann (2012) [115]	y	y	y	y	y	y	y	y	o
Gebhard (2009)[49]	y	y	y	y	y	o[d]	y	y	y

Abbreviations:

[a] – not mentioned explicitly

[b] – not mentioned but obvious

[c] – not mentioned but obvious

[d] – not mentioned but obvious

gated planning and detailed production scheduling. Specific approaches differentiate between more than two hierarchical planning levels. Both Buzacott (1985) [16] and Jaikumar and Van Wassenhove (1989) [63] describe a three-stage hierarchical planning approach. Buzacott (1985) [16] introduces the planning levels pre-release, order release and operational control for the mid- to short-term hierarchical planning system of flexible manufacturing systems. Jaikumar and Van Wassenhove (1989)[63] cluster in top-, medium- and bottom level. The top level incorporates mid-term planning decisions, which coordinate parts and production volumes. The medium level corresponds to the lotsizing level in Günther and Tempelmeier (2016) [54] and the bottom level manages the scheduling (cf. Askin (1992)[4]). Figure 3.1 sets the understanding of the hierarchical planning system in this work in relation with the approaches of Buzacott (1985) [16], Meyr (2002) [83] and Günther and Tempelmeier (2016) [54].

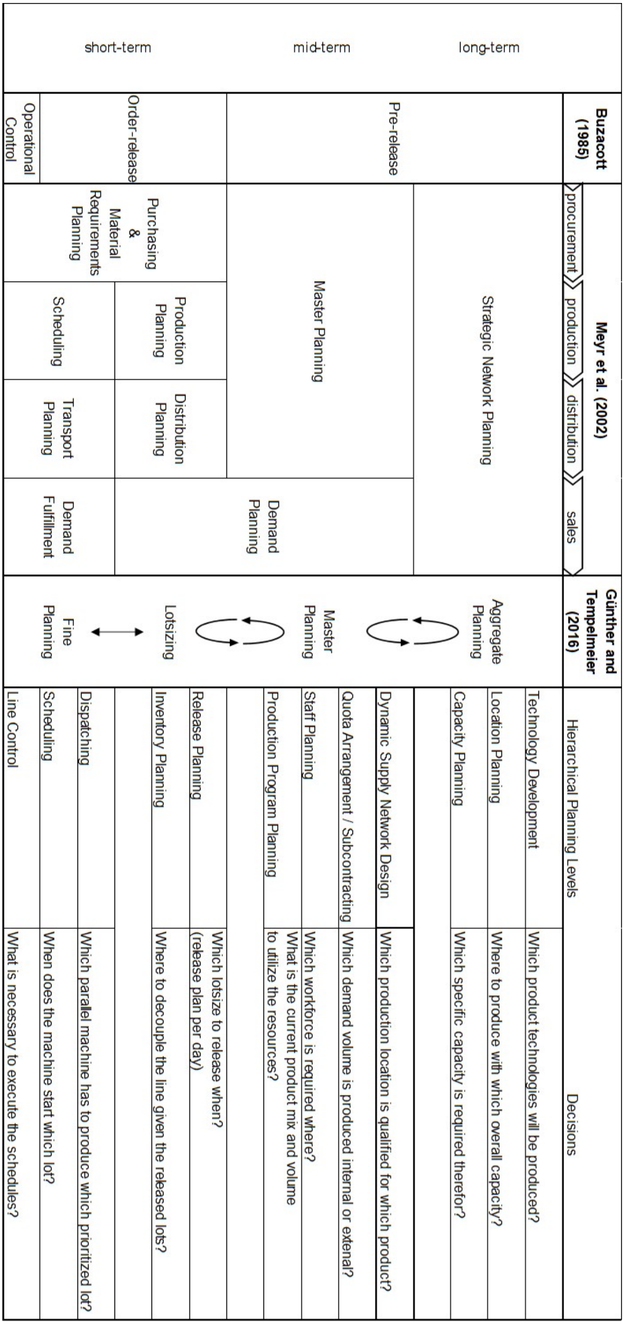


Figure 3.1: Classical Hierarchical Planning Systems

Recent approaches are mostly influenced by the supply chain planning matrix from Meyr (2002) [83] described in 3.2 (e.g. Stadtler (2012) [115]). Rohde (2004) [105] is differentiating between strategic network planning, which operates with a long-term scope, master planning, which coordinates mid-term decisions and production planning / scheduling, which coordinates the short-term production schedules. This hierarchical clustering is quite related to the approach from Günther and Tempelmeier (2016) [54], who differentiate in the four hierarchical levels, mentioned earlier. Recent approaches focus on improving the consistency of the stepwise graded planning levels. Gebhard and Kuhn (2008) [50], Gebhard (2009) [49] as well as Lasserre and Merce (1990) [71] therefor propose robust aggregate planning approaches and a specific range of variation for the detailed production plans. Thereby, Gebhard and Kuhn (2008) [50] consider entrance probabilities to cope with the uncertainty. Subsequent planning levels can use their specific detailed information to vary around the robust aggregate plan. To improve the consistency of planning, often the feedback loop approach from Hax and Golovin (1977) [59] is used. Chung and Krajewski (1987) on this basis focus on bottom-up feedback loops in rolling horizon planning to improve planning consistency. The detailed planning levels provide useful information for the aggregate planning level within a rolling planning horizon (Chung and Krajewski (1987) [21]). Other approaches manage the improvement of planning consistency with simulation-based feedback loops or even the help of artificial neural networks (cf. Rohde (2004) [105], White (2012) [98]). The aim is to explore detailed information from the granular levels at the aggregate level. White (2012) is introducing the simulation-based approach to explore different scenarios in the hierarchical planning process e.g. the effect of different kinds of feedback between the levels [98]. Rohde (2004) is training an artificial neural network with detailed planning results from the granular level to approximate the details with the artificial neural network on the aggregate level [105]. Although there has been quite some effort in making the hierarchical planning system more efficient and

ensuring higher planning consistency, the basic structure of the hierarchical planning system stays constant for years.
Summarizing this section of the literature review, hierarchical planning systems more than ever have an indisputable use in planning. For specifying and embedding the focussed DSNDP this work assumes a hierarchical planning system with four hierarchical planning levels according to Günther and Tempelmeier (2016) [54] and three planning horizons according to Anthony (1965) [3].
In order to motivate as well as embed the DSNDP in the hierarchical planning system, the following section will introduce the state of the art planning problems and their objectives. The last section of the literature review will focus exclusively on contributions in the area of dynamic supply network design.

3.2 Typical Supply Chain Planning Problems

This section of the literature review reviews the four hierarchical planning levels approach from Günther and Tempelmeier (2016) [54]. It is substructured in three subsections. One for the aggregate planning level, another for the master planning level. The third subsection combines the lot-sizing level and fine planning level. Each subsection comprises a set of typical planning problems of the particular planning level. The involved planning problems of each level depend on each other and can again be hierarchically structured within the planning level. There are different hierarchical problem structures existing in literature. Depending on the methodological focus, as well as the industrial domain, the structures and problems can differ. The introduced state of the art planning problems assumed in this work are leaning on the general structure of the hierarchical planning process provided by Günther and Tempelmeier (2016) [54] and to the supply chain planning matrix provided by Meyr et al. (2002) [83] and aligned with the hierarchical planning structure in typical semiconductor supply networks.

3.2.1 Aggregate Planning Problems

Motivated by these two contributions, this work assumes, that the task of aggregate planning is to develop the physical and organizational infrastructure of the supply chain. Meaning, deciding, about the technologies and markets to focus on, followed by the decision, where to produce and store, and thereafter, which amount of capacity to install where. Fleischmann et al. (2015) [42] structure these decisions in the following long-term planning problems: Product Program Planning, Planning of Physical Distribution Structure, as well as Plant Location and Production System Planning. Leaning on this clustering and adjusted to the domain-specific environment, this work assumes the following planning problems involved in the aggregate planning level:

1. Technology Development
2. Location Planning
3. Capacity Planning

In Technology Development it has to be decided, which kind of product technology to focus on. In the Location Planning it is decided, which product groups are necessary for the decided product technologies and where the production and storage locations are efficiently located. The location of suppliers, customers, technology, infrastructure and staff is influencing this decision. After deciding, where to locate the facilities, it has to be decided, which capacity is necessary to fulfill the estimated demand. Due to the long planning horizon of multiple years these investment decisions are based on demand forecasts for product groups. Due to the high investments as well as long procurement times of machine capacities, the capacity planning problem clearly is a problem of the aggregate planning level. From this point in time, the technologies, locations, and capacities are given and the master planning level has to efficiently use it. Especially in semiconductor industry, the investments and procurement times of effective machine capacity are quite long. In parallel, product life cycles are tremendously shortening. Hence, with shorter product life cycles, the static capacitated locations should somehow be flexibilized in the underlying master planning level.

3.2.2 Master Planning Problems

The master planning level coordinates the demand with the given resources. The aim is to cover the volatile demand with the given resources. According to Albrecht et al. (2015) [2] the state of the art master planning level therefor considers the following degrees of freedom:

1. Pre-production
2. Alternative sites with higher transportation costs
3. External capacities
4. Work overtime

The four degrees of freedom do not consider any change of production focus of a resource itself. Albrecht et al. (2015) [2] only consider additional external capacities, additional shifts, or pre-production as possible options to cope with volatilty.

There is not much contribution in literature yet, covering volatility by designing dynamic supply networks with flexible resource capabilities.

Fleischmann and Koberstein (2015) [42] introduce Strategic Network Design, which deals with long-term network design assigning capacities. Albrecht et al. [2] use this approach, but directly continue to plan dynamic production quantities on the developed static network. Fleischmann et al. (2015) [43] in the long-term aggregate planning level decide about the locations, capacities as well as suppliers and production partners. In the mid-

term master planning they capture this static supply chain and coordinate the distribution planning and master production scheduling as well as the staff planning and material requirements planning. Although, the master production scheduling proposed by Fleischmann et al. (2015) [43] considers changing demand, it does not consider changes of the product portfolio with ex-post qualification of the facility capacities for the required products as a possible reaction to this dynamics.
Due to this issue, this work proposes the dynamic coordination of facility qualification in the dynamic supply network design approach as a possible alternative response to shortening product life cycles. This approach thereby complements the state of the art master planning approaches to increase the flexibility of supply networks in the master planning level.
After deciding, which dynamic production capabilities are qualified on the available static capacitated facilities, the dynamic supply network is prepared for the mid-term planning horizon. In addition to the proposed DSNDP, the following state of the art of hierarchical master planning problems is assumed:

1. External Production Quota Arrangement and Subcontracting
2. Staff Planning
3. Production Program Planning

This classical set of hierarchical planning problems is based on the approach of Fleischmann et al. (2015) [43]. Especially in semiconductor supply networks it is commonly practiced to subcontract production partners for external capacity (e.g. Albrecht et al. (2015) [2]). A specific quota of the demand may be transferred to external production partners to use economies of scale or to simply flexibilize capacity. Of course this triggers high costs, which have to be weighted against the value of the flexibility gain. These external production quotas are coordinated in the so-called quota arrangement problem. After it is decided, which part of the demand has to be finally fulfilled

in each facility, considering the capacity and capability constraints, necessary staff can be coordinated in the staff planning problem. As staff can be hired or trained quite flexible, the staff planning problem clearly can be assigned to the master planning level. The staffing decision is followed by the production program planning problem, which details the rough production plans from ”above” in higher granularity and prepares the inputs for the following lotsizing activities. The production program is now considering single products and no longer product groups as the other master planning problems (Fleischmann et al. (2015) [43]).
Altogether, the following set combines the proposed additional DSNDP with the classical set of master planning problems leaned to Fleischmann et al. (2015) [43]:

1. **Dynamic Supply Network Design**
2. External Production Quota Arrangement and Subcontracting
3. Staff Planning
4. Production Program Planning

3.2.3 Lotsizing and Fine Planning Problems

The short-term lotsizing and fine planning levels, proposed by Drexl et al. (1993) [32] and elaborated by Günther and Tempelmeier (2016) [54], consequently use the solution of the master production program. The lotsizing level proposed by Günther and Tempelmeier (2016) [54] contains the release planning problem or capacitated lotsizing problem (CLSP) reviewed by Quadt and Kuhn (2008) [97]. The aim of this problem is to cluster the product demand considering the given resource capabilities to production orders for the single resources. On this basis the inventory planning aims to hold the right number of lots at the right place, such that costs are minimal and demand can be fulfilled (cf. Engelmeyer (2016) [37]).

Two further planning problems can be assigned to the fine planning level. Dispatching / Scheduling as well as production controlling. When the actual, machine specific dispatching and scheduling problems are solved, the short term production schedule is defined. From this point, the production controlling only has to prioritize or deprioritize the production lots, if an unexpected resource breakdown occurs. With the production control the hierarchical planning activities merge into the real-time control activities.
Altogether, summarizing the planning problems from the four planning levels, the following hierarchical set of classical planning problems can be concluded. It combines the major contributions from Albrecht et al. (2015) [2], Meyr (2002) et al. [83], Tempelmeier (2017)[118], Günther and Tempelmeier (2016) [54], Fleischmann and Koberstein (2015) [42] and Fleischmann et al. (2015)[43].

1. Technology Development
2. Location Planning
3. Capacity Planning
4. Quota Arrangement
5. Staff Planning
6. Production Program Planning
7. Release Planning
8. Inventory Planning
9. Dispatching / Scheduling
10. Production Controlling

This work complements this state of the art hierarchical planning system, introduced above, by the necessary **Dynamic Supply Network Design Problem**. It will be integrated as an additional planning problem between the

capacity planning problem and the quota arrangement problem.
As mentioned, the nomenclature of the planning problems is applied to the specific concerns of this work and may differ in different industrial domains. By the hierarchical coordination of these planning problems, globally optimized production schedules can be generated across the entire supply chain. Thereby, it can be ensured, that each resource follows a plan, which is strategically aligned within the supply network. Depending on the structure and complexity of the considered domain and supply network, some planning problems have to be considered more and some less extensively.
The figure 3.2 embeds the resulting state of the art planning problems extended by the introduced DSNDP in the four hierarchical planning levels proposed by Günther and Tempelmeier (2016) [54].
The subsequent section captures the generated understanding of the hierar-

Extended Hierarchical Supply Network Planning Process

	Hierarchical Planning Levels	Decisions	Objective Function	Given
Aggregate Planning	Technology Development	Which product technologies will be produced in SC?	Max. market share	- demand (forecast) - customers
	Location Planning	Where to produce with which overall capacity?	Min. SC investment	- demand - technologies
	Capacity Planning (MAE inv.)	Which specific capacity is required therefor?	Min. SC cost	- service level - demand
Master Planning	Dynamic Supply Network Design	Who is qualified for which product	Min. SC cost	- service level - capacities - demand – hist. capabilities
	Quota Arrangement / Subcontracting	Which actual volume is produced internal or external? (capa flexibilization)	Min. SC cost	- service level - capacities - demand
	Staff Planning	Which workforce is required for each step?	Max. service level	- service level - capacities - demand
	Production Program Planning (MAE util.)	What is the actual product mix and volume to utilize the resources?	Max. utilization	- service level - capacities - demand
Lotsizing	Release Planning	With given product mix, which lot size to release when? (release plan per day)	Max. service level	- service level - capacities - demand
	Inventory Planning	Where to decouple the line given the released lots?	Max. bottleneck utilization	- demand variability - production variability
Fine Planning	Dispatching	Which parallel machine has to produce which prioritized lot?	Max. bottleneck utilization	- machine setup times - machine capabilities
	Scheduling	When does the machine start the dispatched lot?	Min. due date deviation	- dispatch list - due dates
	Line Controlling	What is necessary to execute the schedules? (excursion management)	Min due date deviation	- Resource spec. schedules - due dates

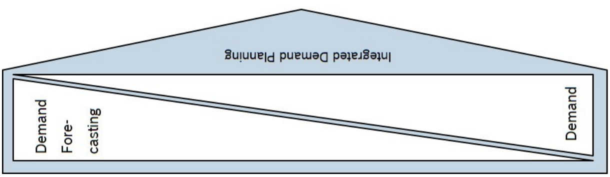


Figure 3.2: Extended Set of Hierarchical Planning Problems

chical set of planning problems and centers the focus of the literature review further on the Supply Network Design Problem. This most specific section 3.3 of the literature review evaluates already existing contributions to this planning problem.

3.3 Supply Network Design

After the state of the art planning problems have been elaborated and the new planning problem "Dynamic Supply Network Design" has been embedded, this section analyzes already existing approaches for specifically this problem from the literature.

In this literature review the term supply network design problem will be used equivalently to the term supply chain design problem as it is used synonymously in literature. As borders between the planning problems are often fluent in literature, special focus is not only set on the DSNDP but also on the quite related location planning problem. Some mature contributions treat the supply network design problem as part of the location planning problem, others treat the location planning problem as part of the supply network design problem. This review section will consequently start with analyzing the aggregate location planning approaches to evaluate, if it already answers the DSNDP. Afterwards, this section evaluates different contributions for supply network design from either the aggregate, long-term or the mid-term master planning view. In the end this section will summarize the remaining research gap and motivate the subsequent problem formalization of this thesis.

The location planning problem is discussed for quite a long time. The official scientific trigger for systematic location planning was given by Weber (1909) [122] in his book "Über den Standort der Industrien". Until now recent publications tackle the location planning problem with different algorithms and in different applications and domains. More than ever, in recent globalized markets the problem shows attraction for research. In the past 40 years there have been numerous impacting contributions to this topic (e.g. Francis et al. (1974) [44], Handler (1979) [55], Love et al. (1988) [76], Mirchandani and Francis (1990) [84], Drezner (1995) [34], Drezner and Hamacher (2001) [35], Nickel and Puerto (2006) [87], Church and Murray (2009) [22], Farahani and Hekmatfar (2009) [38], Daskin (2011) [23], Drezner (2014) [33]). In some major contributions the location planning problem is treated as a part of the supply network design problem such as Bangert (2014) [9] as well as Melo et al. (2004) [80]. According to Melo et al. (2009) [81] the supply network design problem is originating from the location planning problem. The production location problem is thereby assumed to define the supply network. Following the hierarchical planning theory according to Yan et al. (2003) [125] the supply network design builds the fundament for all subsequent supply chain management processes. As part of the supply network design the location planning has to assign the production locations minimizing the overall supply network costs (e.g. Chopra and Meindl (2013) [62], Bangert et al. (2014) [9], Simchi-Levi et al (2009) [111]). The perspective of these contributions assumes a static supply network. According to Bangert et al. (2014) [9], location planning can be divided to two different decisions: Production location choice and production location planning. Most contributions approach the location planning problem to be a multi-objective problem. A survey on multi-criteria location problems from Farahani et al. (2010) [39] lists 63 publications related to multi-criteria location planning problems. It depends on the area of application, how many criteria are suggested for the optimization. A basic approach from Ohsawa (1999) [88] is considering the location decision for a single facility with a bi-objective quadratic Euclidic distance model. He combines the minisum and minimax objectives considering efficiency and equity. Nickel (1997) [86] presents an extended version of a bi-criteria location optimization problem with regional restrictions. According to Harrison (2001) [57], Simchi-Levi (2009) [111], Ballou (2001) [8], Freiwald (2005) [45], Kohler (2008) [68] the decision about production location depends on the locations of suppliers and the customers, but also on the targeted size and capacity of the production site. This already anticipates parts of the subsequent capacity decision but is necessary due to facility issues. Considering capacities, literature can be divided into uncapacitated and capacitated location planning problems (cf. Farahani et al. (2010)[39]). Ding et al (2006) [28], as well as Villegas et al. (2006) [119] modelled a bi-objective uncapacitated location planning problem. Whereas, Galvao et al. (2006) [47] proposed a capacitated model with two objectives (travelling distance and load imbalance). This thesis considers the location planning problem as an uncapacitated problem. Following the planning hierarchy described by Albrecht et al. (2015) [2], Meyr (2002) et al. [83], Tempelmeier (2017)[118], Günther and Tempelmeier (2016) [54], Fleischmann and Koberstein (2015) [42] and Fleischmann et al. (2015)[43] the facilities are capacitated after its location has been defined.

There are multiple approaches handling more than two objectives in the location planning problem. For example Awasthi et al. (2011) [5] identify the following 11 relevant criteria for the location planning problem: Accessibility, security, connectivity, costs, environmental impact, proximity to customers, proximity to suppliers, resource availability, conformance to suitable freight regulations, possibility of expansion, and quality of service. Whereas, Doerner et al. (2009) [30] only differentiate four criteria: The minisum facility location criterion, the maximal covering location criterion, a risk criterion, and the overall costs consisting of setup costs and additional costs for the capacity. Chen (2001) presents five influencing criteria which are considered in his fuzzy approach for location planning [17]: The costs for investment, the expansion possibility, the availability of required material, human resources, and the closeness to the demand market. Chou et al. (2008) [20] consider the location planning for a hotel. Therefore they introduce 21 influencing criteria concerning the geographical location, traffic conditions, hotel characteristics, and operations management. Kahraman (2003) [66] propose an optimization approach considering five criteria:

Proximity of customers, infrastructure, quality of labor, free trade zones, and competitive advantage. Harris (2009) [56] considers three evaluation criteria for a facility location problem: Minimization of overall costs, minimization of environmental impact, and minimization of uncovered demand. Additionally, in a multi-level supply network many authors propose to consider and optimize not only the locations for a single site but for the entire production process as a whole (e.g. Harrison (2001)[57], Kohler (2008) [68], Pfohl (2010) [92], Chopra and Meindl (2013) [62]). The optimal location for a site in a single-level supply network and a multi-level supply network can differ.

Summarizing the review of location planning approaches, there are various approaches proposed in the last decades. Most treat the location planning problem as an uncapacitated multi-objective problem. In most cases the capacities are considered to be defined after the location is decided. None of the publications is considering systematic ex-post capacity flexibilization policies at this point in the hierarchical planning process, even if the capacities are decided already in the location planning problem. In none of the approaches a capacitated location is able to dynamically change its production focus. Hence, the recent location planning approaches provide static supply networks and do not fulfill the requirements for dynamic supply network design.

Consequently, literature for specifically the supply network design problem has to be evaluated in the second part of this section to clarify the state of the art in supply network design. Ballou (2001) [8] evaluates supply network design approaches beyond the location planning problem and claims, that especially the area of strategic supply network design suffers from lack of realistic capable and performant models. Models lack in representation of complex and dynamic networks and in performant data acquisition and calculation. Since the contribution of Ballou in 2001 there have been a lot of contributions proposed to this problem, but also the challenges in this field changed since then. The recent approaches of supply network design

problems on the one hand differentiate according to their planning and optimization scope, but also on their modelling assumptions.
The major focus in recent literature is concerned with the development of stable but flexible supply networks (e.g. Tanimizu (2018)[117]). Most contributions on supply network design focus on logistical problems, such as minimization of transportation costs. These contributions will not be analyzed in detail, as they do not tackle the mid-term resource flexibilization problem.
In recent years supply network design literature additionally focusses on ecological issues. For example to design green supply chains or to design and manage close loop supply chains. For example Pinto and Coves Moreno (2014) [93] focus on efficient supply network design concerning minimization of CO_2 emissions. Dubey et al. (2015) [36] include uncertainty of environmental circumstances to their sustainable supply chain optimization model. Also Rezaee et al. (2017) [102] propose a green supply network design approach considering stochasticity in demand and carbon prices.
Some contributions tackle the supply network design problem exclusively on the aggregate planning level by planning optimal locations. For example Hiremath et al. (2013) [61] design the supply network by optimizing the location and capacities in a multi-objective mixed-integer linear programming (MILP) model in order to minimize total costs, maximize facility fillrates and maximize system utilization. Singh et al. (2013) [112] plan the locations minimizing expected inventory- and loss-of-opportunity costs in a two stage stochastic programming model with flexible demand. Another paper of Singh et al. (2012) [113] includes supply risks like shipment delays, production risks, quality problems, etc. The proposed mathematical model of Barzinpour and Taki (2018) [11] is linked to location planning and tries to create an efficient supply network by the right choice of locations with optimizing the trade-off between costs, and emissions for a dual channel supply network. All of these contributions try to develop efficient static supply networks. Babazahdeh et al. (2012) [7] claim the lack of agile sup-

ply network design approaches taking into account capacities as a decision variable. In their work, they develop a MILP approach minimizing the total costs of the supply network. These include fixed opening costs, production cost, outsourcing cost, inventory holding cost, transportation and processing costs, alliance costs between opened facilities as well as shortage costs. The capacity is not given in the model from Babazahdeh, but determined, when the facility is opened. The approach tackles the aggregate planning level and does not consider any qualification issue and no decision, which facility should be qualified for which kind of production in which period in the mid-term master planning level. Like the others so far, also the contribution of Babazahdeh et al. (2012) [7] decides about the static supply network before the capacities are set.

Other contributions are going into the direction of the present work, where locations and capacities are fixed in the aggregate planning level before dynamic supply networks develop in mid-term horizon according to the current market requirements (e.g. Prakash et al. (2018) [95], Ramezani et al. (2013) [100], Fernandes (2015) [40]). These contributions locate the supply network planning problem in the mid-term master planning level. Wadhwa et al. (2007) [121] focus on different flexibilization strategies to keep the supply network agile. This approach directly goes into the direction of the present work. But the approach does not consider the change of resource capabilities according to the current market requirements. Other contributions propose a so-called robust supply network design approach, to cover sources of uncertainty in already capacitated supply chains. For example Prakash et al. (2018) [95] propose a robust optimization approach for stable close loop supply chains assuming supply risks and demand uncertainty. Ramezani et al. (2013) [100] propose a robust optimization approach for designing close loop supply networks considering uncertain environments and demand stochasticity. Fernandes et al. (2015) [40] claim the high demand volatility in the Portuguese Petroleum Supply Chain and propose a robust model including this volatility in agile supply network design. Their approach includes planning problems from the strategic and tactical planning levels. The approach designs and capacitates the supply network first and than optimizes the load per period. This approach seems most helpful for the task of dynamic supply network design. But it does not provide the degree of freedom of changing product qualifications after capacities are planned in the supply network. Instead it just optimizes the volumes of the products assigned in the strategic level. Consequently, it does not develop a dynamic supply network in the understanding of this thesis. Rienkhemaniyom and Pazhani (2015) [104] focus on the stability of supply networks against environmental events like earthquakes, etc. Therefor, they concentrate on location planning in the supply network. Their bi-criteria MILP maximizes total profit and the density of the supply network.

Reyes Levalle (2018) [101] does not propose any optimization model for supply network design, but summarizes strategies for practioners to build stable, resilient supply networks. Mainly, he focusses on the strategies of redundancy, excess resources, communication network efficiency. Change of production capabilities is not considered as an option for flexibilization. In 2016 Jouzdani and Fathian (2016) addressed the supply network design problem under both demand and supply uncertainties and proposed a mixed integer programming model [64]. There are many more contributions, which are designing robust supply networks (e.g. Rezaei et al. (2019) [103], Cheraghalipour et al. (2019) [18], Gao and Ryan (2014) [48], Zokaee et al. (2017) [127], Rahmani (2018) [99], Yaghoubi et al. (2019) [124], Omrani et al. (2017) [90]). They are all from the recent years and from different industrial domains. All are facing the current problem of dealing with uncertainty in capacitated static supply chains. But none of them tackle this uncertainty with flexibilization of resource capabilities.

To summarize this review, literature faces the problem of handling volatility in static systems, but does not provide any proper approach for developing dynamic supply networks on a mid-term level by optimizing the production capabilities under given capacities. Facing the direct industrial requirement,

this thesis formulates this lack as the research gap, which will be tackled and closed in the proposed optimization model for the DSNDP.
With this motivation, the following chapter formalizes the problem in three mathematical models. The three build up on each other. For each model specific model assumptions have to be stated.

4 Problem Formalization

Based on the problem characterization and the literature review, this chapter formalizes the dynamic supply network design problem for the multi-product multi-facility case and formulates a basic as well as two extended mathematical models, which capture necessary industrial characteristics. By developing the optimization models, this chapter answers the third research question, how the costs of a dynamic supply network can be minimized.
The chapter is structured in four sections:
In section 4.1 the basic mathematical model is formulated. For this purpose, the basic model assumptions are defined in subsection 4.1.1. Thereafter in section 4.2 the first model extension is introduced to the model. This second model requires additional model assumptions as well as a pre-calculation routine, which both are introduced in the subsections 4.2.1 and 4.2.5. In the next section, 4.3, a third model is presented as an extension of the previous. It implements further model assumptions from subsection 4.3.1 as well as an extended pre-calculation routine in 4.3.2. The last section 4.4 evaluates the implemented extended model from section 4.3 and its performance and motivates further steps of the thesis.

4.1 Basic Dynamic Supply Network Design Model

The basic mathematical model of the DSNDP captures the basic problem characteristics from section 2.2. It develops a dynamic supply network by qualifying the given capacitated facility resources with the suitable product

portfolios. In this way, the demand can be efficiently fulfilled with minimum overall costs.
In order to formulate the mathematical model, some basic model requirements are derived in the subsequent section.

4.1.1 Basic Model Assumptions

Considering the problem characterization from chapter 2, the basic mathematical model follows some specific model assumptions, which are introduced in this section.
The basic model assumes a multi-product, multi-facility, multi-period case with $n \in (1..N)$ products, $f \in (1..F)$ facilities and $t \in (1..T)$ periods. Consequently the N products can be combined in 2^N different product portfolio combinations. The derivation of the 2^N different product portfolio combinations is introduced in the subsequent subsection. The facilities are treated as single independent resources. Capacities are assumed to be given for every facility and period. In this thesis the demand is assumed to be given and deterministic for every product and every period [1]. As introduced in chapter 2, due to the planning horizon of two years, demand is based on forecasts for product groups. The basic model has the opportunity to react on the variation of demand with a qualification of the suitable product portfolios in every facility and period. A facility can produce product portfolios containing multiple products (multitasking facility). Consequently, not single products but product portfolios are assumed to be qualified. This specific assumption will be introduced in the following subsection 4.1.2. All the qualification time and costs are calculated for the specific product portfolios and not, as commonly done, for single products.
For the basic DSNDP a big bucket structure with monthly planning buckets

[1] A model extension may integrate either service levels or backlog costs and allow, but penalize delay in delivery. This extension is not considered in this thesis. It depends on the use case but in most cases this extension better represents the industrial situation. (For simplification reasons the introduced basic model treats demand fulfillment as a constraint.)

and quarterly planning frequency is assumed. Hence, it is allowed to change product portfolios within the same period. The qualification effort itself is capacity-relevant.

The qualification costs in this basic model are assumed to be constant throughout the time and not dependent on a previously qualified product portfolio. This will be different in the first and second model extension. For this basic model, only a qualification cost matrix and a qualification time matrix of the dimension $Fx2^N$ are required.

In order to mathematically formulate the basic DSNDP the subsequent subsection 4.1.2 specifies the introduced assumption of multitasking resources in detail.

4.1.2 Multitasking Resource

As introduced in section 4.1.1, a facility resource in this approach is assumed to be able to produce more than one product at the same time. Hence, it is able to have multiple products qualified at once and it can perform many operations at one point in time[2].

To mathematically justify that N products lead to a set of 2^N product portfolios, one can apply the rules of combinatorics. The number of possible portfolio combinations of the N products can be derived from the problem of the N-fold coin toss. N times a coin is thrown. Each time there is a chance to toss either head or tail. Equivalently, a product can either be qualified or not qualified. In both applications, there are two possible outcomes for each toss. In the theory of coin tossing, the order of events is taken into account, which must also be taken into account, when combining products. In the coin tossing and corresponding product qualification case tossing a coin N-times generates 2^N result options (cf. Whitt (2013). This can also be proven

[2] In the classical capacitated lotsizing models resources represent single machines which are assumed to be unimodal and thereby only able to produce one product at the same time (e.g. Tempelmeier (2017) [118])

by mathematical induction (see appendix A.1). [123])[3].
Each of the 2^N resulting product portfolios is represented by a vector of the length N. The vector contains a binary variable for each product. Each of the 2^N vectors is different. This vector is containing all N binary decision variables, which indicate, if a particular product n is qualified in the particular period and facility or not. A product can consequently be produced as a part of different portfolio vectors, which are qualified. Also the zero vector is included in the set of 2^N portfolios since it can be qualified, when the facility stays idle. If an empty facility should only be qualified for one product, the product portfolio vector containing only this product can be qualified. If a product is part of a qualified product portfolio, it can be produced, as long as there is capacity left. In the DSNDP the facility has an assumed infinite potential for different operations. The resource capacity can be distributed across the products qualified in this period in the particular facility. Neither from the economical nor from the technical side it will be efficient to qualify all F facilities of the system with all N products. According to the demand structure, it is decided for each facility resource, which product portfolio has to be qualified, involving only as many products as necessary.
In the model, every facility in period one starts with product portfolio 1, which represents the zero vector and indicates an unqualified facility. Altogether, a facility will always be qualified for one out of 2^N product portfolios. Obviously qualifying the zero vector does not cost anything. Disqualifying any of the products in the current product portfolio also is free of costs. For example, if in the three-product-case in period t product mix vector $(1,1,1)$ is qualified and in period $t+1$ only the product mix vector $(1,1,0)$ is required, the disqualification of product 3 is assumed to be free. On the other side, generally, qualifying product portfolio $(0,1,1)$ is more

[3] This can also be derived from the binomial term $\sum_{k=0}^{N} \binom{N}{k}$. In this case k corresponds to the number of draws from an urn or to the number of products decided to be qualified or not qualified. Principally there are $\sum_{k=0}^{N} \binom{N}{k}$ potential production mix combinations existing which equals the described 2^N combinations. This can be proven by mathematical induction, which can be found in the appendix A.1

expensive, than qualifying $(0,0,1)$.
Summarizing this, the given capacitated facility resources can produce multiple products at the same time. This requires the qualification of a suitable portfolio vector out of 2^N possible combinations. The more products the vector includes, the more expensive and time consuming the qualification process is. Hence, it represents a cost tradeoff, to change qualification just-in-time or to produce to stock. The model optimizes this basic tradeoff in order to develop an efficient dynamic supply network to fulfill the volatile demand in every period.
Based on these assumptions, the basic mathematical model is formulated in the subsequent section. Thereafter, the basic model will be extended following further assumptions to make it even more realistic for industrial practice.

4.1.3 Formulation of the Basic Mathematical Model

In this section, the basic mathematical model is introduced, considering the basic model assumptions. The model will be formulated in a mathematical mixed integer linear programming (MILP) approach. Later in this section the single objective function and constraints will be explained in detail.
Mathematical model of the basic DSNDP

Objective function

$$MinCosts = \sum_{t=1}^{T}\sum_{f=1}^{F}\sum_{j=1}^{2^N}\sum_{n=1}^{N}(cq_{f,j} * y_{f,t,j} + ch_n * Y_{t,n}) \tag{4.1}$$

s.t.

$$D_{t,n} = Y_{t-1,n} + \sum_{f=1}^{F} \sum_{j=1}^{2^N} (Q_{f,t,n,j}) - Y_{t,n} \qquad \forall n \in 1..N; t \in 1..T \tag{4.2}$$

$$C_{f,t} \geq \sum_{j=1}^{2^N} \sum_{n=1}^{N} (tq_{f,j} * y_{f,t,j} + PT_n * Q_{f,t,n,j}) \qquad \forall f \in 1..F; t \in 1..T \tag{4.3}$$

$$Q_{f,t,n,j} \leq BigM * P_{j,n} * y_{f,t,j} \qquad \forall j \in 1..2^N; t \in 1..T; f \in 1..F \tag{4.4}$$

$$Y_{0,n} = 0 \qquad \forall n \in 1..N \tag{4.5}$$

$$y_{f,t,j} \in (0,1) \qquad \forall f \in 1..F; t \in 0..T; j \in 1..2^N \tag{4.6}$$

$$Q_{f,t,n,j} \in \mathbb{N}_0 \qquad \forall f \in 1..F; t \in 1..T; n \in 1..N; j \in 1..2^N \tag{4.7}$$

$$Y_{t,n} \in \mathbb{N}_0 \qquad \forall t \in 0..T; n \in 1..N \tag{4.8}$$

As introduced in section 2.2 the objective of the DSNDP is to minimize the overall costs. Consequently, the objective function (4.1) considers the decision-relevant costs among all periods t, facilities f, products n and portfolios j. To decide about a period-specific production program and the required qualification in each facility, the alternatives of just-in-time production and to-stock production are balanced against each other. Hence, the optimization function considers the decision-relevant qualification costs $cq_{f,j}$ on the one hand and the decision-relevant holding costs ch_n on the other hand.

A major architectural assumption of the model is, that the demand is formulated for single products $n \in 1..N$, but the qualification is managed for product mixes $j \in 1..2^N$. Thereby, the model considers the assignment of products to product mixes in the binary product mix assignment matrix $P_{j,n}$. This matrix follows a dimension of 2^N by N. Consequently, to produce a specific product in a specific period and facility, a suitable product mix has to be qualified in this period and facility, which includes this product.

There are a number of additional constraints leading to realistic qualification schedules and executable production programs.
Firstly, due to the production balancing constraint (4.2) the product-specific demand has to be fulfilled either from the stock from previous periods $Y_{t-1,n}$ or from the current period production quantity $Q_{f,t,n,j}$. The residual lots are building the resulting stock $Y_{t,n}$.
Secondly, the capacity restriction (4.3) limits the overall production and qualification volume to the available capacity of each facility and period $C_{f,t}$. The available capacity is not allowed to be exceeded in any period or facility.
Further, the qualification requirement (4.4) forces the model to qualify a suitable product mix, if a specific product has to be produced. The assignment of suitable product mixes to be qualified for the single product to be produced is managed by a multiplication with the binary auxiliary product mix assignment matrix $P_{j,n}$. This auxiliary matrix assigns the particular covered products to each of the specific 2^N product mixes. It thereby contains all 2^N possible product mix vectors. With this auxiliary assignment matrix $P_{j,n}$ the model is forced to qualify one of the suitable product mixes for the necessary production of a specific product n. The constraint itself thereby multiplies a suitable big number "*BigM*" with binary qualification variable $y_{f,t,i,j}$ and with the auxiliary assignment matrix. The product of this multiplication is forced to be greater or equal than the intended production quantity itself. Thereby it is avoided to multiply *BigM* with a zero either from the auxiliary assignment matrix or from the sum of qualification options. This means, a suitable product mix has to be qualified and the necessary product has to be covered by the qualified product mix.
The following initial inventory constraint (4.5) avoids filled stock in the first period. At the beginning of the planning horizon, the stock is assumed to be empty.
The subsequent constraint (4.6) restricts the qualification variables to be binary decision variables. Either a product portfolio is qualified respectively

transferred or not. The last two constraints (4.7) and (4.8) limit the production quantities $Q_{f,t,n,j}$ and stock sizes $Y_{t,n}$ to be positive integer variables in $\mathbb{N}_0$.

This first model covers the main idea of the DSNDP to design a dynamic supply network of capacitated facilities with suitable qualification decisions to fulfill the given demand.

To make the model more realistic to the industrial practice, the subsequent section extends this approach by the additional characteristic of mix-dependency.

4.2 Mix-Dependent Dynamic Supply Network Design Model

In industrial use cases from different domains, one can often experience that the effort for qualifications of a new product is specifically related to the knowledge and system infrastructure, which is already existing in the production system. This section includes the realistic assumption, that the qualification effort depends on the relationship of the portfolio, to be qualified, with its predecessor. This assumption is called ”mix-dependency”. Following the idea, that every product portfolio can be qualified in every facility, makes this assumption necessary. The idea is that a portfolio qualification is more expensive and time-consuming, if the portfolio differs a lot from its predecessor. Therefore, it has to be evaluated, how similar the two portfolios are. An approach to calculate the so-called relationships of product portfolio is therefore introduced. Obviously, this assumption makes the problem more realistic, but also more complex. Hence, the next subsections specify the approach in higher detail. Thereafter, the necessary pre-calculation of the qualification matrices is introduced in section 4.2.5.

4.2.1 Mix-Dependent Model Assumptions

It is obvious to imagine, that a major change to a very different product portfolio costs the facility a lot of qualification time and money. Consequently, the qualification costs for a product portfolio j are assumed to depend on the previously qualified product portfolio i (while $i, j \in 2^N$). If it is closely related, there is not a big intervention necessary to update the facility for the target product portfolio. Whereas, if the portfolio differs quite a lot from the already installed product portfolio the effort for qualification is higher.
The hypothesis motivating this mix-dependency is, that a new demand is most likely, or better to say, most efficiently assigned to a facility, which already produces familiar products. With this strategy, observed in more and more industrial supply chains, the facilities are centering their production focus. Consequently, facilities gain economies of scale not only in the qualification, but also during production. With the evolvement of new demand, also the focus of the facilities collaborating in the supply networks smoothly changes.
The next subsection derives the details of the new mix-dependency assumption.

4.2.2 Mix Dependency

Already installed infrastructure or knowledge and experiences make it easier to qualify related products in the upcoming periods. For example, if a semiconductor fab is already producing ASIC products, it is easier to qualify an additional ASIC product, than a MEMS product[4]. The reason for this is, that the equipment and support infrastructure are specialized and can not be changed too easy to MEMS production. Also, the knowledge of the employees is specialized. It would require a major staff qualification program to provide the production knowledge, which is necessary. Additionally the product-specific experience of the workers leads to significant

[4] ASIC = Application Specific Integrated Circuit; MEMS = Micro-ElectroMechanical System

economies of scale. Each facility plays a specialized role in the supply network. Of course, on a long run, this role can change according to the current emphasis of the supply network and the structure of demand. But, this is obviously connected with higher qualification effort. This approach for the dynamic supply network design problem is providing the flexibility of arbitrarily changing the focus of a capacitated facility by qualifying different product portfolios. It takes into account the already installed product portfolio and thereby the production focus of the facility. Therefore, it proposes quadratic qualification matrices, which provide the costs and time for qualifying from one product portfolio to the other. The dimension of the qualification matrices increases to $2^N * 2^N$. In industrial practice, these large scale mix-dependent qualification matrices obviously do not exist systematically. Hence, they have to be pre-calculated, using the existing data. The degree of similarity of two consecutive product portfolios can be determined with the new approach of ”relationship of products”, respectively ”relationship of product portfolios”. This approach is introduced in subsection 4.2.4 in order to specify the mix-dependent qualification costs and times. The relationship itself is calculated from the similarity of capacity consumption. If two products use the same set of machines to a similar extent, the relationship is assumed to be high. This relationship, dependent on the capacity consumption of the products, can be expressed in the coefficient of product relationship. The relationship of products will be derived from the ratio of product specific requirement of machine capacity. This can consequently be derived from the Linear Capacity Program. This system of product specific machine capacity requirements as defined in section 2.1 is existing in industrial practice and can be extracted from the common MES . When the relationship of all particular products is generated, the relationships of product portfolios have to be derived on this basis. The relationships of the particular products involved in the product portfolio are combined to a portfolio relationship, which is a necessary input for the mix-dependent qualification matrices.

On this basis, the new assumption of mix-dependency will extend the basic DSNDP. In advance, the pre-calculation routine will be introduced in detail in the subsequent three subsections: Firstly the Linear Capacity Program is described in section 4.2.3. It provides the capacity requirement inputs, necessary for the calculation of product relationships. Secondly, subsection 4.2.4 introduces the approach to calculate the coefficient of product relationship as well the coefficient of product portfolio relationship from the inputs of the Linear Capacity Program. In the third subsection 4.2.5 the resulting coefficients of product portfolio relationship serve as an input for the generation of mix-dependent qualification cost and time matrices.

4.2.3 Linear Capacity Program

The following inequality specifies the capacity requirements of all N products on a specific machine m. The products consume the capacity of the machine C_m to a different extent:

$$C_m \geq Q_1 * PT_{1m} + Q_2 * PT_{2m} + ... + Q_n * PT_{nm} + ... + Q_N * PT_{Nm} \tag{4.9}$$

Following the idea of multitasking resources, a machine has to distribute its capacity to a specific combination of products n ($n \in 1,..,N$). How much each product affects each capacity, is influenced firstly by the processing time requirement PT and secondly by the production quantity Q. In addition, the qualification time influences the utilization, as a machine can not produce anything during qualification. Hence, the qualification time has to be considered in the capacity inequality. If a facility is qualified for a specific product portfolio, all machines, affected from this, have to spend the capacity-relevant qualification time. In this thesis, this system is called Linear Capacity Program.

$$C_1 \geq Q_1 * PT_{11} + ... + Q_N * PT_{N1} + y_{1tk1} * ti_{1k1} + ... + y_{1tkN} * ti_{1kN} \tag{4.10}$$

$$...$$

$$C_m \geq Q_1 * PT_{1m} + ... + Q_N * PT_{Nm} + y_{mtk1} * ti_{mk1} + ... + y_{mtkN} * ti_{mkN} \tag{4.11}$$

...

$$C_M \geq Q_1 * PT_{1M} + ... + Q_N * PT_{NM} + y_{Mtk1} * ti_{Mk1} + ... + y_{MtkN} * ti_{MkN} \tag{4.12}$$

This system can be used to derive the capacitive relationship of products. Therefore, it is suitable to transform the linear inequation system to a linear equation system adding a capacity buffer b_m. A typical capacity equation of the linear capacity program now looks as follows:

$$\begin{aligned} C_m = & Q_1 * PT_{1m} + ... + Q_n * PT_{nm} + ... + Q_N * PT_{Nm} \\ & + y_{mtk1} * ti_{mk1} + ... + y_{mtkn} * ti_{mkn} + ... + y_{mtkN} * ti_{mkN} + b_m \end{aligned} \tag{4.13}$$

For simplification reasons, the system is expressed in matrix syntax. At this point, the qualification-caused utilization is ignored to keep it understandable[5]:

$$\begin{pmatrix} C_1 \\ ... \\ C_m \\ ... \\ C_M \end{pmatrix} = \begin{pmatrix} PT_{11} & ... & PT_{n1} & ... & PT_{N1} \\ ... & ... & ... & ... & ... \\ PT_{1m} & ... & PT_{nm} & ... & PT_{Nm} \\ ... & ... & ... & ... & ... \\ PT_{1M} & ... & PT_{nM} & ... & PT_{NM} \end{pmatrix} * \begin{pmatrix} Q_1 \\ ... \\ Q_n \\ ... \\ Q_N \end{pmatrix} + \begin{pmatrix} b_1 \\ ... \\ b_m \\ ... \\ b_M \end{pmatrix} \tag{4.14}$$

The resulting capacity requirement matrix has to be multiplied with the production quantity vector to calculate the workload. The production quantity-

[5] Thereby, it is assumed, that the qualification times do not significantly differ between the products and hence are not necessary to be included to the determination of product relationships. The integration of the marginal product-specific qualification times would over-complicate the problem without gaining much more input

related workload of machine m plus the capacity buffer b_m equals C_m.
Assume as an example a facility with four machines, which produces four different products. The following linear capacity program represents this facility:

$$\begin{pmatrix} 600 \\ 400 \\ 800 \\ 500 \end{pmatrix} = \begin{pmatrix} 5 & 4 & 1 & 4 \\ 0 & 1 & 10 & 4 \\ 6 & 12 & 8 & 2 \\ 9 & 8 & 0 & 18 \end{pmatrix} * \begin{pmatrix} Q_{P_1} \\ Q_{P_2} \\ Q_{P_3} \\ Q_{P_4} \end{pmatrix} + \begin{pmatrix} b_{M_1} \\ b_{M_2} \\ b_{M_3} \\ b_{M_4} \end{pmatrix} \tag{4.15}$$

The four machines have 600, 400, 800 and 500 minutes available time per day, which equals the particular capacity. Altogether, the facility has a capacity of 2300 minutes per day. One lot of product P_1 requires 5 minutes of M_1, no time of M_2, 6 minutes of M_3 and 9 minutes of M_4. Altogether, one lot of product P_1 requires 20 minutes, one lot of P_2 requires 25 minutes of the facility's capacity. Hence, if only product P_1 was produced for one entire day the facility could deliver $\frac{2300}{20} = 115$ lots. If one day the customer requires 10 lots of P_2 assuming full utilization, consequently only $10 * \frac{25}{20} \approx 13$ lots less of P_1 can be delivered, which results in an overall delivery of 112 lots. Due to the higher capacity requirement of P_2 the overall output of the facility obviously reduces according to the displacement of production quantities.
To summarize, the products are interrelated according to their capacity requirement. As a consequence an increase of production quantity Q_{P_2} leads to a decrease of production quantity Q_{P_1}. The product n displaces product k with the ratio $\frac{PT_n}{PT_k}$. For one new unit of n $\frac{PT_n}{PT_k}$ units of product k have to move .
This relationship-dependent displacement will be exploited in a later stage in the so-called Displacement Heuristic in chapter 5.

The following section 4.2.4 will use a linear capacity program to formally express this capacitive relationship of the products.

4.2.4 Relationship of Products

This subsection describes the approach to calculate the relationship of products in order to derive the relationship of product portfolios. The concept of relationship of products used for the DSNDP can be derived from micro economics. In micro economics the concept of Marginal Rate of Substitution describes how the demand for a product n reacts on a change of price of product k. The more related the products are, the more direct the demands are interrelated (e.g. Dorfman (2008) [31]). Economists differentiate between substitution products and complementary products. The demand of complementary products is positively correlated, while the demand substitution products is negatively correlated. (cf. Dorfman (2008) [31])
As assumed, in section 4.2.1, if two products are related to each other, they influence each other not only in demand, as studied in micro economics, but also in production. In detail in multitasking facilities, products are assumed to compete for capacities. Referencing the semiconductor industry, this is highly reasonable. The competition can be observed in the Linear Capacity Program. If the capacity requirements are set in relation among the products, the relationship of products can be derived. For estimating the qualification effort in the dynamic supply network problem, it is consequently necessary to consider the relationship of all products. The qualification effort influenced by the relationship of products can be visualized in a quadratic NxN-dimensioned qualification matrix. Such matrices are known from classical sequence-dependent lotsizing problems (e.g. Quadt and Kuhn (2008) [97]). If the production of products k and n consumes exactly the same time at each machine, the relationship is assumed to be 1 or 100%. The products substitute themselves with a factor of 1:1. In the other extreme case, if two products never require the same capacity, they are treated as com-

pletely independent with a relationship of 0 or 0%. The products can not be substituted at all. A qualification of such unrelated products provides maximum effort. The relationship of every product combination ranges between 0 and 1 within these two extreme cases. If the capacity requirement of the products n and k is similar, the division of the sum of common capacity requirement on each machine with the overall capacity requirement of the targeted product n, describes its capacitive relation to the other product k.
Formally, this coefficient of capacitive relationship of products is proposed to be expressed by the following term:

Relationship of single product *n* with *k*

$$r_{k,n} = \frac{\sum_{m=1}^{M} (PT_{nm} \cap PT_{km})}{\sum_{m=1}^{M} PT_{nm}} \qquad \forall k,n \in 1..N \tag{4.16}$$

This term is introduced to express the relation of product n with product k. In the numerator the intersection of the machine-specific process times of the two products n and k is summed up over all machines $m \in (1..M)$. The denominator expresses the overall processing time of the targeted product n on all machines. If there is no intersection of processing time existing at all, the numerator is becoming 0 and thereby the relationship is 0. With a relationship of 0 the two products n and k are completely independent from a capacity point of view. The qualification of the two products n and k is assumed to affect completely different machines and is thereby not supporting each other.
The intersection of processing times can maximally reach the overall processing time of the targeted product. In this case the targeted product n is perfectly described by the other product k, hence $r_{k,n} = 1$. The relationship of n to k is perfect. If product n is qualified after product k, the qualification is assumed to be maximally simplified, as the previous qualification of the predecessor product k has already initiated the major preparations.
While $PT_{nm} \cap PT_{km} = Min(PT_{nm}, PT_{km})$ The relationship of products is not

symmetric, as it directly depends from the sum of overall processing time of product n. $r_{k,n} \neq r_{n,k}$ as $\frac{\sum_{m=1}^{M}(PT_{nm} \cap PT_{km})}{\sum_{m=1}^{M} PT_{nm}} \neq \frac{\sum_{m=1}^{M}(PT_{nm} \cap PT_{km})}{\sum_{m=1}^{M} PT_{km}}$. Per definition $r_{n,n} = 1$.

To support the mix-dependent DSNDP the pre-calculation algorithm has to deliver the $2^N x 2^N$ dimensioned qualification matrices. Therefore, the product relationship approach, has to be extended in a second step, to derive the portfolio relationships $R_{i,j}$ for every destination portfolio from every source portfolio. For calculating the mix-dependent qualification matrices, the relationships of product portfolios have to be derived from the relationships of products involved. According to section 4.2.2, there are 2^N different product portfolio combinations derived from the N different products. Hence, there are 2^{N*2} product mix relationships existing. The relationships of product portfolios result from the combination of the single product relationships of the products included in the destination portfolio with products included in the source portfolio. Therefore, it is assumed that each product n in the destination product portfolio j gains most benefits for qualification from its nearest relative in the source product portfolio i. The maximum relationship of each product $n \in j$ with the nearest related product $k \in i$ is considered for the calculation of the portfolio relationship between j and i. The maximum relationship of all products in the destination product portfolio j with products from source portfolio i are summed up. Depending on the number of products in the destination product portfolio j the sum of maximum product relationships will increase. Hence, the overall portfolio relationship has to be divided by the overall number of products included to the destination product portfolio j. The number of products included to a product portfolio j represents the dimension of the portfolio vector Dim_j. The formula below represents this approach to calculate the coefficient of relationship of product portfolio $R_{i,j}$ of the destination product portfolio j with source product portfolio i:

Relationship of product portfolio j with product portfolio i

$$R_{i,j} = \frac{\sum_{n \in j}(max(r_{P_k P_n}))}{Dim_j} \qquad \forall k \in i; n \in j \qquad (4.17)$$

As a consequence, the matrix of portfolio relationships is asymmetric, just like the relationship matrix of single products. With these definitions, the product portfolio relationship matrix R can be derived step by step using the supporting product relationship matrix r. The procedure is demonstrated, using the example from subsection 4.2.3. For transparency reasons the introduced example is reduced from initially four to only three products. Otherwise, the product portfolio matrix would not be printable properly anymore.

The following Linear Capacity Program is the starting point for the calculation of product relationship:

$$C_{m,n} = \begin{array}{c} \\ C_1 \\ C_2 \\ C_3 \\ C_4 \end{array} \begin{array}{c} \begin{array}{ccc} P_1 & P_2 & P_3 \end{array} \\ \begin{pmatrix} 5 & 4 & 1 \\ 0 & 1 & 10 \\ 13 & 12 & 8 \\ 9 & 8 & 0 \end{pmatrix} \end{array} \qquad \forall m \in 1..M; n \in 1..N \qquad (4.18)$$

To calculate the matrix of product relationships for visualization reasons, first the sum of process time intersection over all machines of each pair of products is described in the following matrix.

$$\sum_{m=1}^{M} PT_k \cap PT_n = \begin{array}{c} \\ P_1 \\ P_2 \\ P_3 \end{array} \begin{array}{c} \begin{array}{ccc} P_1 & P_2 & P_3 \end{array} \\ \begin{pmatrix} 27 & 24 & 9 \\ 24 & 25 & 10 \\ 9 & 10 & 19 \end{pmatrix} \end{array} \qquad \forall k, n \in 1..N \qquad (4.19)$$

By division of the overall process time intersection of the destination product n with the source product k, the relationship of each product can be expressed in matrix r. Thereby, the relationship is simply determined by the ratio of overlapping processing time of product n and k with the overall processing time of the destination product n. The following matrix r shows these product-specific relationships:

$$r_{kn} = \begin{array}{c} \\ P_1 \\ P_2 \\ P_3 \end{array} \begin{array}{c} \begin{array}{ccc} P_1 & P_2 & P_3 \end{array} \\ \begin{pmatrix} 1 & 0,\overline{888} & 0,\overline{333} \\ 0,960 & 1 & 0,400 \\ 0,473 & 0,526 & 1 \end{pmatrix} \end{array} \tag{4.20}$$

The maximum product relationship matrix r_{max} represents the product pairs with the highest relationship:

$$r_{max} = \begin{array}{c} \\ P_1 \\ P_2 \\ P_3 \end{array} \begin{array}{c} \begin{array}{ccc} P_1 & P_2 & P_3 \end{array} \\ \begin{pmatrix} & 0,\overline{888} & \\ 0,960 & & 0,400 \\ & & \end{pmatrix} \end{array} \tag{4.21}$$

Interpreting matrix r_{max} delivers P_1 and P_3 are most related with P_2. This is realistic, as P_2, from its process times on each machine, indicates the highest complexity. P_2 is most related with P_1. This means, P_1 and P_3 can be most efficiently described with P_2, while P_2 can be most efficiently described with P_1. Thereby, qualifying one of the products P_1 and P_3 gains most qualification benefits if P_2 is installed right before. Whereas, the qualification of P_2, itself, gains most benefits with product P_1 as a predecessor.

Furthermore, to develop the mix-dependent qualification matrices, the product portfolio relationships have to be generated, using the single product relationships.

In the reduced example, there are three products (P_1, P_2, P_3), hence there are $2^3 = 8$ possible product portfolios. Consequently, the product portfolio relationship matrix has a dimension of $8x8$ and there are $8^2 = 64$ product portfolio relationships expected. Applying the formula 4.17, the following product portfolio relationship matrix R results:

$$R_{i,j} = \begin{array}{c} \\ (000) \\ (001) \\ (010) \\ (011) \\ (100) \\ (101) \\ (110) \\ (111) \end{array} \begin{array}{cccccccc} (000) & (001) & (010) & (011) & (100) & (101) & (110) & (111) \\ \end{array} \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0,526 & 0,763 & 0,473 & 0,737 & 0,499 & 0,666 \\ 0 & 0,400 & 1 & 0,700 & 0,960 & 0,680 & 0,980 & 0,787 \\ 0 & 1 & 1 & 1 & 0,960 & 0,980 & 0,980 & 0,987 \\ 0 & 0,\overline{333} & 0,\overline{889} & 0,611 & 1 & 0,\overline{667} & 0,9\overline{44} & 0,741 \\ 0 & 1 & 0,\overline{889} & 0,9\overline{44} & 1 & 1 & 0,9\overline{44} & 0,963 \\ 0 & 0,400 & 1 & 0,700 & 1 & 0,700 & 1 & 0,800 \\ 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \end{pmatrix} \tag{4.22}$$

The structure of the resulting matrix shows some characteristics: Firstly, the matrix is obviously quadratic, but not symmetric. Secondly, the diagonal values are always one as each product portfolio is perfectly related to itself. Thirdly, the first row and first column, carrying all possible qualifications from the empty source product portfolio $(0,0,0)$ or to the empty destination portfolio $(0,0,0)$, obviously have a relation of 0 in every case (where $i \neq j$). Fourthly, if all products to be qualified with the destination portfolio j are already part of the source portfolio i the relationship of j to i is obviously 1. Therefore, below the diagonal, there is a significant number of perfect relationships. Fifthly, the reverse direction is not true because, if $j \subseteq i \nrightarrow i \subseteq j$. These relationships influence the qualification costs as well as qualification time. How the qualification matrices are calculated on the basis of relationship matrices, is described in the next section 4.2.5.

4.2.5 Pre-Calculation of the Mix-Dependent Qualification Matrices

Based on the matrix of relationship of the product portfolios R, the qualification cost and time matrices are pre-calculated in this subsection. While the costs influence the overall objective function, the time only has to be considered for the capacity limits. Both matrices are three-dimensional in the model, depending on source and destination portfolio as well as on the facility. For visualization purposes, these matrices are only printed two-dimensional here (source-portfolios x destination-portfolios).

The qualification costs are proposed to consist of a basic part and a variable, mix-dependent part. Thereby, the costs follow a linear function, influenced by the relationship of product portfolios. This formula is based on the standard linear function $y = a + b * x$. While x is represented by $(1 - R_{i,j})$, b represents the mix-dependent cost / time factor, called mdc (mdt) , which is multiplied with the relationship-dependent representation of x. The variable, mix-dependent part of the term linearly increases with a decrease of the coefficient of portfolio relationship. Hence, qualification costs are higher for a sequence of less related portfolios. However, even, if the product portfolios are perfectly similar with a portfolio relationship of 1 and consequently the mix-dependent cost component is zero, still the basic cost factor, representing a, has to be spent for qualification. In practice, as defined in section 2.1, this constant a represents a fix qualification effort, and will here be called qmc for fix qualification costs and qmt for fix qualification time. To provide a realistic representation of the fix part of the qualification costs / times the basic cost / time factor has to be multiplied with the dimension of the destination portfolio. It has to be adjusted by the number of products intended to be qualified in the destination portfolio, because independent from the relationship, in practice a portfolio with many products is more complex to qualify, than a portfolio with fewer products. Practically, these basic qualification costs and times in particular represent all fix cleaning and adjustment

processes, which are mandatory in any case. In both cases, the extent of the actions does not depend on the products itself, but on the number of products in the portfolio.
Altogether, the linear mix-dependent cost function includes the two components, basic costs (times) and mix-dependent costs (times). These two parameters have to be estimated, considering the industrial domain in advance of the pre-calculation. Hence, the formula deriving the qualification costs (and times) considering the dimension of the destination portfolio as well as the relationship of the destination portfolio with its predecessor looks the following:

$$cq_{f,i,j} = qmc * Dim_j + mdc * (1 - R_{i,j}) \qquad \forall f \in 1..F \tag{4.23}$$

Continuing the example from subsection 4.2.4 leads to the following qualification cost matrix. For this matrix basic cost factor of 10 and a mix-dependent cost factor of 1000 have been assumed:

$$CQ_{i,j} = \begin{array}{c} \\ (000) \\ (001) \\ (010) \\ (011) \\ (100) \\ (101) \\ (110) \\ (111) \end{array} \begin{array}{c} \begin{array}{cccccccc} (000) & (001) & (010) & (011) & (100) & (101) & (110) & (111) \end{array} \\ \begin{pmatrix} 0 & 1010 & 1010 & 1020 & 1010 & 1020 & 1020 & 1030 \\ 0 & 10 & 484 & 257 & 537 & 283 & 521 & 364 \\ 0 & 610 & 10 & 320 & 50 & 340 & 40 & 243 \\ 0 & 10 & 10 & 20 & 50 & 40 & 40 & 43 \\ 0 & 677 & 121 & 409 & 10 & 353 & 76 & 289 \\ 0 & 10 & 121 & 76 & 10 & 20 & 76 & 67 \\ 0 & 610 & 10 & 320 & 10 & 320 & 20 & 230 \\ 0 & 10 & 10 & 20 & 10 & 20 & 20 & 30 \end{pmatrix} \end{array} \tag{4.24}$$

Consequently, the mix-dependent qualification matrices can be specified with certain realistic characteristics: Firstly, the first column only incorporates zero costs. According to the assumptions, it does not cost anything to do nothing and leave the facility empty. Hence, qualifying the start product

portfolio $(0,0,0)$ in column one will always be free.
Secondly, all values in the last row will contain the basic costs. From the full qualification product portfolio $(1,1,1)$ it can only be disqualified or maintained.
Thirdly, the diagonal also contains the basic costs. In this version of the DSNDP the qualification costs on the diagonal are used, if the same portfolio is intended to be qualified again in the next period. In the next extension in section 4.3, this procedure will change.
Fourthly, several product portfolio combinations only contain product disqualifications. These product portfolio combinations consequently only incorporate basic costs multiplied with the dimension of the destination portfolio Dim_j (where $Dim_j \leq Dim_i$). Therefore $\forall n \in j \rightarrow n \in i$. All products in the destination product portfolio j have already been qualified in portfolio i in case of disqualifying i to j. Hence, no additional qualification is necessary. Consequently, only basic costs for maintaining the products in the destination portfolio have to be spent. The so-called binary product mix assignment matrix $P_{j,n}$ with the dimension 2^N x N assigns each particular product to the particular product portfolio, with either 1 if it is part or 0, if it is not part of the product portfolio.
Beyond the two qualification matrices, there is no additional pre-calculation effort necessary. The number of periods, products, facilities has to be entered manually as well as the demand matrix. The Linear Capacity Program can either be specified from the MES or manually. Also, the period-specific capacity of every facility has to be specified manually. The product-specific holding costs is manual input as well. As introduced in section 4.2.3, the overall process time PT_n of a product n can be calculated as a sum of all machine-specific process times ($PT_n = \sum_{m=1}^{M} PT_{nm}$), which are manually specified or red from the MES.
The next section 4.2.6 introduces the mathematical model of the mix-dependent DSNDP based on these assumptions.

4.2.6 Formulation of the Mix-Dependent Mathematical Model

In this section the second mathematical model following the additional assumption of mix-dependency is introduced on the basis of the first model. It will be formulated in a mathematical mixed integer linear programming (MILP) approach. Later in this section the changes in the terms will be explained in detail.

Mathematical model of the mix-dependent DSNDP

Objective function

$$MinCosts = \sum_{t=1}^{T}\sum_{f=1}^{F}\sum_{j=1}^{2^N}\sum_{i=1}^{2^N}\sum_{n=1}^{N} cq_{f,i,j} * y_{f,t,i,j} + ch_n * Y_{t,n} \tag{4.25}$$

s.t.

$$D_{t,n} = Y_{t-1,n} + \sum_{f=1}^{F}\sum_{j=1}^{2^N}(Q_{f,t,n,j}) - Y_{t,n} \qquad \forall n \in 1..N; t \in 1..T \tag{4.26}$$

$$C_{f,t} \geq \sum_{j=1}^{2^N}\sum_{n=1}^{N}\sum_{i=1}^{2^N}(tq_{f,i,j} * y_{f,t,i,j} + PT_n * Q_{f,t,n,j}) \qquad \forall f \in 1..F; t \in 1..T; i \neq j \tag{4.27}$$

$$Q_{f,t,n,j} \leq BigM * P_{j,n} * \sum_{i=1}^{2^N}(y_{f,t,i,j}) \qquad \forall j \in 1..2^N; t \in 1..T; f \in 1..F; i \neq j \tag{4.28}$$

$$y_{f,t,j,j} \leq y_{f,t-1,i,j} - y_{f,t-1,j,i}$$

$$\forall j \in 1..2^N; t \in 1..T; f \in 1..F; i \neq j \quad (4.29)$$

$$\sum_{j=1}^{2^N} (y_{f,t,j,i}) \leq \sum_{j=1}^{2^N} (y_{f,t,i,j} + y_{f,t-1,i,j})$$

$$\forall i \in 1..2^N; t \in 1..T; f \in 1..F; i \neq j \quad (4.30)$$

$$Fy_{f,j,t} \geq \quad Fy_{f,i,t} + 1 - 2^N * (1 - (y_{f,t,i,j}))$$

$$\forall f \in 1..F; t \in 1..T; i, j \in 1..2^N; i \neq j \quad (4.31)$$

$$Y_{0,n} = \quad 0 \qquad \forall n \in 1..N \quad (4.32)$$

$$y_{f,t,i,j} \in \quad (0,1) \qquad \forall f \in 1..F; t \in 0..T; i \in 1..2^N; j \in 1..2^N; i \neq j \quad (4.33)$$

$$Q_{f,t,n,j} \in \quad \mathbb{N}_0 \qquad \forall f \in 1..F; t \in 1..T; n \in 1..N; j \in 1..2^N \quad (4.34)$$

$$Y_{t,n} \in \quad \mathbb{N}_0 \qquad \forall t \in 0..T; n \in 1..N \quad (4.35)$$

$$Fy_{f,j,t} \in \quad \mathbb{N}_0 \qquad \forall f \in 1..F; j \in 1..2^N; t \in 0..T \quad (4.36)$$

This MILP contains the entire DSNDP, extended by mix-dependency. Several terms have to be added or changed in comparison to the basic DSNDP. The objective function (4.25) stays the same from its structure. But the indices of the binary qualification variables have to be extended from $y_{f,t,j}$ to $y_{f,t,i,j}$. As the qualification sequence from portfolio i to j now influences the qualification costs. In addition, the costs have to be summed up for all possible source portfolios.

The production balance constraint (4.26) does not have to be changed from the basic version (4.2).

However, the capacity constraint (4.27) has to be extended to be sensitive for the qualification sequence. Consequently, the qualifiction time variables are extended by the index i to reference the source portfolio.

The qualification requirement (4.28) also has to be extended by index i.

The next constraint (4.29) for qualification transfer has to be introduced to regulate the mix-dependency between periods. It is only possible to maintain the qualification state of portfolio j in period t, if j has been qualified

in period $t-1$ from any portfolio i and has not been disqualified.
In addition to that the qualification sequence constraint (4.30) has to be introduced to ensure a consistent qualification sequence.
The subtour restriction constraint (4.31) is now necessary to avoid qualification sequence loops within one period. Therefore, the new counter variable $Fy_{f,j,t}$ restricts, that a portfolio j is re-qualified in the same facility and period.
The initial inventory constraint (4.35) is not changed by the extension of mix-dependency.
The last three constraints (4.33), (4.34), (4.35) and the additional constraint (4.36) specify the possible range of the variables $y_{f,t,i,j}$, $Q_{f,t,n,j}$, $Y_{t,n}$, $Fy_{f,j,t}$.
This first extension of the DSNDP justifies the idea, that theoretically every facility can be qualified for every product by introducing the assumption of mix-dependency. In addition to the realistic assumption of mix-dependency, it is conceivable, that a facility may be able to qualify product portfolios in a simplified manner based on its wealth of experience from previous periods. In particular, if it had already been qualified for the same portfolio in a previous period. The subsequent section introduces an essential model extension categorizing different kinds of qualification, depending on the experience of the facility. This additional extension is called qualification differentiation.

4.3 Mix-Dependent Dynamic Supply Network Design Model with Qualification Differentiation

This section on the basis of the mix-dependent DSNDP presents the additional model extension of qualification differentiation. This extension is motivated by industrial observations.

4.3.1 Model Assumptions for Qualification Differentiation

In addition to the mix-dependent effects, also effects from the qualification history are assumed to influence the qualification effort. It is assumed to simplify the qualification, if the portfolio, to be qualified, has already been qualified in the specific facility or is maintained in this facility throughout the periods. Beyond mix-dependent qualification effects, this second extension of the DSNDP proposes to consider the following three different types of qualification:

1. Initial qualification
2. Re-qualification
3. Qualification maintenance

The initial qualification is the most comprehensive type of qualification. It has to be managed, if the particular product portfolio has never been qualified in the considered facility before. In practice, necessary installation of infrastructure, modification of hardware and software components, training of employees and development and adaptation of production processes leads to high qualification costs and time.

If the corresponding product portfolio has already been installed in the facility once before, only a more favorable re-qualification is necessary. The re-qualification omits certain installation, development and training expenses, as it is assumed, that these were already performed the first time and are still available. Consequently, the experiences and preparations from the initial qualification support the re-qualification. The approach assumes, that each product portfolio once has to undergo a major initial qualification, when installed in a facility for the first time. When this is managed in any future period, it can be qualified with an easier re-qualification. It is assumed, that it is time-independently possible to re-qualify a portfolio with less effort, if it has been qualified once in the particular facility. But the experiences and

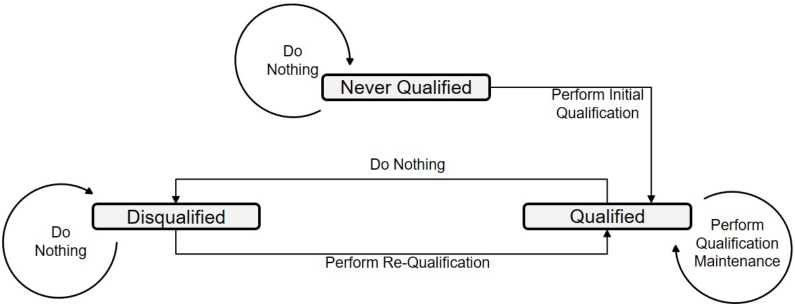


Figure 4.1: Three Ways of Qualification

pre-cautions can not be transferred to other facilities. Hence, if a product should be re-qualified in a facility, it is mandatory, that it already has passed an initial qualification in this particular facility before.

Another, even easier possibility is, to only transfer the previous product portfolio in a facility to the subsequent period, if the product portfolio is still required. In this case, only a qualification maintenance has to be performed. In practice, this means that systems have to be cleaned and maintained and wearing parts have to be exchanged from one period to the next in order to continue with production in the following period. This option is covered in the model in the so-called qualification maintenance and is obviously only possible, if the same product portfolio has already been installed in the previous period in the same facility. A qualification maintenance is obviously only possible within the same facility.

The interrelations of the three qualification options are visualized in figure 4.1

The qualification maintenance is the reason, that production systems are not step by step qualified for all products, to become more and more flexible. The optimization model will choose to maintain certain product portfolios, although in a particular period, the one or the other product involved is not required. In every cost structure a negative break even point can be analyzed,

which makes it inefficient to maintain a specific portfolio even longer. Beyond this individual point it is more efficient to drop the qualification state and re-qualify it again, when required.
According to this effect, two contrary strategies for qualification can be introduced, which strongly depend on the structure of qualification costs of the different qualification types. The so-called "stability strategy" and the "flexibility strategy". The optimization model will choose its policy within the range of these different "poles".
The stability strategy tends to maintain a portfolio even if it is not needed to avoid re-qualification costs later.
The flexibility strategy tends to drop and re-qualify a portfolio and is thereby more flexible.
The ratio of maintenance costs and re-qualification costs determines, which "pole" will be chosen by the optimization model. Specifically, it will answer, which facility will maintain a product for how many periods, even if there currently is no demand forecasted, to avoid expensive re-qualification later.
The second extension of the DSNDP requires additional pre-calculation steps. The subsequent section will extend the pre-calculation routine from section 4.2.5.

4.3.2 Pre-Calculation for Qualification Differentiation

Considering the new qualification differentiation assumption, this section introduces the additional pre-calculation tasks, continuing, what was specified in subsection 4.2.5. The differentiation of qualification requires separate qualification matrices for initial qualification as well as re-qualification. Altogether, the following four matrices are now required:

1. Mix-dependent initial qualification cost matrix ($ci_{f,i,j}$)

2. Mix-dependent re-qualification cost matrix ($cr_{f,i,j}$)

3. Mix-dependent initial qualification time matrix ($ti_{f,i,j}$)

4. Mix-dependent re-qualification time matrix ($tr_{f,i,j}$)

The four matrices contain cost and time-effort for all three kinds of qualification (initial qualification, re-qualification, qualification maintenance). The mix-dependent initial qualification cost matrix as well as the mix-dependent initial qualification time matrix can be directly transferred from the mix-dependency pre-calculation in subsection 4.2.5. They do not require any update. Nevertheless, the matrices are now called $ci_{f,i,j}$ and $ti_{f,i,j}$ instead of $cq_{f,i,j}$ and $tq_{f,i,j}$ to make clear, that they now only include times and costs for initial qualification. In addition, this section introduces the two matrices, mix-dependent re-qualification cost matrix ($cr_{f,i,j}$) and mix-dependent re-qualification time matrix ($tr_{f,i,j}$). The calculation of the re-qualification cost matrix $cr_{f,i,j}$ principally follows exactly the same procedure as the calculation of the initial qualification cost matrix, introduced in subsection 4.2.5, but with lower cost factors *qmc* and *mdc*.
The information about qualification maintenance is part of the re-qualification matrices. A qualification maintenance is a special case of re-qualification, where product i will be requalified directly in the next period ($i = j$). Hence, the costs and times for the qualification maintenance originate from the diagonal of the re-qualification matrices. Consequently, all a qualification maintenance only requires the basic re-qualification costs and time, as i and j are perfectly similar in this case. In the first extension, the effort of a qualification of the same portfolio in the next period was specified in the diagonal of the initial qualification cost matrix. Now, including the specific option of qualification maintenance, the diagonals of the initial qualification matrices are no longer used at all.
Altogether, all four qualification matrices use the same formula, introduced in subsection 4.2.5 but with separate cost and time factors *qmc*, *qmt* and *mdc*, *mdt* for initial qualification and re-qualification. Beyond preparation of these four matrices, this pre-calculation takes over all preparation of

necessary input specified in subsection 4.2.5. Using this input the next subsection introduces mathematical model of the final mix-dependent DSNDP with the new extension of qualification differentiation.

4.3.3 Formulation of the Mix-Dependent Mathematical Model with Qualification Differentiation

According to the differentiation of qualifications in initial qualification, requalification and qualification maintenance, several additional constraints are required. Additionally the existing terms require a differentiation of the binary qualification variables. This section represents the entire mathematical model of the DSNDP considering all model assumptions. Later in this section the extensions and changes will be explained in detail.

Mathematical model of the mix-dependent DSNDP with qualification differentiation

Objective function

$$MinCosts = \sum_{t=1}^{T}\sum_{f=1}^{F}\sum_{j=1}^{2^N}\sum_{i=1}^{2^N}\sum_{n=1}^{N} ci_{f,i,j} * y_{f,t,i,j} + cr_{f,i,j} * x_{f,t,i,j} + cr_{f,j,j} * z_{f,t,j} + ch_n * Y_{t,n} \tag{4.37}$$

s.t.

$$D_{t,n} = \quad Y_{t-1,n} + \sum_{f=1}^{F}\sum_{j=1}^{2^N}(Q_{f,t,n,j}) - Y_{t,n} \qquad \forall n \in 1..N; t \in 1..T \tag{4.38}$$

$$C_{f,t} \geq \quad \sum_{j=1}^{2^N}\sum_{n=1}^{N}\sum_{i=1}^{2^N}(tr_{f,j,j} * z_{f,t-1,j} + PT_n * Q_{f,t,n,j} + ti_{f,i,j} * y_{f,t,i,j}) +$$

$$\sum_{j=1}^{2^N}\sum_{n=1}^{N}\sum_{i=1}^{2^N}(tr_{f,i,j} * x_{f,t,i,j})$$
$$\forall f \in 1..F; t \in 1..T; i \neq j \tag{4.39}$$

$$Q_{f,t,n,j} \leq \quad BigM * P_{j,n} * \sum_{i=1}^{2^N}(z_{f,t-1,j} + y_{f,t,i,j} + x_{f,t,i,j})$$
$$\forall j \in 1..2^N; t \in 1..T; f \in 1..F; i \neq j \tag{4.40}$$

$$z_{f,t,j} = \quad z_{f,t-1,j} + \sum_{i=1}^{2^N}(y_{f,t,i,j} + x_{f,t,i,j} - y_{f,t,j,i} - x_{f,t,j,i})$$
$$\forall j \in 1..2^N; t \in 1..T; f \in 1..F; i \neq j \tag{4.41}$$

$$\sum_{j=1}^{2^N}(y_{f,t,j,i} + x_{f,t,j,i}) \leq z_{f,t-1,j} + \sum_{j=1}^{2^N}(y_{f,t,i,j} + x_{f,t,i,j})$$
$$\forall i \in 1..2^N; t \in 1..T; f \in 1..F; i \neq j \tag{4.42}$$

$$Fxy_{f,j,t} \geq \quad Fxy_{f,i,t} + 1 - 2^N * (1 - (x_{f,t,i,j} + y_{f,t,i,j}))$$
$$\forall f \in 1..F; t \in 1..T; i,j \in 1..2^N; i \neq j \tag{4.43}$$

$$1 \geq \quad \sum_{i=1}^{2^N}(y_{f,t,i,j} + x_{f,t,i,j})$$
$$\forall f \in 1..F; t \in 1..T; j \in 1..2^N; i \neq j \tag{4.44}$$

$$1 = \quad \sum_{j=1}^{2^N} z_{f,t,j} \qquad \forall f \in 1..F; t \in 1..T \tag{4.45}$$

$$1 \geq \quad \sum_{i=1}^{2^N}\sum_{t=1}^{T} y_{f,t,i,j} \quad \forall f \in 1..F; j \in 1..2^N; i \neq j \tag{4.46}$$

$$\sum_{i=1}^{2^N} x_{f,t,i,j} \geq \quad \sum_{i=1}^{2^N}\sum_{d=1}^{t-1} y_{f,t,i,j} \quad \forall f \in 1..F; t \in 1..T; j \in 1..2^N; i \neq j \tag{4.47}$$

$$z_{f,0,1} = \quad 1 \qquad \forall f \in 1..F \tag{4.48}$$

$$Y_{0,n} = \quad 0 \qquad \forall n \in 1..N \tag{4.49}$$

$$y_{f,t,i,j} \in \quad (0,1) \qquad \forall f \in 1..F; t \in 0..T; i \in 1..2^N; j \in 1..2^N; i \neq j \tag{4.50}$$

$$x_{f,t,i,j} \in \quad (0,1) \qquad \forall f \in 1..F; t \in 0..T; i \in 1..2^N; j \in 1..2^N; i \neq j \tag{4.51}$$

$$z_{f,t,j} \in \quad (0,1) \qquad \forall f \in 1..F; t \in 0..T; j \in 1..2^N \tag{4.52}$$

$$Q_{f,t,n,j} \in \quad \mathbb{N}_0 \qquad \forall f \in 1..F; t \in 1..T; n \in 1..N; j \in 1..2^N \tag{4.53}$$

$$Y_{t,n} \in \quad \mathbb{N}_0 \qquad \forall t \in 0..T; n \in 1..N \tag{4.54}$$

$$Fxy_{f,j,t} \in \quad \mathbb{N}_0 \qquad \forall f \in 1..F; j \in 1..2^N; t \in 0..T \tag{4.55}$$

To cover the new approach of differentiation of qualifications the objective function (4.37) has to be extended. Instead of one qualification costs factor $cq_{f,i,j}$ now an initial qualification cost factor $ci_{f,i,j}$, a re-qualification cost factor $cr_{f,i,j}$ and a qualification maintenance cost factor $cr_{f,j,j}$ are required. These cost factors are multiplied with specific binary qualification variables for initial qualification $y_{f,t,i,j}$, re-qualification $x_{f,t,i,j}$ as well as qualification maintenance $z_{f,t,j}$. Altogether, the cost minimizing structure of the objective function in the tradeoff of just-in-time production versus production to stock stays equivalent to the previous model versions.

Also the production balancing constraint (4.38) stays equivalent to the two previous model versions.

The capacity restriction (4.39) stays equivalent from its structure, but now has to consider the different qualification options with the specific time factors $ti_{f,i,j}$, $tr_{f,i,j}$ and $tr_{f,j,j}$.

Also the qualification requirement (4.40) has to be extended by the three qualification options. It makes sure that at least one of the qualification options is chosen to qualify a suitable portfolio if a product has to be produced.

The qualification transfer constraint (4.41) makes sure, that a portfolio can only be maintained to the next period, if it has already been qualified and not disqualified in the previous period. Beyond its original purpose in the first model extension, the constraint requires a qualification maintenance for the transfer of the portfolio.

In addition to that, the qualification sequencing constraint still ensures a consistent qualification sequence from i to j. However, it now has to handle all different qualification options.

The subtour restriction constraint (4.43) in this second extension has to avoid qualification loops specifically between initial qualification and re-qualification. Otherwise unnecessary product portfolios are qualified in order to reach a cheap qualification sequence for a desired portfolio. This would generate inconsistent subtours.

The initial inventory constraint (4.35) is not changed by the extension of mix-dependency.

The four following constraints (4.44) to (4.47) express the interrelation of the specific qualification options and guarantee, that there is always the suitable kind of qualification performed. These four constraints obviously are motivated exclusively by the new qualification differentiation extension.

Following constraint (4.40) a suitable product portfolio j has to be qualified to produce a specific product n. But therefore, it is possible to choose one of the three qualification options $y_{f,t,i,j}$, $x_{f,t,i,j}$ or $z_{f,t-1,j}$. Nevertheless, the model has to be restricted in its choice. According to the qualification redundancy avoidance constraint (4.44) the sum of the binary initial qualification variable and the binary re-qualification variable is forced to be maximally 1. Thereby, it is guaranteed that not both $y_{f,t,i,j}$ and $x_{f,t,i,j}$ are 1 at the same time. In principle, this is already ensured by the cost minimizing objective function. However, to avoid problems in case of specific qualification cost structures this has to be guaranteed with this hard constraint.

Additionally, constraint (4.45) ensures that exactly one qualification state is transferred to the subsequent period. In combination with constraint (4.42) it is exactly defined, which qualification states can be transferred to the subsequent period.

The third constraint regulating the interrelation of the different qualification options (4.46) guarantees, that the initial qualification is performed maximally once in the planning horizon. As this qualification option in reality is intended to be the most expensive one, in most cases this option will already be chosen by the cost-minimizing objective function.
The fourth constraint (4.47) concludes the necessary restrictions of the interrelation of qualification options. It ensures, that the cheaper re-qualification option $x_{f,t,i,j}$ can only be chosen, if in one of the previous periods 1 to $t-1$ the initial qualification has been performed.
The remaining nine constraints limit the ranges of the specific variables. Therefore, constraint (4.48) is introduced here, to ensure, that each facility starts empty in the first period with product portfolio 1. Product portfolio 1 does not contain any product. All facilities have to transfer product portfolio 1 to the first period.
The following initial inventory constraint (4.49) does not require an update from the basic version (4.5).
The subsequent three constraints (4.50), (4.51) and (4.52) indicate, that the three different qualification variables are binary decision variables. Either a product portfolio is qualified, respectively transferred, or not. Obviously, only one constraint was required for this purpose in the previous two model versions. The next two integrality constraints (4.53) and (4.54) do not require an update from the basic versions (4.7) and (4.8). The last constraint (4.55) determines the range for the integer-type decision variable $Fxy_{f,j,t}$ to be greater or equal to zero, equivalent to its simple mix-dependent version (4.36).
To be summarized, the mathematical optimization model for the mix-dependent DSNDP with qualification differentiation considers multiple facilities available for the dynamic supply network as well as multiple products required

by the volatile markets[6]. It qualifies the suitable product portfolios in the available facilities in order to fulfill the demand in every period. In each period, the facility capacity limits the demand assignment. The demand of a specific period can either be fulfilled from just-in-time production or from stock. The tradeoff between just in time production, generating mix-dependent qualification costs, and production to stock, generating holding costs is intended to be solved optimally in this model. Solving this problem utilizes the capacities of the available facilities and thereby designs the dynamic supply network out of the given resources.

The model is designed as a mixed integer linear programming (MILP) approach, which is NP-complete. As the number of variables is dynamic, solving the problem requires exponential time (see: Lenstra (1983) [73] and Kimms (1998) [67]). This is the reason similar realistic problems are most of the time solved heuristically. The subsequent section aims to evaluate the performance of the MILP, solving different problem sizes optimally. Therefore, the mathematical model is implemented in JAVA using the IBM ILOG CPLEX Solver class. For JAVA the latest editor of ECLIPSE IDE 2019 is used. The CPLEX solver uses the meta heuristic "branch and cut". It represents a combination of the meta heuristics cutting planes and branch and bound.

The following section evaluates the performance of the implemented approach for realistic industrial problem settings. It therefore introduces a set of suitable experiments. Only the most advanced model with mix-dependency and qualification differentiation is evaluated, as it best represents the industrial practice. In this thesis from now on, the term DSNDP refers to this most advanced model.

[6] As the DSNDP belongs to the early stage of the Master Planning Level, single products are aggregated to product groups (see section 3.1). Nevertheless, for simplicity, this model considers the term 'products'

4.4 Performance Evaluation of the Mix-Dependent DSNDP with Qualification Differentiation

After the MILP for the DSNDP has been developed and extended in the previous sections 4.1.3, 4.2.6 and 4.3.3, the performance of the extended model has to be tested. As introduced, the NP-complete MILP requires exponential time, to be solved optimally (Lenstra (1983) [73] and Kimms (1998) [67]). To be useful for practical applications, it is important, that the approach models and solves realistic problem sizes in acceptable time. The aim of this section is to test the performance of the optimization model for different realistic problem sizes. Therefore, the mathematical model has been implemented in JAVA using the IBM ILOG CPLEX solver class. To answer the performance question, two questions have to be answered:

- Firstly, how is the computation time and the optimal solution affected by the problem size?
- Secondly, what are the maximum problem sizes, which can be executed in acceptable time?

The computation time is influenced by the number of variables as well as the available computation power and memory.
The optimization model as well as the pre-calculation are implemented in JAVA using the latest Eclipse IDE version 2019. The optimization model is solved using the IBM ILOG CPLEX 12.9 Solver class from the Developers Edition in JAVA. For the optimization scenarios a physical server with 14 Core 2.40 GHz Intel Xeon (R) E5-2680 v4 processor and 262 GB RAM is used.
The problem size (number of variables) is influenced by the following three input parameters:

1. Number of periods
2. Number of facilities
3. Number of products

The problem size increases with number of products, periods or facilities. To test the performance of the optimization model on the mentioned server, all three input parameters have to be varied separately. Ceteris paribus, while varying one parameter, the other parameters are kept constant. This enables reliable statements about the specific influences of the single parameters on the performance of the optimization model. The performance evaluation is specifically focused on the influence of each parameter variation on computation time and on the optimal model solution.
As introduced in chapter 3 the DSNDP is part of the Master Planning Level. On this level, the production is still planned on product groups. Referring to semiconductor supply chains. it is assumed, that a realistic problem incorporates six product groups or more (c.f. Ponsignon and Mönch (2012)[94]). As introduced in section 4.1.1, the realistic planning horizon of this planning problem is suggested to be 1 to 2 years with monthly periods (c.f. Leachman (2002)[72]). Hence, a realistic number of periods lies in between 12 and 24 (c.f. Ponsignon and Mönch (2012)[94]). A realistic dynamic supply network may involve five facilities or more (c.f. Ponsignon and Mönch (2012)[94]). Hence, the number of variables is problem-specifically quite high. However, the problem does not have to be solved in real time. As the planning frequency is quarterly, each planning run should be calculated within one up to a few days. The performance evaluation refers to these realistic problem scales. It varies the three parameters separately in these realistic scales to evaluate the effects on feasibility and on computation time.
The parameters are varied in 43 different scenarios. All scenarios are based on one common reference scenario. Hence, it is easier to compare the influence of the single parameter variation. This reference scenario consid-

ers three products, three periods and three facilities. The demand of each product is constantly 10 per period. Each facility has a constant periodic capacity of 100 for the variation of facilities and periods. For the variation of products, keeping the number of facilities constantly three, the capacity per facility has to be lifted to 300 to ensure feasibility of the scenarios. However, as it does not influence the number of variables, the computation time is not affected by the higher capacity. To enable reliable statements about the performance of the model, the cost, capacity and demand parameters are kept constant in each period, each facility and each product. Obviously, the structure of those static scenarios does not follow realistic assumptions. However, the aim of this section is to analyze the performance of the model for different realistic problem sizes. The evaluation of realistic scenarios is part of the later section 6.2.

In each scenario, in addition to the optimal solution the computation time is reported. The table in appendix A.3 specifies the 43 scenarios in terms of capacity and demand.

It can be observed, that the different input parameters differently influence the computation time and optimal solution. While an increasing number of facilities does not lead to significant increase in optimization time and optimal costs, increasing periods and products has great influence on computation time and optimal costs.

The subsequent three subsections analyze the influences of periods, facilities and products in detail.

4.4.1 Parameter Variation of Periods

The scenarios show a significant influence of number of periods on the computation time of the model as well as on the resulting minimum costs. It is obvious, that the cost for a dynamic supply network is higher, the longer the planning horizon is. At least the qualification maintenance costs are increasing the overall costs in longer planning horizons. In the simplified validation

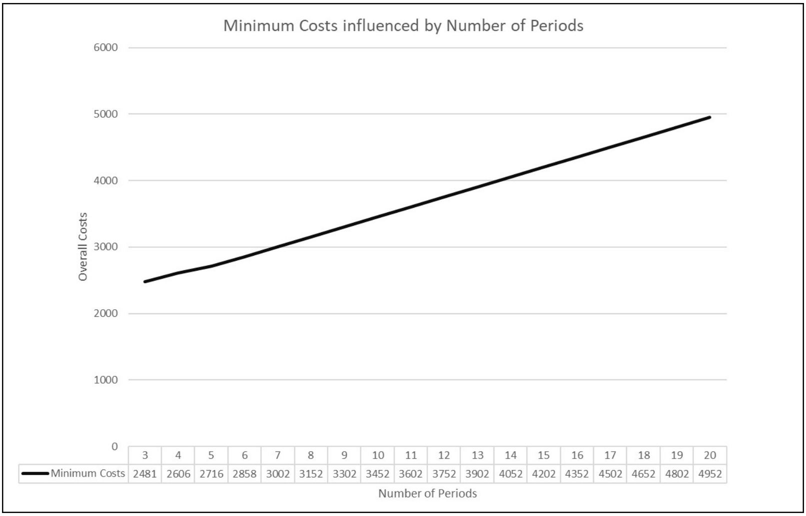


Figure 4.2: Minimum Cost Evaluation for different Number of Periods

scenarios, the number of periods has been varied from 3 to 20. Obviously, the minimum qualification costs could never become lower, when increasing the number of periods. At least there is a linear influence of number of periods on minimum costs as the following figure 4.2 visualizes:

The figure shows a linear growth of costs with linear increase of periods. This linear dependency is quite intuitive, as the demand is constant in the validation experiment. Hence, each additional period requires the same additional costs for maintenance of the qualification in this experiment. As introduced in section 4.4 the demand and capacity are held constant in this performance evaluation experiment, to exclusively correlate the influence on costs and computation time on the variation of the given parameter. If the capacity or demand was volatile, even stronger non-linear influences of periods on costs can be imagined.

The problem size is increasing linearly to an increase of periods. This can be derived from the decision variables and constraints of the model. The size of the solution space follows an increase of periods according to the following terms (4.56) and (4.57):

$$NumVar_{f,t,n} = 2 * 2^{2n} tf + 2^n f * (tn + t + n) + tn \tag{4.56}$$

$$NumConstr_{f,t,n} = 4 * 2^{2n} tf + 2^n f * (3t + nt + n + 1) + tn + 2tf \tag{4.57}$$

$$for\ parameter\ variation\ of\ n, f, t$$

These terms shows, how the three parameters, products, facilities, periods, affect the number of variables, *NumVar*, and number of constraints, *NumConstr*, and thereby the problem size.

If the number of periods is increased, the number of variables in the model increases linearly. Also, the number of constraints increases linearly. Expressed in Bachmann-Landau notation: $T \in \mathcal{O}(T)$. This can lead to a longer search for the optimal solution. As the following figure shows, in this example the computation time of the search algorithm increases exponentially. The recorded computation time as well as the growth of the problem size depend on the number of periods. The following figure 4.3 visualizes the computation time of the optimization model and the problem size of this evaluation experiment in relation to the number of periods:

Figure 4.3 shows, that on the used server in this evaluation experiment, the computation time is growing slightly at the beginning but extremely for more than 16 periods. In addition it is conspicuous, that the number of used variables is higher for an increasing number of periods. This observation is stable and results in multiple repetitions. That the function is not increasing monotonous, is related to the search algorithm of the CPLEX class. For some problems, even if the problem size is bigger, it finds the solution faster. In the trend, the computation time influenced by number of periods follows a exponential growth function.

The next subsection analyzes the resulting computation time and minimum costs in the parameter variation of facilities.

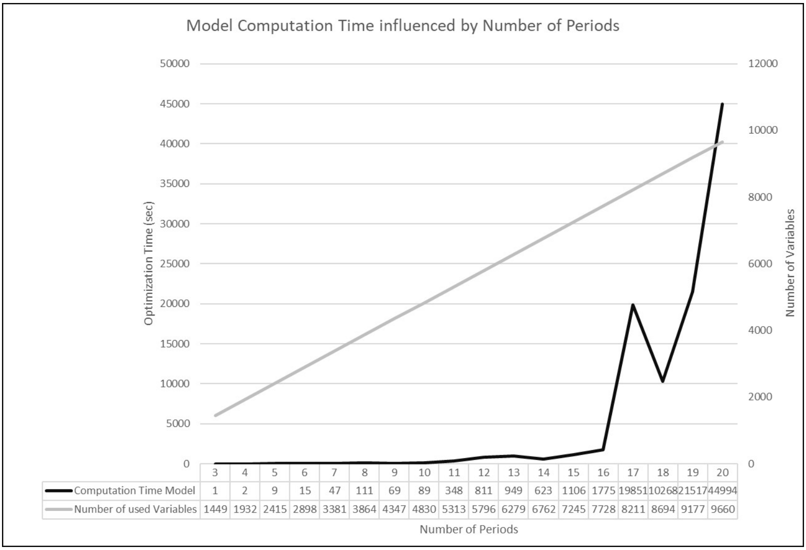


Figure 4.3: Model Computation Time Evaluation for different Number of Periods

4.4.2 Parameter Variation of Facilities

Regarding the cost minimization, no general statement about the effect of the number of facilities on the optimization result can be made. According to term (4.56), the number of facilities linearly increases the problem size ($F \in \mathcal{O}(F)$). But as an additional facility does not limit the solution space, it just leaves more options to reduce the costs. Hence, the minimum costs maximally stay constant or can be reduced, due to an additional facility. The existing product mixes can either be better resorted including the new facility, or the facility is left idle. The following figure 4.4 visualizes the effect of increase of number of facilities on the minimum costs. In this experiment there is no effect on costs due to additional facilities. Hence, the demand assignment is already cost-efficient with a low number of facilities. An additional facility does not provide a more efficient solution.

The figure 4.4 shows, that the additional options generated by the increase

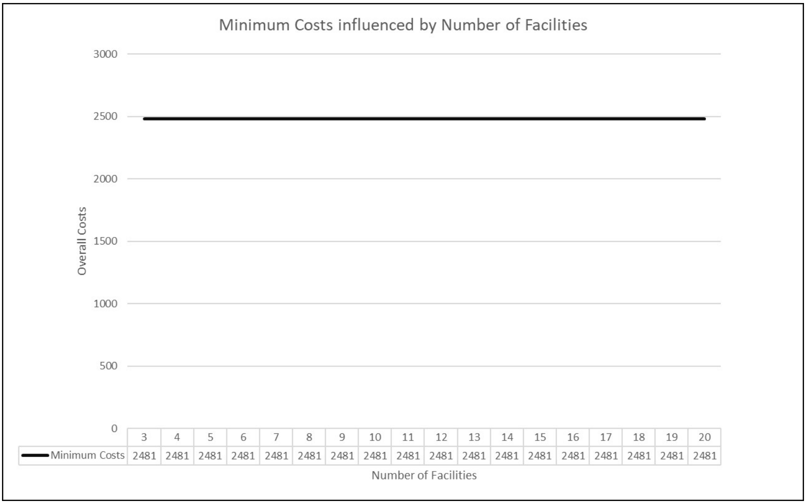


Figure 4.4: Minimum Costs Evaluation for different Number of Facilities

of facilities do not reduce the costs in this example.
Considering computation time, these new options gained by the additional facilities have to be evaluated by the model. An optimal solution has to be found in a bigger solution space. Hence, the computation time increases due to an additional facility. The following figure 4.5 shows, how the computation time raises according to the linear increased solution space.
The figure 4.5 shows, that the increase of facilities causes a linear increase of computation time with several outliers.
Concluding, both, the number of periods and the number of facilities increase the solution space linear, but other than number of facilities, increasing number of periods caused an exponential growth in computation time. The next subsection analyzes the effects of the last remaining influencing factor, number of products, on computation time of the model and minimum costs.

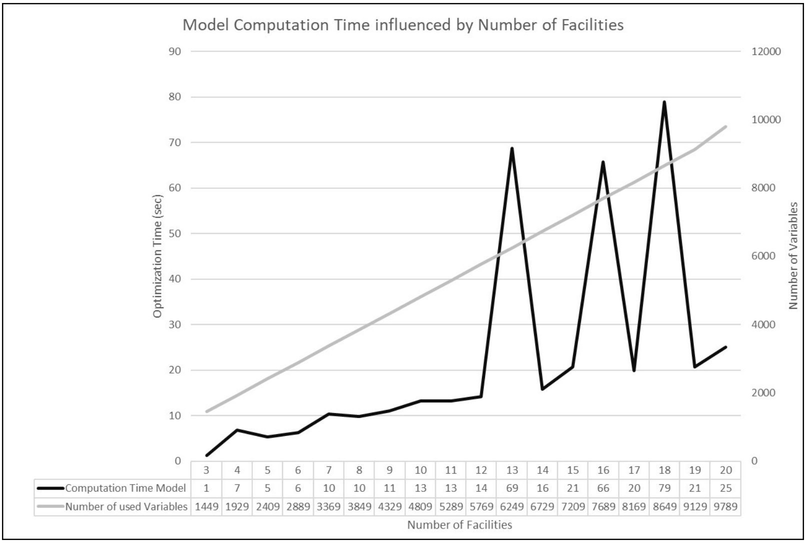


Figure 4.5: Model Computation Time Evaluation for different Number of Facilities

4.4.3 Parameter Variation of Products

The previous two parameter variations of periods and facilities increased the solution space linear. This could be derived from the effect on number of variables. Term (4.56) determines, how the number of variables is affected by a change of one of the parameters, period, facility or product. Other than for period and facility, the term reports an exponential expansion of the solution space, when increasing the number of products linearly ($N \in \mathcal{O}(2^{2n})$). The solution space grows so fast, that the number of variables can no more be handled by the given memory of the server, already at a low number of products. The reason is, that there are 2^n possible product mixes, which have 2^{2n} possible options to be combined for mix-dependency. Hence, the $n+1$st product increases the number of variables as well as the number of constraints by more than $2^{(2n+2)}$, which leads to tremendous growth of the problem size. This is the reason, that the computation time for finding the

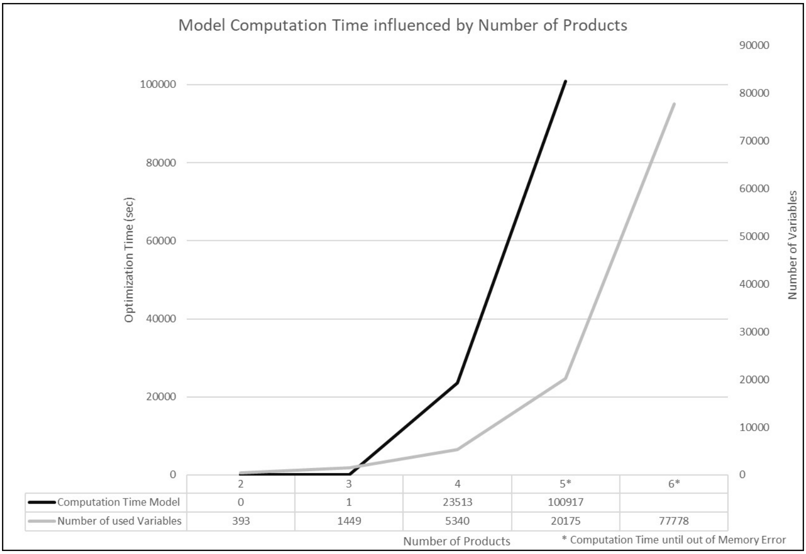


Figure 4.6: Model Computation Time Evaluation for different Number of Products

minimum costs increases extremely. Figure 4.6 shows this high exponential growth.

Already with only five products the calculated number of variables is 20655, according to the term (4.56), introduced in section 4.4.1. Though IBM ILOG CPLEX does not touch every variable, it still has to handle 20175 variables. The calculated number of constraints, according to the term (4.57), is 30561. Though some constraints are inferior to others, still 20289 constraints have to be handled in this problem size. The huge influence of increase of products on the problem size causes the shown extreme increases of computation time. Already for a problem setting of five products, after 28 hours the RAM of the server of 262 GB is overwhelmed. It could not solve the DSNDP for five products optimally at all. A relaxation of the model removing the integrality constraints (4.53), (4.54) and (4.55) leads to the same outcome. Although, the computation times for executable

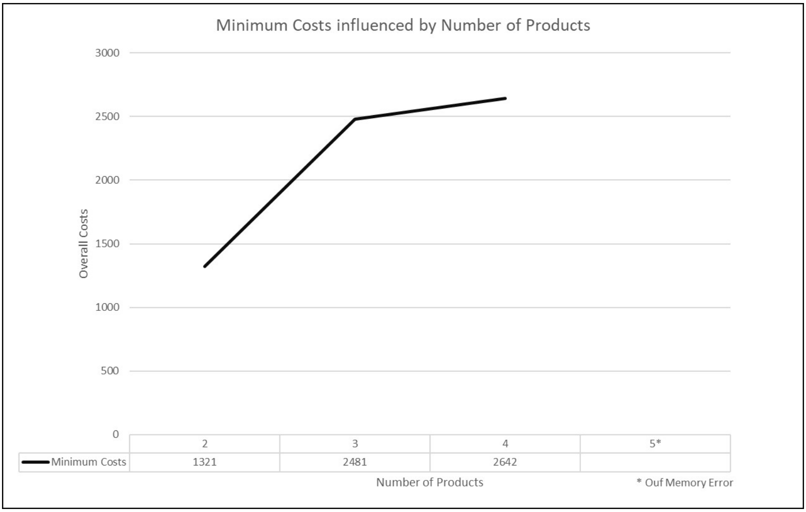


Figure 4.7: Minimum Costs Evaluation for different Number of Products

problems are lower, still problem settings with five products or more can not be executed, due to memory problems. Since realistic numbers of product groups in the master planning level are assumed to lie above six, the performance of the model is too limited.
Figure 4.7 is visualizing the effect of linear increase of number of products on the minimum costs.

As described, the model could not find an optimal solution for five products or more, because the memory was over-utilized. Although the resulting costs can only be visualized for two to four products, it is impressing to see, how the growth of costs could be reduced with more products. The reason is, that there are more options to combine products according to their relationship. The bigger the set of products is, the more efficient the products can be clustered to the available facilities.
The next section concludes the performance evaluation of the Dynamic Sup-

ply Network Optimization Model and motivates further steps for industrial treatment of the DSNDP.

4.4.4 Performance Conclusion

The performance evaluation of the optimization model analyzed the effects on model feasibility of all the three influencing factors, number of periods, number of facilities, number of products. For both parameter variations, number of periods as well as number of facilities, the model finds the optimal solution in acceptable time. Although the variation of number of periods affected the computation time of the model exponentially, realistic problem sizes of up to 20 periods have been feasible. The number of facilities has been varied up to 20 facilities. The parameter variation of facilities did hardly affect the computation time of the model. Hence, also problems with realistic numbers of facilities could be solved optimally in acceptable time.

The major challenge occurs in the parameter variation of products. Since the number of products, other than periods and facilities, is increasing the problem size exponentially, the computation time and also RAM is extremely affected by the increase of number of products. On the used server with 262 GB RAM only problems with up to four products could be solved. For the fifth product the available RAM was overwhelmed after 28 hours. The same problem occurred to a relaxed model, excluding the integrality constraints.

Especially for the DSNDP, with the background of dynamic markets and shortening product life cycles, the most volatile parameter is products. Hence, even if the DSNDP is part of the Master Planning Level, where products are used to be aggregated to product groups, the maximum capability of four product groups is not sufficient. Hence, the model can not cover realistic problem sizes sufficiently. The most important parameter to be varied is the number of products in this problem The higher the number of products is, the more diverse and manifold the product mix combinations can be.

This is the reason, extremely sensitive modelling for the mix-dependency and qualification structure of this parameter is proposed in this work.

Altogether, the two performance questions, raised in the beginning of the performance evaluation, can now be answered: Firstly, the computation time raises exponentially with linearly increasing problem size.

Secondly, especially the number of products limits the problem size. The maximum number of products, leading to a feasible solution, is 4. This is not sufficient for applying the model to realistic industrial supply network design problems.

Therefore, a heuristic approach is developed in the following part of this work. The heuristic approach has to consider the same assumptions and has to use the same inputs, but has to solve the DSNDP more efficiently, so that only promising parts of the solution space are searched and a good solution can be found in reasonable time for realistic problem sizes. As searching the entire solution space is overwhelming the memory of conventional servers, limiting the search on the promising parts of the solution space will increase the search process but also will not guarantee optimality.

Motivated by the challenge to solve realistic problem sizes, the following chapter 5 introduces a heuristic approach for the DSNDP, as a performant alternative for the exact optimization model. The heuristic considers all assumptions of multitasking resources, mix-dependency and qualification differentiation and solves the problem focussed on feasibility.

5 Displacement Heuristic

Motivated from the model performance evaluation, this chapter develops a heuristic approach to cover realistic problem sizes of the DSNDP. This chapter focusses the fourth research question, how to solve a DSNDP in of realistic size in acceptable time. The heuristic, developed here, is called Displacement Heuristic, as it iteratively assigns and displaces all demand to the dynamic network until a cost-effective solution is found. It represents the idea, that a change at one point in a network may affect the entire network. The Displacement Heuristic is intended to have an option to re-assign the demand in the network completely new, if a new order is assigned. Therefore, it assumes the same mix-dependency and qualification differentiation principles like the optimization model.

Altogether, the idea of the assignment and displacement can be described with the well-known ripple effect. Throwing a cup of water into a filled water barrel results in homogenously diffusing circular waves, which at a certain point in time cover the entire surface. Either the water spills over or finds its balance again in the barrel. Following this metaphor, a new demand for the system can trigger an entire re-design of the dynamic supply network. The water and especially the level of the water is troubled and needs some time to balance again to an acceptable level. If the cup of water thrown into the filled barrel is too big, the water will spill over. Assuming a chain of water barrels, another barrel could capture the volume of water spilled out. Again, the water of this barrel is troubled and needs some time finding its balanced level. Again, it can happen, that due to the additional portion of water the barrel spills over. Altogether, an inserted drop may trig-

ger a re-arrangement of water in the barrel and might lead to a displacement of water from one barrel to another. Thereby, depending on the amount of water inserted, not all the water in the barrel might be re-arranged. Water deep down in the barrel may not even recognize the trouble on the surface. And different barrels far down the chain may also not recognize any change. This example describes, what is happening with new demand in a dynamic supply network. As described in earlier sections, modern supply networks, facing shortening product life cycles and increasing volatility in demand, might be described with a network of water barrels standing in the rain. The water constantly has to re-arrange and does not find a steady state at all.
This example shows a demand change may not only affect the facility, responsible for this demand, but also other facilities, collaborating with this facility. However, the example also shows, the demand change does not necessarily affect all facilities (barrels) in the chain. In difference to the optimization model, the idea of the Displacement Heuristic is to only cost-efficiently guide the demand-triggered displacement process in the network, but not to re-search all the solution space (leave not affected barrels out of scope). The assumption of the heuristic is that the not affected part of the solution space is already in a pretty cost-efficient assignment balance. If capacity in the best fitting facility is over-utilized, only the assigned products with the best alternative are displaced. Thereby, the heuristic manages not only the introduction of the new demand with the aim to minimize costs, but also the displacement chain, triggered by this new demand.
The idea of the Displacement Heuristic originates from the relationship of products. Resources attract related kinds of products and displace unrelated ones to avoid extensive qualification. Following this theory of centering the facilities production focus by attraction of related products, can reduce overall costs of the supply network. Thereby, every emerging demand changes the situation and the optimal assignment of products. Products, which have been produced in one facility, may be displaced, because the new demand fits better. Thereby, the entire dynamic supply network might change. It

might be easy in an empty supply chain to assign related groups of products to the facilities and thereby specialize the facilities for a certain core product group. However, in an operational use in a non-steady state system with a certain system starting state it is much more realistic to generate an algorithm, which searches a good overall supply network plan by including and efficiently re-assigning the orders to the existing facilities. Additionally, accepting, that the optimum is not found, it is possible to handle much bigger problem sizes then the optimization model could in shorter time. The Displacement Heuristic follows the paradigm of non-steady state dynamic supply networks. It assigns and re-assigns the upcoming demand according to the theory of attraction and displacement to the facilities, where it is fitting best. Consequently, it designs the dynamic supply network iteratively without searching the entire solution space. Hence, it can handle much bigger problem sizes and generate good plans much faster but maybe miss the global optimum solution. The validation of the Displacement Heuristic in comparison to the Dynamic Supply Network Design optimization model will be part of the next chapter. This chapter focusses on describing the Displacement Heuristic from the rough idea down to the algorithm details, to enable the reader to re-build and maybe further extend the approach.

In the Displacement Heuristic the dynamic supply network is designed and re-designed every period in a rolling manner. The cost-efficient demand assignment is done iteratively. Iterating through all periods, step by step, each upcoming demand is assigned to the facility with the most similar production focus (to avoid extensive qualifications). In the first step this assignment is done with pure focus on costs, ignoring the capacity limits. In a second step it is checked, if the cost-efficient assignment exceeded the capacity limit of the facility. If this is the case, the product with the cheapest alternative facility is searched in this facility and displaced there. This is done until the capacity limit in every facility is respected again. Then the next demand of the considered period is assigned. The heuristic continues, until every demand of the period is cost-efficiently assigned and iterates to

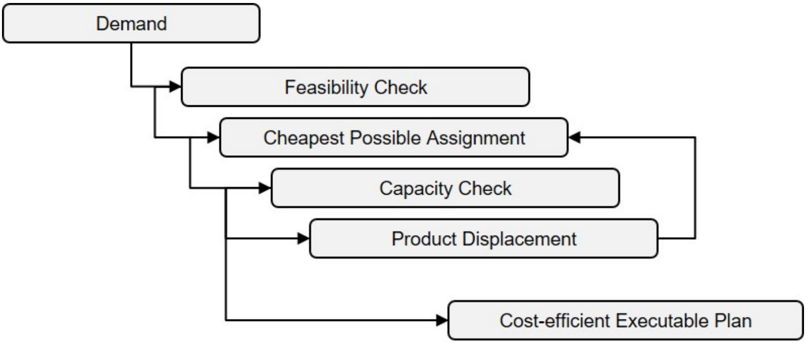


Figure 5.1: Outline of the Displacement Heuristic

the next period. Consequently, all periods are solved and the overall costs are calculated in the end. To check, if the scenario is executable at all, in advance two kinds of capacity pre-checks are performed. The first one checks, if the overall capacity is covering the overall demand at all. The second checks, if the periodic capacity is covering the periodic demand and if possible determines the necessary amount of pre-production (under additional storage costs). Altogether, the algorithmic approach changes from creating the optimal supply network plan for the whole planning horizon at once in the optimization model, to iteratively finding a good and executable plan with a heuristic. The optimization model finds the optimal solution but is slower and restricted to a certain maximum problem size, while the Displacement Heuristic does not guarantee to find the optimal solution, but can solve much bigger problems much faster.

The basic idea of the Displacement Heuristic is outlined in figure 5.1.

The implementation of the Displacement Heuristic algorithm is described in detail in the following sections. The subsequent section 5.1 briefly focusses the basic idea of product displacement derived from the product relationship from subsection 4.2.4. Basing on the displacement fundaments, section 5.2 gives detailed insights to the structure and implementation of the Displacement Heuristic algorithm.

5.1 Product Displacement

As introduced in the previous section, the approach of the Displacement Heuristic assigns a new demand to the facility with the minimum costs. Thereby, actively the capacity constraint is ignored, to increase the options of assignment. Hence, the costs for the assignment, ignoring capacity, are smaller or equal to the costs considering the capacity limit. Of course, after the assignment it has to be checked, if the capacity limit is exceeded. If this is the case, the Displacement Heuristic searches for the product to displace with the least alternative qualification costs in an other facility. This may also be the product just assigned. This approach is different to classical assignment approaches. It ignores the capacity constraint in order to increase the solution space. After the assignment, it includes the ignored capacity constraint and makes the solution feasible by displacing the product with the cheapest alternative. As the Displacement Heuristic, due to ignoring one constraint in the beginning, has more options, compared to the capacitated alternative, it finds better solutions. The reason is, that for each assignment it has the option to re-assign again all the demand, already assigned to consider the capacity restrictions with reduced costs. In the Displacement Heuristic the new demand triggers an entire re-organization of the dynamic supply network, searching for the minimum overall costs. A little example compares the intuitive assignment, considering the capacity limits directly with the displacement alternative. In the example, there are three facilities producing two products. For simplification the qualification costs are not mix-dependent and there is only one period, hence no qualification differ-

	Classical Assignment		**Displacement Heuristic**
(1)	$assign\ 100\ P_1\ to\ Fac_1$	(1)	$assign\ 110\ P_1\ to\ Fac_1$
(2)	$assign\ 10\ P_1\ to\ Fac_3$	(2)	$displace\ 10\ P_1\ to\ Fac_3$
(3)	$assign\ 90\ P_2\ to\ Fac_3$	(3)	$assign\ 100\ P_2\ to\ Fac_3$
(4)	$assign\ 10\ P_2\ to\ Fac_2$	(4)	$displace\ 10\ P_1\ to\ Fac_2$
$\rightarrow$	**overallCosts = 120**	$\rightarrow$	**overallCosts = 80**

Table 5.1: Displacement Heuristic Comparison

entiation considered. The following necessary input is given:

$$D_1 = 110; \quad D_2 = 100;$$
$$PT_1 = 1; \quad PT_2 = 1;$$
$$C_{Fac_1} = 100; \; C_{Fac_2} = 100; \; C_{Fac_3} = 100$$

$$cq_{n,f} = \begin{array}{c} \\ P_1 \\ P_2 \end{array} \begin{array}{c} \begin{array}{ccc} Fac_1 & Fac_2 & Fac_3 \end{array} \\ \begin{pmatrix} 10 & 50 & 30 \\ 100 & 60 & 20 \end{pmatrix} \end{array} \tag{5.1}$$

The two alternative assignment procedures are compared in table 5.1:
This example shows, that the Displacement Heuristic is able to find better solutions in the same solution space, with the option of re-assignment, than the intuitive capacitated approach. Nevertheless, as there are not all possible solutions evaluated, the optimal solution can not be guaranteed by the Displacement Heuristic.
To find the best solution possible, the product displacement routine related to the theory of relationship of products, introduced in subsection 4.2.4.

According to the product-specific capacity requirements, described in the Linear Capacity Program, each product displaces another product to a specific extent. As described in subsection 4.2.3, a typical capacity equation including the capacity requirements from all products looks as follows:

$$C_f = Q_1 * PT_1 + ... + Q_n * PT_n + ... + Q_N * PT_N + b_f \tag{5.2}$$

For simplification reasons, f represents an entire facility, instead of a machine m within a facility. Hence PT_n represents the overall necessary processing time for product n. C_f represents the overall capacity of the facility. As described in subsection 4.2.3 due to the capacity buffer b_f, the term can be expressed in an equation. Beyond that, the capacity buffer b_f indicates, how much volume can still be accommodated by the considered facility. A displacement to another facility only has to be considered, if the assigned demand, exceeds b_f. Thereby, the capacity and the capacity buffer are given in time units. Hence, the product displacement not only depends on the amount of lots assigned, but also on the overall processing time of the particular product. In detail, the following parameters determine the volume of product displacement:

1. Process time of the product assigned (PT_n)
2. Process time of the product to be displaced (PT_k)
3. Production quantity of the product assigned (Q_n)
4. Remaining capacity buffer in the facility assigned (b_f)

Those four parameters indicate the quantity of k, which has to be displaced to make room for the assignment of the new demand of product n to the best fitting facility f. To determine the volume for displacement of a specific product, basically the capacity buffer b_f has to be subtracted from the demand assigned. The resulting exceeding capacity has to be divided by the process time of the product to be displaced. The resulting production volume has to be displaced. Altogether, the simple term considers all the four parameters and determines the displacement volume of product k, according to additional production volume of product n:

$$Q_{(k,displ)} = \frac{((Q_n * PT_n) - b_f)}{PT_k} \tag{5.3}$$

As the heuristic is iteratively assigning the demand, only single products have to be handled. Hence, there is no need for a coefficient of product portfolio displacement.
The displaced production quantity strongly depends on the product k to be displaced. If PT_k is high, less lots have to be displaced, compared to a product with a smaller process time. But the number of lots to be displaced is not critical for the decision about the suitable product for displacement. The decision is only influenced by costs. The product with the least alternative costs will be displaced. In the best case, there is already one of the candidates qualified in another facility. The minimum alternative costs for displacement are 0, in this case. Hence, for finding the right displacement product leading to the least alternative costs in another facility, the current qualification states and qualification costs of the alternative facilities have to be searched for the minimum. This procedure of finding the right candidate for displacement and determining a suitable volume for displacement for this candidate includes the two necessary steps to perform a displacement.
As described earlier, the cost-efficient displacement routine continues until all capacities are back to an acceptable solution. Then, the next demand of the period considered is assigned.
After the fundamentals about product displacement are introduced, the following section describes the iterative algorithm of the Displacement Heuristic in more detail.

5.2 Displacement Heuristic Approach

As introduced in chapter 5 the displacement heuristic changes the logic from planning the entire planning horizon at once to an iterative approach, which iteratively selects the necessary options. Therefore, the problem-specific solution space is searched much more efficient. But there is a risk, that only a good, but not optimal solution is found in the end. In several problem cases this risk can be accepted, as the heuristic on the one hand solves the problem tremendously faster and on the other hand is capable for bigger problem sizes. The insights about the performance of the Displacement Heuristic will be given in section 6.1.

Altogether, the Displacement Heuristic algorithm can be divided into three parts:

The first part (preparation) checks, if the scenario is feasible at all, prepares the periodic demand and sorts the facilities according to their capacity. These steps support the fast search for a feasible and good solution.

The periodic demand is prepared in a backward loop for all periods from the last to the first minimizing the necessary holding costs.

The second part (assignment and displacement) includes several forward loops to assign the specific product demand to the facility minimizing the overall qualification costs. According to the idea of the Displacement Heuristic, it assigns a new demand to the cheapest facility, ignoring its capacity limit. If necessary, it displaces other products to their cheapest alternative, to make space for the assigned demand in this facility.

The third part (re-optimization) takes the assignment plan and re-optimizes the qualification and maintenance schedule according to the introduced stability vs. flexibility tradeoff.

The following figure 5.2 shows the iterative procedures of all three parts of the Displacement Heuristic:

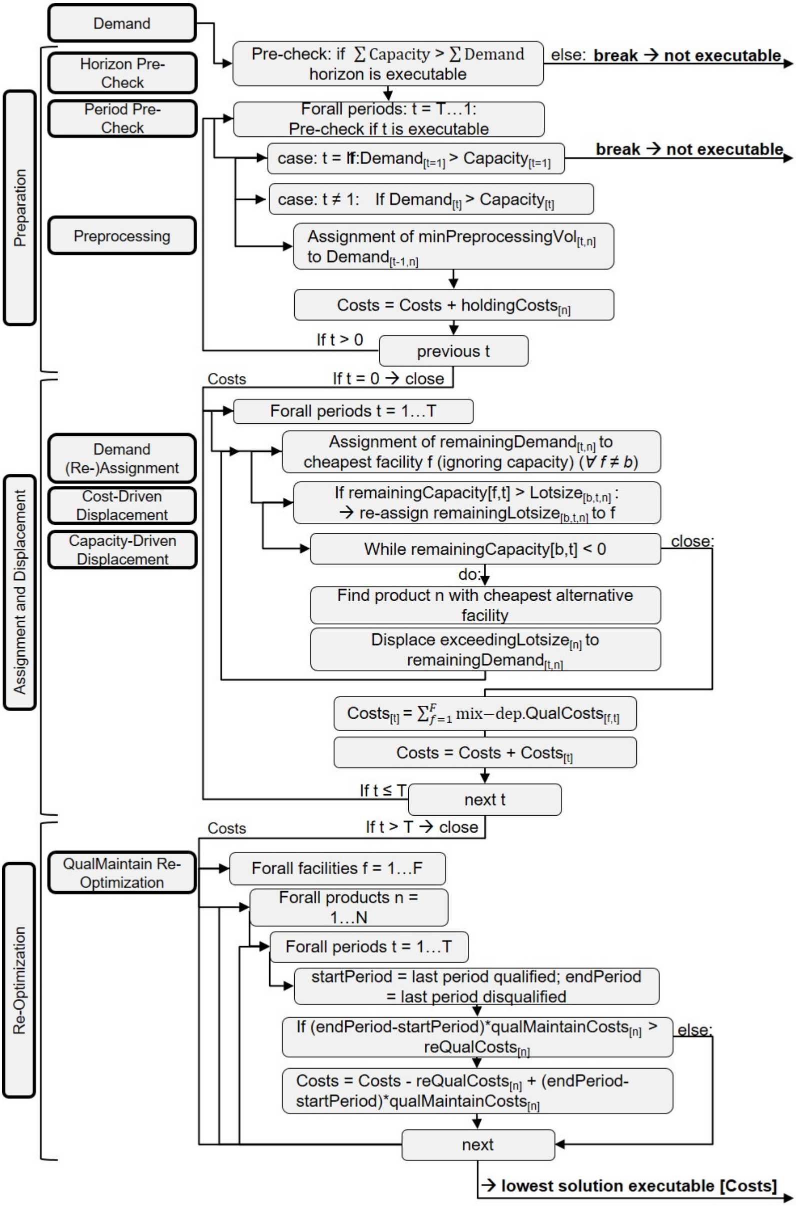


Figure 5.2: Displacement Heuristic Approach

The figure shows the three iterative parts of the heuristic, **Preparation**, **Assignment and Displacement**, and **Re-Optimization**. It thereby details the basic idea from the start of this chapter even more.

5.2.1 Displacement Heuristic Preparation

To prepare the problem for an executable solution in the first part, three different preparation steps are performed.
Firstly, the horizon pre-check is done. It has to be checked, if the sum of capacities of all the facilities and all the periods is able to fulfill the entire demand of all the products in all periods. If this is not ensured, the problem has no executable solution at all. If the overall capacity can provide all the demand, still there can be single periods, where the demand exceeds the capacity. Therefore, the assumptions of the DSNDP foresee the option for pre-processing and holding (under holding costs). Altogether, other than in the proposed optimization models of the DSNDP, the pre-processing option just tries to make the problem executable, but is not part of the optimization objective itself. This approach bases on the strategy to avoid cost-intensive stocks. This is one of the reasons, the Displacement Heuristic will fast reach a good executable solution, but might miss the optimal solution.
The second preparation step (period pre-check) loops through all periods backwards, from the last to the first, and checks, if the periodic capacity is able to cover the demand of the period. If this is not possible, the exceeding demand is pushed to the period before for pre-processing. The pre-processing volume of period t directly increases the demand of the period $t-1$, as specified in the term (5.5). This of course increases the overall costs due to additional holding. To keep the holding costs as small as possible, the least amount possible is sent for pre-processing. The determination of the volume to be pre-processed is specified in the following term (5.4):

$$Vol_{(t-1,preproc)} = min((\sum_{n=1}^{N}(D_{t,n} * PT_n) - \sum_{f=1}^{F} C_{f,t}), 0) \quad \forall t \in 2..T \tag{5.4}$$

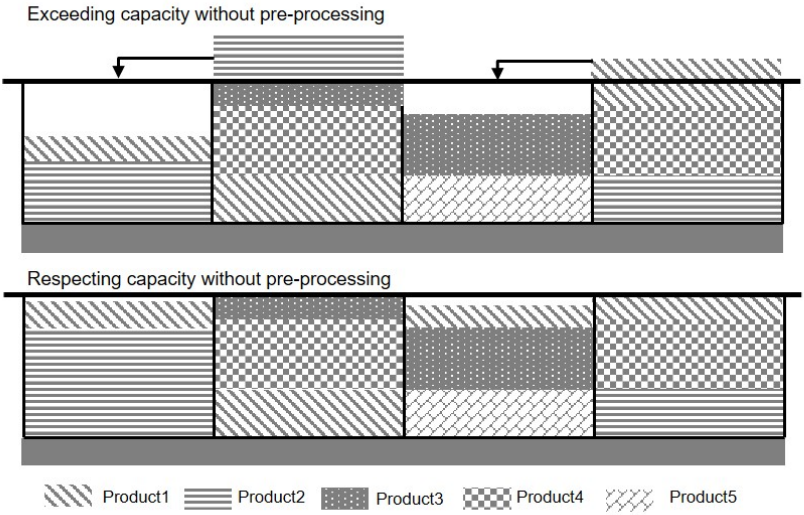


Figure 5.3: Period Preparation with Pre-Processing

$$If\ (Vol_{(t-1,preproc)} > 0)\ then$$
$$D_{(t-1,n)} + \frac{Vol_{(t-1,preproc)}}{PT_n} \quad for\ n\ with\ PT_{(n,max)} \tag{5.5}$$

Figure 5.3 visualizes the period feasibility check determining minimum pre-processing volumes.

The transfer of the product n with maximum process time $PT_{(n,max)}$ minimizes the amount of products to be pre-processed and thereby minimizes the necessary holding costs ch_n.

Intuitively, the first period has to cover the resulting demand including the remaining pre-processing volume autonomously, as it has no earlier period to pre-process it. No pre-processing can reduce load from the first period. This is described in the term (5.7). Hence, in the end, in the first period it is decided, if the problem possesses an executable solution. The periods have to be looped backwards in the period pre-check, as it has to push the necessary volume for pre-processing period for period back in the horizon. The following two terms (5.6) and (5.7) are the core of the first part of the heuristic. They formulate the two pre-checks:

$$\sum_{f=1}^{F}\sum_{t=1}^{T}(C_{f,t} - ti_{(f,i,j,max)}) \overset{!}{\geq} \sum_{t=1}^{T}\sum_{n=1}^{N}(D_{t,n} * PT_n) \tag{5.6}$$

$$\sum_{f=1}^{F}(C_{f,1} - ti_{(f,i,j,max)}) \overset{!}{\geq} \sum_{n=1}^{N}(D_{1,n} * PT_n) \tag{5.7}$$

For both pre-checks, the capacity is reduced by the maximum possible qualification time $ti_{f,i,j,max}$ to ensure, that the capacity of a facility in any case is not exceeded, which ever qualification has to be chosen to enable the necessary product portfolio. This of course may reduce the capacity too much and hence exclude possible solutions, which could lead to lower overall costs. But, because it is not possible to foresee, which qualification is adequate in the particular period and facility, this is a necessary step.

After all the periods have been made executable by iteratively adding the minimum necessary pre-processing amount to the demand of the previous period, a third preparation step has to be executed in advance of the demand assignment.

The third preparation step prepares the order of the facilities to be filled. It sorts the facilities according to their average capacity in descending order. Hence, the facility with the highest average capacity is on the top of the list. As the algorithm fills the empty facilities according to this order, assuming the qualification costs are the same, it is ensured, that first the facility with the highest capacity is filled. This increases the probability of being able to rather use a re-qualification instead of an expensive initial qualification in later iterations.

Now, all three preparation steps are performed. If the problem is decided to be able to find executable solutions, in the second part of the Displacement

Heuristic approach the main assignment and displacement routine can start from the first period to the last.

5.2.2 Displacement Heuristic Assignment and Displacement

The main part of the Displacement Heuristic, the iterative assignment and displacement routine, loops through all periods from the first to the last. Within each period, it iteratively assigns all demand, product by product.
For every product demand, there are three steps performed.
The first step coordinates the assignment of demand to the cheapest facility, ignoring the capacity limit. The second and third step coordinate the necessary displacement, considering the capacity limit. Depending on the capacity, there are two cases of displacement. Either there is capacity remaining after the assignment or the assignment led to an overload of capacity. Hence, either the second step performs a cost-driven displacement, or the third step performs a capacity-driven displacement.
The first step captures the demand of a particular product in a particular period and assigns it to the facility, where it is fitting best (according to the relationship of the product with the qualified product mix) ignoring the capacity limit. For the cost-optimal assignment two issues have to be respected: Firstly, the costs for qualification are mix-dependent and are expressed for product portfolios, as introduced in section 4.2.2. Secondly, the qualifications can gain from experiences, as introduced in section 4.3
To cope with the mix-dependent portfolio qualifications, an array of product qualifications is generated for each facility in each period during the assignment loop. This array for every potential assignment is translated into a potential product portfolio to indicate the upcoming qualification costs. To save qualification costs according to the qualification differentiation strategy, the resulting portfolio variables are stored in a so-called product history for all facilities. This product history indicates, if a given product portfo-

lio has ever been qualified or may be maintained from the previous period. These inputs are influencing the assignment of products.
After the assignment is done, the Displacement Heuristic has to care about the displacement in the second and third step of this part.
The second step performs the cost-driven displacement, if there is still capacity left in the facility. It tries to reduce the overall costs by avoiding qualification steps in other facilities, which may be no more necessary after the current assignment. Therefore, it checks, if the currently assigned product has already been displaced to other facilities in other iterations of this period. If this is the case, the cost-driven displacement step tries to collect these production quantities from the other facilities back to this facility, as long as the capacity allows it. It starts with the cost-driven displacement at the facility with the smallest production quantity of the considered product, with the aim of exonerating as many facilities as possible from the qualification. Hence, the cost-driven displacement tries to reduce the qualification costs as much as possible by avoiding redundant qualifications in other facilities.
The third step of the assignment and displacement routine coordinates the capacity-driven displacement. It is only relevant, if the capacity is exceeded after the assignment. In this case, it searches in the overloaded facility for the product with cheapest alternative facility to be displaced to. Again, it respects the two modelling assumptions, mix-dependent portfolio qualification as well as qualification differentiation. It does not directly assign the displaced volume to the cheapest alternative facility, but returns the necessary production volume back to demand, so that the capacity constraint is fulfilled. From the demand the displaced production quantity can be assigned to the cheapest facility, where it has not yet been assigned, in one of the next product iterations. Hence, the displaced production quantity returns to step 1 with the next product demand to assign. The assignment and displacement routine continues this loop, until all product demand is assigned and the displacement has ensured, that the capacity is not exceeded

anywhere. In this way all product demands are step by step assigned to the best possible facility. Due to the displacement of products the potential qualification states may change until all product demand is assigned and the displacements are coordinated. Hence, the resulting production portfolio of each facility for the considered period can be summarized, when all the assignment and displacement is finished in one period. This is the reason the logic of the iterative structure of the Displacement Heuristic follows a small bucket approach. Hence, other than in the model approach, there is only one chance to decide about the suitable, cost-efficient qualification. Compared to the optimization, model this can in some cases lead to higher costs. In the end of every period iteration, the resulting qualification costs of every facility of the considered period can be added to the overall costs. This procedure is proceeded for every period. In the end the overall costs contain the holding costs from the necessary pre-processing as well as the mix-dependent qualification costs of every facility in every period.
Part one and two of the Displacement Heuristic lead to executable good solutions, but the costs can even be reduced in the third part, the re-optimization.

5.2.3 Displacement Heuristic Re-Optimization

The third part of the Displacement Heuristic, the re-optimization, tries to reach even lower overall costs in the given dynamic supply network, by ex post adjusting the qualification policy.
The qualification differentiation leads to a cost tradeoff of maintaining and re-qualifying a product mix, if it is temporary not required. This tradeoff is described in section 4.3 with the stability strategy and the flexibility strategy. The tradeoff is considered in the third re-optimization part of the heuristic. The re-optimization does not affect the assignment of product demand in the single period but just tries to reduce the costs with another qualification setup. It tries to reduce the costs even a bit more by maintaining a product

portfolio instead of dis- and re-qualifying it. Depending on the structure of costs for re-qualification and costs for qualification maintenance, it may be more efficient to maintain a qualification instead of disqualify and re-qualify it again, when required. If the re-optimization can reach lower overall costs with applying this tradeoff, the qualification plan is changed and the costs are updated. The production program is not changed by the re-optimization. The following term (5.8) visualizes this re-optimization:

$$
\begin{aligned}
& if((endPeriod - startPeriod) * cm_{f,n} > cr_{f,t,n})\ then \\
& \quad for(period : t = startPeriod \rightarrow endPeriod) \\
& \qquad qualification_{f,t,n} = 1 \\
& \quad closeLoop(periods) \\
& \quad overallCosts = overallCosts - cr_{f,t,n} + \\
& \qquad\qquad (endPeriod - startPeriod) * cm_{f,n} \\
& endIf
\end{aligned} \tag{5.8}
$$

After all the costs have been calculated, the heuristic returns the structure of the designed dynamic supply network as well as the resulting overall costs. The appendix A.4 outlines the Displacement Heuristic algorithm in a pseudo code in detail. This is necessary to re-build the Displacement Heuristic algorithm. The pseudo code is readable but does not contain all the details (like variable declarations and -initializations, etc.), which are used in the implementation in JAVA. To enable the reader to reproduce the heuristic and maybe optimize it even more, it is displayed in A.4.

The Displacement Heuristic is implemented in JAVA using Eclipse IDE 2019 based on the pseudo code. On this basis the Displacement Heuristic is validated against the optimization model in the subsequent chapter. Thereafter, the performance evaluation analyzes specific scenarios, to evaluate the quality of the Displacement Heuristic for realistic industrial cases. Special attention is given to the capability of practical problems (sizes) and the applicability in real supply networks. In specific scenarios the heuristic is tested and the particular effects are analyzed in detail. The performance evaluation chapter ends with a conclusion on the findings of the heuristic and specific managerial insights for planning of Dynamic Supply Networks in volatile markets.

6 Performance Evaluation

To evaluate the performance of the Displacement Heuristic, this chapter is structured in three sections. First of all, the Displacement Heuristic has to be validated against the optimization model. For the validation of the Displacement Heuristic, the same scenarios are chosen, as for the evaluation of the optimization model in section 4.4. Similar to section 4.4, the performance of the heuristic has to be validated with special focus on the computation time and quality of the solution. To enable the heuristic for bigger realistic problem sizes, the guarantee of optimality is not maintained. Nevertheless, with the assignment and displacement routine as well as the re-optimization routine, the Displacement Heuristic is aiming at a fast search for a very good solution. The success of this fast search has to be validated against the optimal solution.

After the heuristic has been validated, the second section compares the results of the heuristic using realistic scenarios. Thereby, all effects as well as their interaction are specifically tested in various scenarios. This helps to evaluate the behaviour and solutions of the heuristic in realistic situations.

In the third section of this performance evaluation the observations are concluded. On this basis specific managerial insights for Dynamic Supply Network Design in volatile markets with shortening product life cycles can be postulated. The challenge of increasing volatility and shortening product life cycles was the main motivation of this thesis.

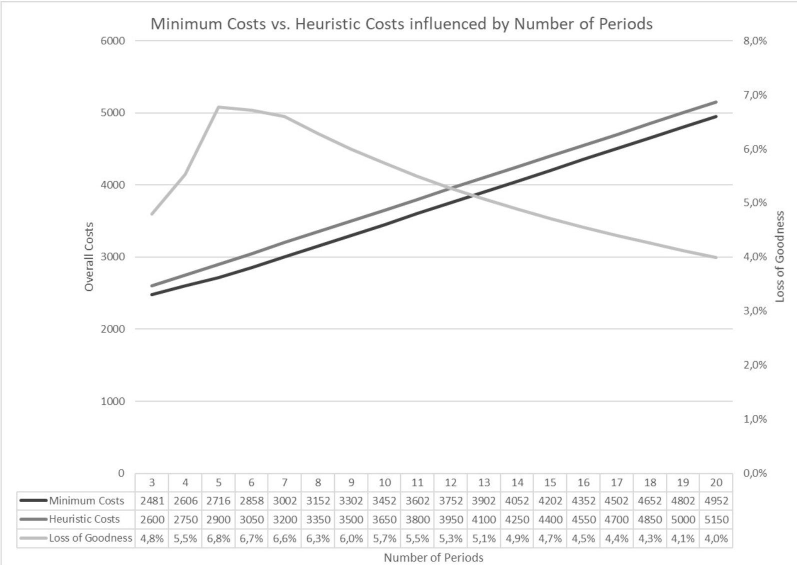
6.1 Performance Validation of the Displacement Heuristic against the Optimization Model

To apply the heuristic for industrial problems, it first has to be validated with realistic problem settings concerning optimality and computation time. For this purpose this section re-captures the same scenarios, used for the validation of the optimization model in section 4.4 and validates the Displacement Heuristic.

Again the scenarios involve variations of all three influencing parameters, number of periods, number of facilities, and number of products. For each of the three parameter variations, there are two figures visualizing the performance of the Displacement Heuristic compared to the optimization model, depending on the specific parameter. One figure visualizes the heuristic costs in comparison to the minimum costs from the optimization model as well as the resulting loss of goodness for the different parameters. The other figure visualizes the computation time of the heuristic in comparison to the computation time of the optimization model for the different parameters. The performance validation starts with the parameter variation of periods.

Equivalent to the model performance evaluation in section 4.4, the smallest period scenario starts with three periods. In parallel, this scenario is the reference scenario to compare the different parameter variations among periods, facilities and products. The parameter variation increases the number of periods up to 20 in 18 scenarios. Beginning with the variation of number of periods, the following figure 6.1 shows the resulting costs of the heuristic in comparison to the reached minimum costs by the optimization model. Another graph in the figure 6.1, summarizes the loss of goodness of the scenarios.

The diagram shows the parallel linear growth of the heuristic and the minimum costs. The loss of goodness is converging towards 4%. It reaches its peak in the scenario with five periods. Altogether, the Displacement Heuristic follows the same trend, but shows a slight gap to optimality. This



	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Minimum Costs	2481	2606	2716	2858	3002	3152	3302	3452	3602	3752	3902	4052	4202	4352	4502	4652	4802	4952
Heuristic Costs	2600	2750	2900	3050	3200	3350	3500	3650	3800	3950	4100	4250	4400	4550	4700	4850	5000	5150
Loss of Goodness	4,8%	5,5%	6,8%	6,7%	6,6%	6,3%	6,0%	5,7%	5,5%	5,3%	5,1%	4,9%	4,7%	4,5%	4,4%	4,3%	4,1%	4,0%

Figure 6.1: Heuristic Cost Validation for different Number of Periods

means, following the period parameter variation, it considers all the effects but reaches a good, but not the optimal solution, just as expected.

The second figure 6.2 of the variation of number of periods visualizes the heuristic computation time in comparison with the computation time of the model.

The heuristic solves each problem size in under one second with a loss of goodness of 4%, while the optimization model needs more than 12 hours for finding the optimal solution with 20 periods. Hence for up to 20 periods, three products and three facilities the model still requires reasonable time to find the optimal solution. But as the figure shows, the computation time of the model grows exponentially. Thus, beyond 20 periods, the model will not find a solution anymore. Consequently, up to 20 periods, three products and three facilities the optimization model can be used. But beyond this problem size the heuristic is necessary, accepting a 4% loss of goodness.

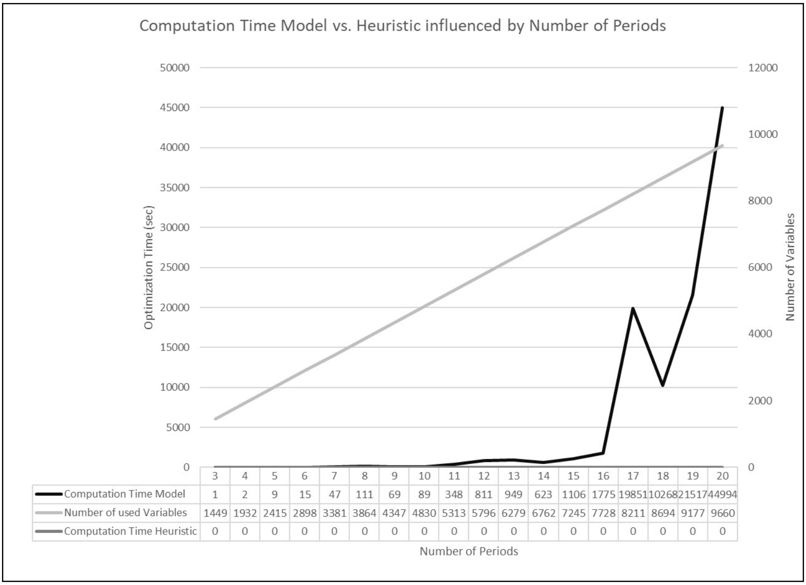


Figure 6.2: Heuristic Computation Time Validation for different Number of Periods

The next parameter variation validates the Displacement Heuristic against the optimization model in a variation of the number of facilities. As in section 4.4, the parameter variation ranges from three to 20 facilities. In section 4.4 the model did not react on additional facilities. The minimum costs could not be reduced by the model in this experiment. As the following figure 6.3 shows, also the heuristic from the beginning on is near the optimal solution and does not change the policy, when additional facilities are added.

This again confirms the statement, that the heuristic considers all effects of the scenarios. Altogether, all scenarios of the facility variation show the same loss of goodness of 4,8%. Considering the computation time, the model shows a linear increase with increasing the number of facilities. In addition it shows several computation time outliers as the number of facil-

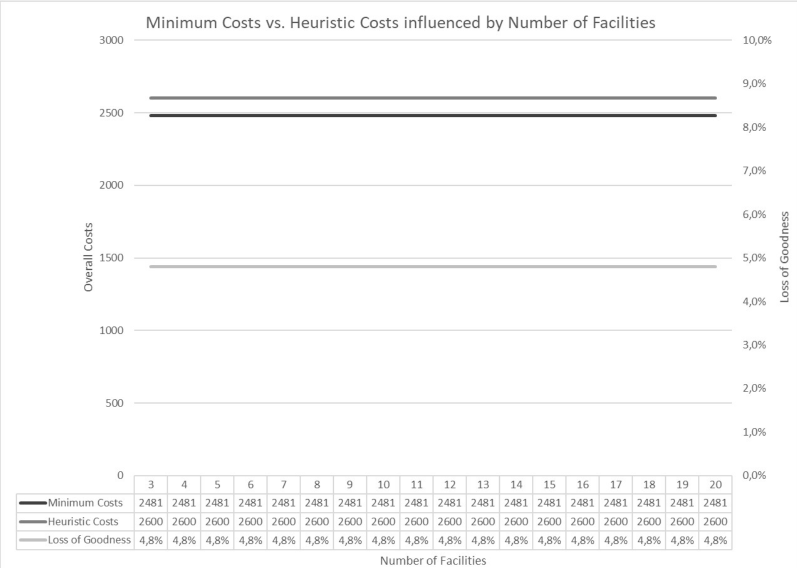


Figure 6.3: Heuristic Costs Validation for different Number of Facilities

ities is increased. In difference to that, the Displacement Heuristic reaches the result in less than one second, as the following figure 6.4 shows:

Concluding the variation of the number of facilities, an increase in facilities does not affect the computation time tremendously and leads to a loss of goodness of 4,8% with the heuristic. Hence, up to a problem size of 20 facilities, three products and three periods, it is advisable to use the optimization model.

The third experiment varies the number of products. Re-capturing the results from the model evaluation in section 4.4, a linear increase of products increased the problem size exponentially, according to the derived terms (4.56) and (4.57). The optimization model of the DSNDP did not find a solution for scenarios with more than four products. For the scenarios, where the model could still find the optimum, the following figure 6.5 shows the costs comparison.

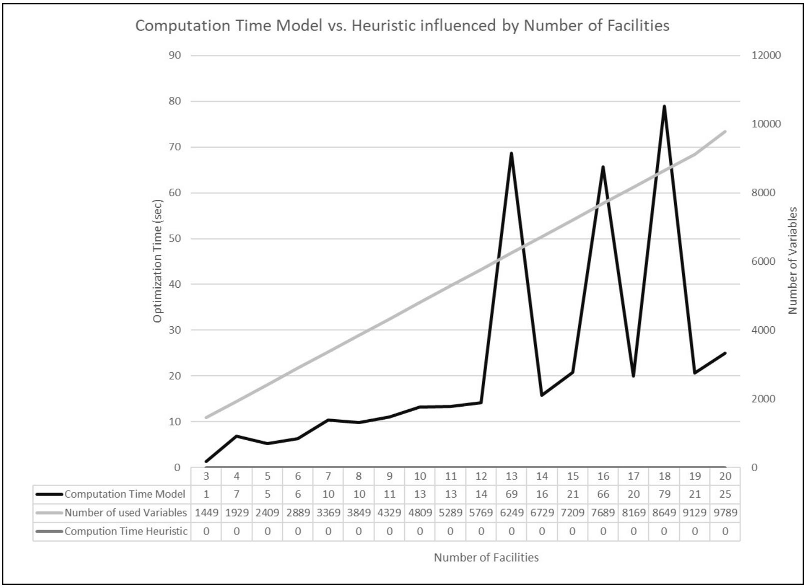


Figure 6.4: Heuristic Computation Time Validation for different Number of Facilities

The diagram shows that the costs of the heuristic are slightly above the minimum costs of the model. The loss of goodness, for the scenarios, where the model could find the optimum, is between 4,8 and 6,0%. Also here, the heuristic costs structure follows the same pattern as the model costs structure. Two further scenarios, where the optimization model could no more be solved, show, that the heuristic continues following this pattern. The stepwise increase of costs originates from the required stepwise opening of additional facilities. Details of this effect will be specifically analyzed in the performance evaluation of the Displacement Heuristic in section 6.2. The following figure 6.6 shows the computation time of the heuristic in comparison with the model for the parameter variation of products. For this validation, it needs to be concluded, that the optimization model of the DSNDP can only be used for up to four products. Beyond a problem size of four

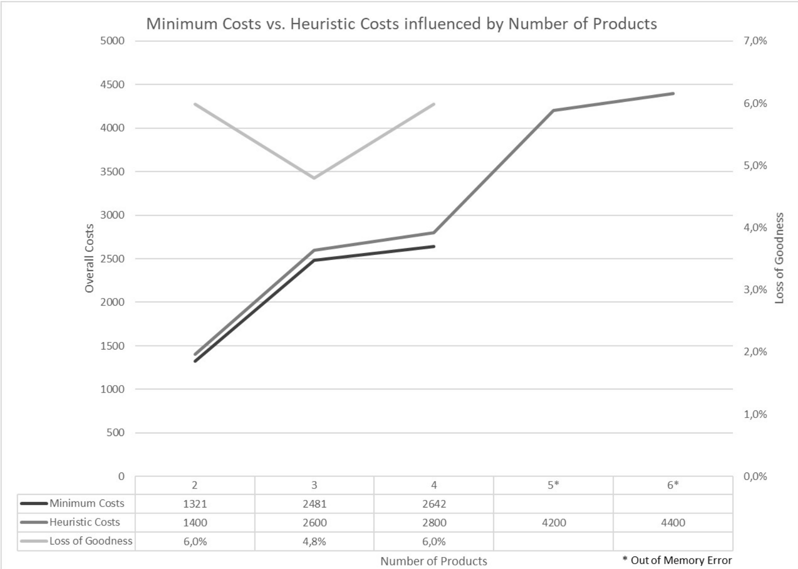


Figure 6.5: Heuristic Cost Validation for different Number of Products

products, the model execution runs out of memory and the Displacement Heuristic is required. The computation time of the Displacement Heuristic on the given server for all scenarios stayed below one second. The bottleneck for the heuristic is not really the computation time, but the memory for pre-calculation. But nevertheless, it can capture problem sizes far above the required realistic range.

Altogether, for small experimental problems the optimization model can be used, but for realistic industrial problem sizes, the optimization model runs out of memory or time. Hence, accepting a loss of goodness of 4 to 6% the Heuristic is required for designing realistic industrial dynamic supply networks with more than four products (product groups). This answers the fourth research question. The Displacement Heuristic is able to solve realistic industrial problems in acceptable time.

The subsequent section serves as an evaluation part to understand the be-

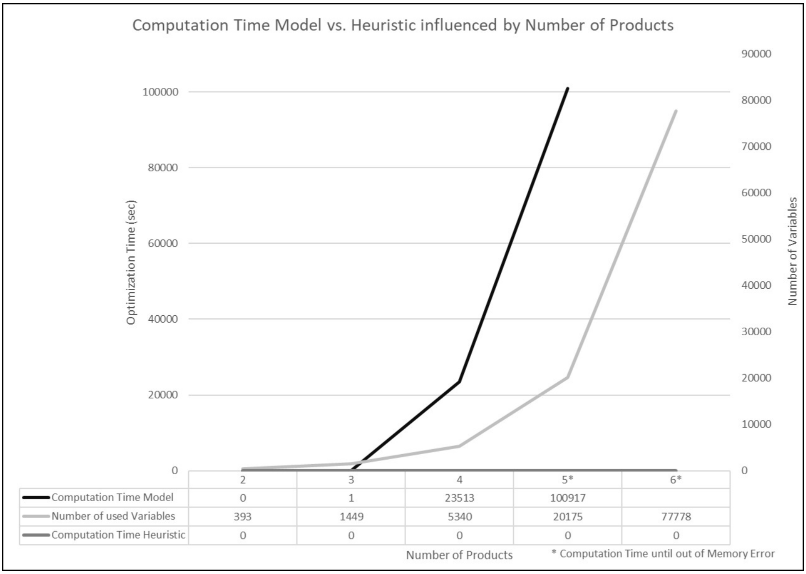


Figure 6.6: Heuristic Computation Time Validation for different Number of Products

haviour of the heuristic for different realistic DSNDP. The subsequent section is structured in different experiments evaluating specific effects in sensitivity analysis. In the end of the subsequent section, a large experiment combines all effects and assumes a completely volatile environment, to test the interaction of all modelling effects.

6.2 Performance Evaluation of the Displacement Heuristic

To test the performance of the Displacement Heuristic for realistic problem settings, different experiments are designed in this section. The experiments are designed to specifically evaluate the different problem characteristics, mix-dependency, multitasking resources and qualification differentiation, formulated in chapter 4. Thereby, it is evaluated, if the Displacement

Heuristic is capable to cover the real-world problem characteristics of the DSNDP, introduced in chapter 2.
Each experiment contains different scenarios, which compare volatile demand, as well as volatile capacities, against the stable case. Additionally, a non-steady-state scenario with shortened product life cycles is tested against a steady state scenario. Table 6.7 provides an overview of all experiments as well as the single scenarios of the Displacement Heuristic evaluation. This section describes the experiments and their motivation step by step, as well as the results concerning overall costs and computation time. In order to evaluate the heuristic for all the problem characteristics step by step, the chapter starts with simpler experiments and increases the complexity. In this way, the behaviour of the heuristic is gradually evaluated for all the problem characteristics, introduced in 2. The experiments designed, start with ceteris paribus sensitivity analysis, where only one factor is varied. This helps to detect cause and effect relations. To specifically evaluate the interaction effects of the different problem characteristics, the interaction of all effects is analyzed in a final experiment, which varies all parameters.

6.2.1 Experiment: Qualification Maintenance versus Re-Qualification

This first experiment analyzes the results for different product relationship scenarios with the heuristic as well as with the optimization model. The experiment aims to support the decision in the tradeoff of stability versus flexibility strategy. This cost-driven tradeoff is introduced in section 4.3. Decisions are coordinated, either to maintain a qualification, although only required in a later period, or to re-qualify just in time, when required again. Four different scenarios are performed in this experiment. All of them differ in their capacity program. Hence, all four scenarios are based on different product relationships. As the relationship of products influences the costs for re-qualification, the qualification scenario will be different for different

ID	Experiment	Scenario	Insights
6.2.1	Qualification Maintenance vs. Re-Qualification	S1: One product is maintained; one product is re-qualified in two small facilities	Maintenance vs. Re-qualification tradeoff works
		S2: One product is maintained; one product is re-qualified in one bigger facility	Extending capacity is cheaper than splitting it
		S3: Same System as S2 but three products instead of two	Re-qualifying a product portfolio with two additional products is more expensive as with only one additional product
		S4: Same system as S3 but only two instead of three products, while P1 overtakes all demand of the earlier P3	Lower costs for qualification of smaller portfolio. Hence, specialization to small, related set of product is efficient
6.2.2	Production Clustering and Displacement	S1: Two product pairs: P1,P2,P5 highly related ; P3, P4 highly related	Intuitive assignment of products 1,2,5 to facility 1 and 3,4 to facility 2
		S2: Different relationship of product 5: Now products 3,4,5 highly related	As capacity limit exceeded when integrating P5 to 3 and 4 in facility 2 → displacement of P3 to unrelated facility 1 leads to higher costs but still more efficient, than direct assignment of P5 to F1
		S3: Different relationship of product 5: Now P5 related to 3 and 4 as well as to 1 and 2	Displacement Heuristic suggest P5 assigned to F2 → Displacement of P3. But direct assignment of P5 to F1 is now cheaper → Test always intuitive assignment against Displacement Heuristic solution. It might in specific cases be better
6.2.3	DSNDP with volatile Demand and volatile Capacity	S1: Four product , eight facilities, volatile demand, volatile capacity	Complex qualification schedules of six required facilities lead to high costs of 8583 → Flexibility is expensive
		S2: Four product , eight facilities, volatile demand, constant capacity	Only four facilities have to be utilized due to stabilization of capacity → less costs of 6448
		S3: Four product , eight facilities, constant demand, constant capacity	Only two facilities have to be utilized due to stabilization of capacity and demand → less costs of 2929
6.2.4	Non-Steady State Dynamic Supply Network –Facility Ramp-up/Ramp-down	S1: Sudden facility ramp-down	Sudden ramp-down events make expensive stock inevitable
		S2: Smooth facility ramp-down	Lower stock necessary in smooth ramp-down
		S3: Smooth capacity transfer	Higher qualification effort in S3 enables large reduction of holding costs from S2 → lower overall costs → flexible qualification is more efficient than holding
		S4: Stable reference scenario	Scenario without ramping or transfer activities leads to minimum costs. Neither qualification nor holding are necessary
6.2.5	Shortening Product Life Cycles	S1: Long product life cycles	Low costs in long product life cycles
		S2: Short product life cycles	High costs in short product life cycles → sensitive coordination of DSNDP necessary in volatile environment
6.2.6	Cost Comparison in Volatile Markets	S1-S22: Step by step increase of number of products from 2 to 12 (Comparison of static vs. volatile scenarios)	Higher qualification costs in volatile markets. Altogether coordination of DSNDP highly advisable as it reduces overall costs in volatile markets

Figure 6.7: Overview of Evaluation Experiments with single Scenarios

product relationships.
For all four scenarios the following two parameters for calculation mix-dependent qualification costs are assumed:

$$ci_{f,i,j} = 100 * Dim_j + 1000 * (1 - R_{i,j}) \qquad \forall f \in 1..F$$
$$cr_{f,i,j} = 50 * Dim_j + 500 * (1 - R_{i,j}) \qquad \forall f \in 1..F$$

The mix-dependent qualification times according to section 4.2.5 are calculated with the following parameters for basic qualification time and mix-dependent qualification time:

$$ti_{f,i,j} = 2 * Dim_j + 20 * (1 - R_{i,j}) \qquad \forall f \in 1..F$$
$$tr_{f,i,j} = 1 * Dim_j + 10 * (1 - R_{i,j}) \qquad \forall f \in 1..F$$

The first and second scenario, both, consider two different products and have a planning horizon of 20 periods and two facilities with different periodic capacity scenarios. Scenario 3 only considers one facility and 20 periods but three products. The capacity of this facility is able to fulfill the demand of all three products. Scenario four imitates the third scenario, but with less products and higher demand per product. All four scenarios have the same volatile demand structure. Product 1 and 3 only have demand in the first and 20^{th} period, while product 2 has demand in more periods throughout the horizon. The four scenarios differ in capacity. Although all facility capacities are constant throughout the periods, scenario 1 has a capacity of 80 in both facilities in each period. Scenario 2 has a capacity of 160 in each facility in every period. Scenario 3 and 4 have a capacity of 300 in the facility in every period. According to the requirements of the pre-calculation in subsection 4.2.5 the following input is given for the three scenarios of the experiment:

1. Vector of periods ($t \in 1..T$)
   (1,..,20)

2. Vector of products ($k,n \in 1..N$)
   (1,2,3)

3. Vector of facilities ($f \in 1..F$)
   (1,2)

4. Vector of possible machines in the facilities ($m \in 1..M$)
   (1,2,3)

5. Demand per product and period ($D_{t,n}$)
   Product 1 = (10,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,10)
   Product 2 = (10,0,0,0,0,0,10,0,0,0,0,0,0,10,0,0,0,0,0,10)
   Product 3 = (10,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,10)

6. Capacity per facility and period ($C_{f,t}$)
   Scenario1: 80 in every period and in every facility
   Scenario2: 160 in every period and in every facility
   Scenario3: 300 in Facility1 and 0 in Facility2 in every period
   Scenario4: 300 in Facility1 and 0 in Facility2 in every period

7. Holding costs per product (ch_n)
   Scenario1: 100 for every product
   Scenario2: 100 for every product
   Scenario3: 100 for every product
   Scenario4: 100 for every product

8. Overall process time of each product (PT_n)
   Product1: 4
   Product2: 3
   Product3: 8

9. Process time of each product at each machine (acc. Linear Capacity Program) ($PT_{n,m}$)

$$\begin{array}{cccc} & P_1 & P_2 & P_3 \\ M_1 & 1 & 2 & 0 \\ M_2 & 2 & 0 & 4 \\ M_3 & 1 & 1 & 4 \end{array} \tag{6.1}$$

With these inputs the following product mix relationship matrix results:

$$Ri,j = \begin{array}{c} \\ (0,0) \\ (0,1) \\ (1,0) \\ (1,1) \end{array} \begin{array}{c} \begin{array}{cccc} (0,0) & (0,1) & (1,0) & (1,1) \end{array} \\ \begin{pmatrix} 1 & 0 & 0 & 0 \\ 1 & 1 & 0,5 & 0,75 \\ 1 & 0,\overline{66} & 1 & 0,8\overline{33} \\ 1 & 1 & 1 & 1 \end{pmatrix} \end{array} \tag{6.2}$$

The experiment is simplified to provide insights from the tradeoff of stability versus flexibility strategy.

Scenario 1 does not have enough capacity in one facility, so it has to spread the two products over two facilities. The obvious case is chosen by the heuristic. It produces product 1 in facility two and product 2 in facility one. As product 1 only has demand in the first and the last period, it is efficient to disqualify the product after the first period and re-qualify it for the last period in facility 2. The situation is different for product 2 in facility 1. As there is also demand in period 7 and 14 it is more valuable to maintain the product portfolio. As introduced in subsection 4.2.5, it depends on the delta between mix-dependent re-qualification and qualification maintenance costs, how long to maintain the product portfolio, until it is more efficient to drop and re-qualify it. In this scenario 1, to fulfill the demand of the first period product 2 has to be initially qualified in facility 1 with qualification costs of 1100. In facility 2 product 1 has to be initially qualified with qualification costs of 1100. As facility 1 maximally has to bridge six periods without demand, the qualification maintenance costs of $7 * 50 = 350$ are lower, than the re-qualification costs of 550. Hence, facility 1 maintains the product portfolio with product 1 throughout the entire planning horizon. In facility 2 product 1 has to bridge 18 periods. Hence the maintenance costs of $20 * 50 = 1000$ are higher than the re-qualification costs of 550. Thus, facility 2 follows the flexibility strategy, while facility 1 follows the stability strategy. Altogether, the Displacement Heuristic leads to overall costs of 3700. The computation time of under one second for heuristic and pre-calculation for scenario 1 is negligible small. Compared to the model, the loss of goodness is 75 ($\sim 2\%$) (Solution of the model: 3625)

Scenario 2 of this experiment only differs from scenario 1 in capacity. Instead of 80 per facility and period, each facility now has 160 per period. Hence, both products can be produced in one facility. This reduces the costs significantly. Instead of 3700, the overall costs are now only 2525. The reason for this is, that only one facility has to be expensively qualified from scratch. But also the efficient policy of qualification maintenance changes. The heuristic proposes to initially qualify the full product portfolio $(1,1)$ in the first period in facility 1. This costs 1200, which is smaller, than in scenario 1 with two times 1100. Facility 2 now stays idle and therefore does not have to be qualified. After fulfilling the demand for both products of the first period by facility 1, it has to maintain $(1,1)$ to the next period (small bucket). In period 2 both products are not required. Product 1 is not required for the next 18 periods. But product 2 is not required for only six periods. Thus, facility 1 is disqualified from $(1,1)$ to $(0,1)$ in period 2. This reaction shows the collaboration of part 2 and part 3 of the Displacement Heuristic. Part 2, the assignment and displacement routine, would disqualify both products, as they are not required in period 2. But part 3, the re-optimization part, decides, that it is cheaper to only disqualify product 1, as it is not required for 18 periods, but maintain product 2 as it is already required in six periods again. Hence, the heuristic proposes to change from $(1,1)$ to $(0,1)$ in period 2. The model would perform this disqualification already in period 1 and then spend less for the maintenance costs for the smaller product portfolio $(0,1)$. But as the heuristic is designed in an iterative structure, it can not foresee the suitable disqualification of period 2 in period 1. Therefore it can not gain the low maintenance costs due to preparing the smaller product portfolio already in period 1. According to the pre-calculated qualification matrices the necessary maintenance of portfolio $(1,1)$ to period 2 costs 100. According to the initial qualification matrix, the disqualification to $(0,1)$ costs 100 in period 2. Further, the heuristic maintains product portfolio $(0,1)$ until the next demand of product 1 has to be fulfilled in period 7. Other than for 18 periods for product 1, maintaining product 2 for six periods is cheaper, than re-qualifying from scratch in period 7 $(6*50 = 300 < 550)$. The Displacement Heuristic continues this cost-efficient policy until the last period, where product 1 and 2 are required again. The maintenance of product portfolio $(0,1)$ ensures, that all demand in period 7 and 14 can be fulfilled. In period 20 the Displacement Heuristic re-qualifies product portfolio $(1,1)$. As the capacity in facility 1 is 160, it can fulfill both demands in facility 1. The costs for re-qualification from $(0,1)$ to $(1,1)$ in period 20 are 225. The overall costs for this second scenario are only 2525. The optimization model reaches a solution of 2475 which is 50 cheaper ($\sim 2\%$), as it oversees the entire planning horizon it can disqualify earlier, than the iterative heuristic. The heuristic requires a computation time of below one second for this scenario. The difference in overall costs of scenario 2 and 1 is 1175. Thus, it can be summarized, extending the capacity in one facility instead of spreading it to many facilities is much more efficient as the fix part of qualifications can be reduced.

Scenario 3 of the experiment for the tradeoff between re-qualification and maintenance follows this strategy. It only considers one facility with high capacity of 300 per period. Hence, the heuristic only decides, where to produce and when to qualify. It integrates three products. The demand of the products 1 and 2 stays, as in the previous two scenarios. The demand of the third product equals the first. It only has demand of 10 in the first and the 20^{th} period. The resulting qualification strategy is similar to the strategy of scenario 2. In the first period product portfolio $(1,1,1)$ is qualified. In the second period $(1,1,1)$ is disqualified to $(0,1,0)$, as it is efficient to only maintain product 2 to fulfill the demand of period 7 and 14. The explanation is the same as in for the maintenance in the second scenario. In the last period product portfolio $(1,1,1)$ has to be re-qualified, to fulfill the demand of all three products. Altogether the additional third product increases the overall costs by 304 from 2525 to 2829. The reason therefore is the more expensive qualification and re-qualification.

Scenario 4 of the tradeoff between maintenance and re-qualification proposes a slight variation of the third scenario. It only has two products again, but product 1 now has a demand of 20 in the first and last period. Hence the overall demand is exactly the same as in scenario 3. There is still no decision, where to produce, since there is still only one facility with enough capacity available. The only difference is, that the demand of the first and 20^{th} period is no longer split between three but two products. Hence the resulting costs of the fourth scenario are lower, than in the third scenario, although in each case the same number of product portfolios has to be qualified. But obviously a qualification of a portfolio including three products is more expensive, than a portfolio with only two products. From this point of view it is more efficient to collect the demand of the products and qualify the minimum set of products in each facility. Qualifying all products everywhere is expensive and inefficient. The reason therefor is, that, although there are only single product portfolios qualified, the qualification of a portfolio with three products is more expensive than with two. Hence specializing the facilities to a small set of related products decreases the costs.

This experiment shows in four scenarios, that it is often efficient to maintain the product portfolio, even if there is no demand. After a certain threshold of periods without demand it becomes more efficient to not maintain but re-qualify the product again, when required. As the product relationship influences the costs for re-qualification but not the costs for qualification maintenance the height of the threshold is influenced by the relationship of product portfolios. As the re-qualification costs are modularly calculated from a fix and a variable part, the threshold can be calculated. Only, if the relationship of product portfolios is 1, the variable part of the costs becomes 0. In this special case the re-qualification costs are equal to the maintenance costs and the heuristic already in the first period is indifferent between maintenance and re-qualification. It will decide to re-qualify a portfolio, if there is only one period without demand of one of the products. If the portfolio relationship is < 1, it depends on the relation between the fix maintenance costs and the variable re-qualification cost factor, for how many periods a maintenance is cheaper. Derived from the cost function from section 4.2.5 the period threshold can be expressed as follows:

$$for\ all\ t\ where: \tag{6.3}$$

$$\lceil t \rceil \geq \left(\frac{mdc * (1 - R_{i,j})}{qmc * Dim_j} \right) + 1 \tag{6.4}$$

$$\rightarrow requalify \tag{6.5}$$

In the four scenarios $19 * 50 = 950 > 550$ but $6 * 50 = 300 < 550$. In the experiment product 2 for example has to bridge 6 periods. Hence, the decision has to be made, whether to maintain $(0,1)$ or to re-qualify from $(0,0)$ to $(0,1)$. According to the term above, beyond a threshold of 11 periods, it would be more efficient to re-qualify $(0,1)$ from $(0,0)$. As $6 < 11$ its cheaper to maintain in this case. The practical intuition often suggests just in time qualifications. But with this approach this tradeoff can be easily optimized and solved.

6.2.2 Experiment: Production Clustering and Displacement

This second experiment focusses on the relationship of product portfolios and evaluates the effects of these for the production clustering in different facilities. The experiment is structured in three different scenarios. The scenarios are designed to examine the mix-dependent production clustering as well as the displacement effect. The following qualification cost parameters are given for this experiment:

$$ci_{f,i,j} = 10 * Dim_j + 1000 * (1 - R_{i,j}) \qquad \forall f \in 1..F$$
$$cr_{f,i,j} = 5 * Dim_j + 500 * (1 - R_{i,j}) \qquad \forall f \in 1..F$$

The mix-dependent qualification times according to section 4.2.5 are calculated with the following parameters for basic qualification time and mix-dependent qualificaion time:

$$ti_{f,i,j} = 2 * Dim_j + 20 * (1 - R_{i,j}) \qquad \forall f \in 1..F$$
$$tr_{f,i,j} = 1 * Dim_j + 10 * (1 - R_{i,j}) \qquad \forall f \in 1..F$$

Additionally the following inputs are given:

1. Vector of periods ($t \in 1..T$)
   (1,..,10)

2. Vector of products ($k, n \in 1..N$)
   (1,2,3,4,5)

3. Vector of facilities ($f \in 1..F$)
   (1,2)

4. Vector of possible machines in the facilities ($m \in 1..M$)
   (1,2,3,4)

5. Demand per product and period ($D_{t,n}$)
   Product 1 = (10,10,10,10,10,10,10,10,10,10)
   Product 2 = (10,10,10,10,10,10,10,10,10,10)
   Product 3 = (10,0,0,10,0,10,0,0,0,10)
   Product 4 = (10,10,10,10,10,10,10,10,10,10)
   Product 5 = (0,0,10,10,10,10,10,10,10,10)

6. Capacity per facility and period ($C_{f,t}$)
   Scenario1: Facility1: 800 in every period
   Scenario1: Facility2: 800 in every period

7. Holding costs per product(ch_n)
   Scenario1: 100 for every product

8. Overall process time of each product (PT_n)
   Product1: 17
   Product2: 22
   Product3: 29
   Product4: 34
   Product5: 22

9. Process time of each product at each machine (Linear Capacity Program) ($PT_{n,m}$)

$$\begin{array}{cccccc} & P_1 & P_2 & P_3 & P_4 & P_5 \\ M_1 & 1 & 3 & 9 & 14 & 4 \\ M_2 & 2 & 4 & 7 & 8 & 4 \\ M_3 & 10 & 12 & 5 & 0 & 10 \\ M_4 & 4 & 3 & 8 & 12 & 4 \end{array} \tag{6.6}$$

With these inputs the following product relationship matrix results:

$$r_{n,k} = \begin{array}{c} \\ P_1 \\ P_2 \\ P_3 \\ P_4 \\ P_5 \end{array} \begin{array}{c} \begin{array}{ccccc} P_1 & P_2 & P_3 & P_4 & P_5 \end{array} \\ \begin{pmatrix} 1 & 0,73 & 0,41 & 0,21 & 0,77 \\ 0,94 & 1 & 0,51 & 0,29 & 0,91 \\ 0,70 & 0,68 & 1 & 0,71 & 0,77 \\ 0,41 & 0,45 & 0,83 & 1 & 0,84 \\ 1 & 0,91 & 0,58 & 0,35 & 1 \end{pmatrix} \end{array} \quad (6.7)$$

The basis for this experiment are five products and two facilities. According to the capacity program products 1, 2, and 5 are highly related and products 3 and 4 are highly related. But the products 1, 2, and 5 are quite unrelated with 3 and 4. Hence, a clustering of products 1, 2, and 5 as well as 3 and 4 can be expected. The capacities of the two facilities are chosen, that not all products fit in one facility, but may be arbitrarily combined. The demand of the products 1, 2, and 4 is constantly 10, while for product 3 and 5 the basic demand is also 10 but some periods do not have demand. Product 3 shows some demand interruptions, while the demand of product 5 is 0 at the first two periods and than 10 for each remaining period. The planning horizon involves ten periods in this experiment.

In **scenario 1** in the first period product portfolio $(0,0,1,1,0)$ is qualified in facility 1 and $(1,1,0,0,0)$ is qualified in facility 2. In period 3 the first demand of product 5 arrives. The capacities of facility 1 or 2 can cover the additional demand of product 5. As expected, the Displacement Heuristic decides to assign it to the cheapest facility 1. The close relation to the already installed products 1 and 2 allows a very cheap qualification of only 60 cost units. These portfolios are now maintained from period 3 to the end of the planning horizon. As the demand is statically 10 in all periods for the products 1,2,4, there is no decision about maintenance or re-qualification.

But product 3 has a different demand structure. Although there are interruptions of demand of up to 3 periods, facility 1 always maintains the portfolio $(0,0,1,1,0)$ throughout the entire planning horizon. The reason therefor are the reduced basic costs, which serve as maintenance costs for in the re-qualification matrix. Because maintaining costs only 10 per period, it is more efficient to maintain product 3. Altogether, the capacity can fulfill all demand of every period. Consequently, there is no holding necessary. Hence, the overall costs for this first scenario of the production clustering and displacement experiment are 2315. The costs consist of the initial qualification of portfolio $(0,0,1,1,0)$ (1020 cost units) in facility 1 and $(1,1,0,0,0)$ (1020 cost units) in facility 2 and 60 for the qualification of the additional product 5 in facility 2 (from $(1,1,0,0,0)$ to $(1,1,0,0,1)$) in period 3 as well as the maintenance for nine periods of 215. Altogether, scenario 1 costs 2315.

Scenario 2 of this experiment investigates the displacement effect. Therefor, the capacity requirement of product 5 is changed in the following way:

$$
\begin{array}{c|ccccc}
 & P_1 & P_2 & P_3 & P_4 & P_5 \\
M_1 & 1 & 3 & 9 & 14 & \mathbf{13} \\
M_2 & 2 & 4 & 7 & 8 & \mathbf{9} \\
M_3 & 10 & 12 & 5 & 0 & \mathbf{0} \\
M_4 & 4 & 3 & 5 & 12 & \mathbf{11}
\end{array}
\tag{6.8}
$$

Now, product 5 is no more related to 1 and 2 but to product 3 and 4. If the capacity would allow it, product 5 was now added to facility 1 with the very related product portfolio of product 3 and 4. But due to the capacity limit facility 1 can only capture two of the related products 3,4,5. The consequence is, that the very related product 3 is displaced from facility 1 to facility 2 to make room for the even more related product 5. Hence, product 4 and 5 are now clustered in facility 1 and product 1, 2 and 3 are now clustered in facility 2. This increases the costs from 2315 to 2481, as the displacement of product 3 to barely related product 1 and 2 in facility 2 generates mix-related qualification costs of 191 instead of 60 in scenario 1. Nevertheless, the assignment and displacement routine of the heuristic helps to limit the increase of costs. An intuitive assignment to facility 2, which could capture product 5 without displacement, would lead to costs of 2552 instead of 2481. Hence the Displacement Heuristic, due to more solution options can reach a cost reduction of 71 compared to the intuitive assignment. An assignment of product 5 straight to facility 2, where it does not exceed the capacity limit would be intuitive and would not lead to an displacement, but would limit the possible solutions and so lead to additional qualification costs of 262 instead of 191 with displacement. The portfolios $(0,0,0,1,1)$ in facility 1 and $(1,1,1,0,0)$ in facility 2 are now maintained until the end of the planning horizon. The maintenance costs do not change because they are not mix-dependent. However, in most cases the assignment and displacement routine of the Displacement Heuristic gains from a bigger solution space and leads to better results, than the direct assignment without the option of displacement. But there are also rare cases where a direct assignment is better.

Scenario 3 of this experiment shows this rare case. This scenario captures the linear capacity program from scenario 2, but changes the capacity requirement of the to be displaced product 3. The capacity requirement of product 3 in this third scenario now looks the following:

$$\begin{array}{cccccc} & P_1 & P_2 & P_3 & P_4 & P_5 \\ M_1 & 1 & 3 & \mathbf{9} & 14 & 13 \\ M_2 & 2 & 4 & \mathbf{7} & 8 & 9 \\ M_3 & 10 & 12 & \mathbf{5} & 0 & 0 \\ M_4 & 4 & 3 & \mathbf{8} & 12 & 11 \end{array} \tag{6.9}$$

With an assignment of product 5 to facility 1 and a displacement of product 3 to facility 2 the overall costs would reach 2550. But the direct assignment of product 5 to the more expensive facility 2 would not require a displacement. Therefore only the portfolio of facility 2 would have to be changed and the costs would be 2512 in this case. The capacity program shows that the to be assigned product 5 is more related to the products 3 and 4 in facility 1, but now also quite related to the products in facility 1. Hence, the challenge of qualifying product 5 to facility 2 is not so much higher, than a qualification in facility 1. Consequently, it is cheaper, to assign the product directly to the second cheapest facility to avoid the displacement, where two product mixes have to be changed. But the Displacement Heuristic would assign the product 5 to the slightly cheaper facility 1 and displace product 3. Hence, it would be better in this case to not follow the Displacement Heuristic. Concluding this observation, in any scenario, the cheapest assignment and displacement policy of the Displacement Heuristic has to be compared to the cheapest direct assignment option.

6.2.3 Experiment: Dynamic Supply Network Design with volatile Demand and volatile Capacity

Both previous examples design the mix-dependent dynamic supply networks in simplified static environments. This experiment intends to design the dynamic supply network in more volatile capacity and demand environment with different number of products and facilities. Therefor three scenarios have been designed to examine trends for assignment and displacement, re-qualification and maintenance, specialization versus generalization of facilities, costs for volatile product portfolios, cost and consequences of volatile capacity and demand, and other effects.
The cost structure stays as assumed in the previous experiment, with basic costs of 10 and mix-dependent cost factor of 1000 for initial qualification (5, 500 for re-qualification) and 100 storage costs per lot and period. The qualification times stay constant for initial qualification with basic time of 2 per product and a mix-related time factor of 20. Consequently, for re-qualification a basic re-qualification time of 1 per product and a mix-related time factor of 10 are assumed.
Scenario 1: Dynamic Supply Network Design with volatile Demand and volatile Capacity
The first scenario considers four products, eight facilities and 20 periods. The capacity as well as demand is assumed to be volatile. The capacity is generated with a random distribution of 50% 0 and 50% a demand value following a normal distribution with mean of 150 and standard deviation of 20. The rate of not available facilities of 50% is thereby quite high, but this scenario intends to test the extreme cases. A non-available facility in this context is not completely shut down, but in a standby state. Hence, it is assumed, that it still has enough capacity to maintain a qualification state, even though it can not produce anything in this period. To increase the probability for executable volatile scenarios, each facility has a start capacity of 1000 in the first period.

The demand is generated with a random distribution between 0 and 20 while 50% of the values are 0. The detailed periodic capacities of each facility and periodic demand of each product can be taken from the Appendix A.2.
The four products show different capacity requirements on the necessary five different machines in this experiment. The capacity requirement of every product can be extracted from the linear capacity program below:

$$\begin{array}{ccccc} & P_1 & P_2 & P_3 & P_4 \\ M_1 & 1 & 2 & 0 & 0 \\ M_2 & 2 & 0 & 4 & 1 \\ M_3 & 1 & 1 & 4 & 2 \\ M_4 & 4 & 1 & 1 & 0 \\ M_5 & 1 & 2 & 3 & 4 \end{array} \tag{6.10}$$

Altogether, $PT_1 = 9, PT_2 = 6, PT_3 = 12$, and $PT_4 = 7$. This basic scenario 1 of the experiment for the analysis of volatility in supply network design reaches overall costs of 8583 with the Displacement Heuristic. 7483 are costs for qualification and 1100 are holding costs. Overall, 17 qualifications have to be managed throughout the planning horizon. On the considered computer the optimization model fails, as it runs out of memory after five hours computation. The computation time of the heuristic stays under one second.
Facility 1,4,5,6,7, and 8 are the most facilities which have to be qualified in the planning horizon. Facilities 2 and 3 are idle throughout the entire horizon. Nevertheless, although these two facilities are never used, this scenario requires pre-processing of 11 lots from period 10. As both facilities do not have sufficient capacity in this period, they are not even qualified in this case. Summarizing this volatile scenario, it can be observed, that a lot of qualification effort has to be managed, even if the scenario has more

facilities, than products, which does not reflect the normal industrial case. What can easily be concluded from this scenario is, that the more volatile the markets become, the more flexible the capacities have to be and the more dynamic supply networks are resulting. This additional flexibility is expensive. There are different ways to provide the required flexibility. The Displacement Heuristic provides a cheap but not necessarily minimum solution.

Scenario 2: Dynamic Supply Network Design with volatile Demand and stable Capacity

The second scenario shows the equivalent case with four products, eight facilities and 20 periods. It assumes the same overall demand and the same overall capacity as scenario 1. The only difference is, that the capacity of each facility is now static over the periods. But the sum of capacity of both scenarios is equal. This scenario assumes, that the facilities are able to provide stable capacity throughout the planning horizon. Still the same volatile demand is assumed, as in the first scenario of this experiment. Hence, all the scenario parameters are the same, just each facility provides a stable capacity throughout the periods, which equals the average capacity of this facility from the previous scenario 1. This means the overall capacity is exactly the same for each facility and consequently for the entire dynamic supply network. The overall capacity of all facilities and periods is ~ 21000 (rounded).

By stabilizing the capacity of scenario 1, scenario 2 can reduce the costs by 25% (2135) from 8583 to 6448. No holding is necessary any more, hence all costs originate from the qualifications. Altogether, the qualification costs are reduced by 14%, due to the stabilization of capacities in each facility. Obviously, the number of qualified facilities decreases. Overall, the Displacement Heuristic has to qualify four of the eight facilities (4,6,7,8), which are two facilities less, than with volatile capacity. Instead of 17 only 14 initial qualification or re-qualification events have to be performed. Altogether, due to the stabilization of capacities, the Displacement Heuristic can reduce 100% of the material buffers (stocksize), 33% of the measurable over-capacity (required facilities) and 12% of the flexibilization effort. This clearly demonstrates the value of stable production systems.

Scenario 3: Dynamic Supply Network Design with stable Demand and stable Capacity

The third scenario of this experiment assumes the same system but with stable capacity and stable demand. In addition to the capacity, scenario 3 also assumes stable demand.

The new demand vector describes the demand of the four products in each of the 20 periods in scenario 3:

$$\begin{pmatrix} P_1 & P_2 & P_3 & P_4 \\ 5 & 6 & 5 & 6 \end{pmatrix} \tag{6.11}$$

The summed demand over the periods equals the summed demand of the volatile scenarios.

For this stable scenario 3 the Displacement Heuristic can reduce the overall cost even more from 8583 (resp. 6448) to 2929. This is a reduction of 66% compared to scenario 1 and 55% compared to scenario 2. There is obviously no holding necessary. Hence costs for qualification can be reduced by 61%. Only two facilities have to be utilized, the other six facilities stay idle for the entire planning horizon. Beyond the two initial qualifications only four changes of product portfolios are suggested.

Summarizing this example, the three scenarios demonstrate the costs of volatile markets and volatile production systems. As introduced in section 5.2 the Displacement Heuristic focusses on the flexibilization of the dynamic supply network, but only uses the pre-processing option, if necessary. This assumption originates from the overall strategy to avoid cost-intensive material stocks. This strategy is especially reasonable in the mid-term master planning level. As pre-processing is assumed to be an expensive

short-term reaction on unexpected demand or production volatility, it is not tactically considered as an optimization criterion in this approach.
Two subsequently following experiments of this section focus on concrete industrial observations.

6.2.4 Experiment: Non-Steady State Dynamic Supply Network - Facility Ramp-up/ Ramp-down

This experiment analyzes the effects of a ramp-up and ramp-down of facilities. Therefor, it contains three different scenarios. The planning horizon for this experiment is ten periods long. The experiment contains four products with stable demand of 10 per period, each. All four scenarios consider two facilities.

Scenario 1: Sudden Facility Ramp-down

The first scenario closes the facility 1 without a ramp-down phase from the fifth to the sixth period. In the first 5 periods before the sudden shut down this facility shows a stable capacity of 320 per period. From the sixth to the last period it has no capacity at all. The second facility has a stable capacity of 160 in all the periods. Thereby, both facilities have the same overall capacity of 1600. The following matrix shows the structure of the capacities:

$$\begin{array}{c} \\ f_1 \\ f_2 \end{array} \begin{array}{c} \begin{array}{cccccccccc} t_1 & t_2 & t_3 & t_4 & t_5 & t_6 & t_7 & t_8 & t_9 & t_{10} \end{array} \\ \left(\begin{array}{cccccccccc} 320 & 320 & 320 & 320 & 320 & 0 & 0 & 0 & 0 & 0 \\ 160 & 160 & 160 & 160 & 160 & 160 & 160 & 160 & 160 & 160 \end{array} \right) \end{array} \tag{6.12}$$

As the stable demand of 10 per period and product requires a capacity of 210 per period ($PT_1 = 8, PT_2 = 4, PT_3 = 9$), the remaining capacity is not sufficient to produce the demand just-in-time in the second half of the planning horizon after the shut down. Hence, the exceeding demand of the remaining

five periods has to be pre-processed with the help of the facility, which will be closed in period six. The experiment assumes holding costs of 10 per lot and period.
The Displacement Heuristic suggests a full qualification of all three products in facility 1 in the first period. For the iterative heuristic, this is advisable, as facility 1 has double the capacity of facility 2. Hence, it can produce all the demand in this facility and does not have to qualify the other facility. in period 1 and 2 the powerful facility 1 uses two third of its capacity for the just in time satisfaction of the periodic demand. But the preparation part of the Displacement Heuristic already recognized, that this facility will close in several periods. The preparation part calculates, that altogether the capacity of period 6 to 10 is exceeded by 450, considering all reservation of capacity for potential qualifications in the periods 6 to 10. Consequently, the Displacement Heuristic starts in period 3 to pre-process the volume, which the remaining facility 2 can not produce just-in-time. To limit the upcoming holding costs it schedules as much pre-processing volume to the fifth period. The Displacement Heuristic decides, to pre-process the most capacity-intense product 3. This is another strategy to reduce the necessary holding costs. Hence, it keeps on producing the just in time demand in facility 1 and pulls in the four remaining lots to the lotsize of the first period. Facility 2 can still stay idle, as the least necessary pre-processing volume still can be captured by facility 1, without displacing something to facility 2. But in the fourth period, facility 2 has to use all its capacity for pre-processing product 3 for the upcoming capacity shortage. Therefore both, product 1 and 2 have to be displaced to facility 2. Since period 4, facility 2 will care about the just-in-time production of the stable demand throughout the entire rest of the planning horizon. Facility 1 can already disqualify the products 1 and 2, which saves qualification maintenance costs of 10. But all demand of product 3 has to be pre-processed, as the capacity of facility 2 is utilized with the two other products. Consequently, in the fifth period the same scenario happens. Facility 1 produces one last time the necessary

pre-processing volume plus the just-in-time demand of product 3. In parallel, facility 2 fulfills the demand of product 1 and 2. At the end of the fifth period the stocksize raised to 50 lots of product 3. The holding costs already increased the overall costs by 310. The holding to the sixth period adds holding costs of 500 to the overall costs. In the sixth period, facility 1 is finally closed and the demand of product 3 is fulfilled from stock. Altogether, until the end of the planning horizon the holding costs raised to 1810. In combination with the 3 initial qualification events the overall costs are 3980 for this sudden close-down scenario.

Scenario 2: Smooth Facility Ramp-down

The second scenario of this non-steady state experiment considers the same problem, but changes the capacity situation. Instead of a rapid shut down from one to the other period, facility 1 is ramped-down smoothly over five periods in this scenario. The overall capacity in both facilities stays the same. Facility 1 starts with 320 per period and from period 3 to period 8 is smoothly ramped-down to 0. Facility 2 has a constant capacity of 160 per period. The following matrix shows the structure of the capacities:

$$\begin{array}{c} \\ f_1 \\ f_2 \end{array} \begin{array}{c} \begin{array}{cccccccccc} t_1 & t_2 & t_3 & t_4 & t_5 & t_6 & t_7 & t_8 & t_9 & t_{10} \end{array} \\ \left(\begin{array}{cccccccccc} 320 & 320 & 320 & 280 & 180 & 120 & 60 & 0 & 0 & 0 \\ 160 & 160 & 160 & 160 & 160 & 160 & 160 & 160 & 160 & 160 \end{array} \right) \end{array} \tag{6.13}$$

The Displacement Heuristic reaches overall costs of 3900. Compared to the sudden shut down scenario the heuristic can reach a cost reduction of 4% with the smooth ramp down. The qualification policy is except for two more maintenances of product 3 in facility 1 exactly the same. Due to the two more maintenances of product 3, which additionally cost two times 5, a major reduction of holding costs is possible. By the equalization of the capacities over 5 periods during the ramp-down, still remaining demand of product 3 can be fulfilled nearer to the demand period. Hence the pre-processing volume of product 3 is reduced from 50 to 36 lots. Also the holding periods can be reduced. Hence, instead of 1810 in scenario 1 in this scenario only holding costs of 1720 are necessary. Summarizing this, as expected a smooth ramp-down helps to limit the necessary pre-cautions to guarantee demand fulfillment.

Scenario 3: Smooth Capacity Transfer

The third scenario shows another situation. While facility 1 smoothly ramps-down, facility 2 in parallel ramps-up and equally overtakes the load step by step. Altogether, from a planning perspective, the capacity stays the same, but the load smoothly is transferred from one to the other facility. This situation represents a common case in globalized dynamic supply networks. It is expected, that it leads to much lower holding costs but significant qualification effort. Altogether, again the capacity is the same. From period 3 to 7 smoothly the capacity of facility 1 is reduced and the capacity of facility 2 is increased in parallel. In every period the overall capacity is 320. Consequently, as in the other scenarios the overall capacity of the planning horizon is 3200. The following matrix visualizes the capacity situation of this third scenario:

$$\begin{array}{c} \\ f_1 \\ f_2 \end{array} \begin{array}{c} \begin{array}{cccccccccc} t_1 & t_2 & t_3 & t_4 & t_5 & t_6 & t_7 & t_8 & t_9 & t_{10} \end{array} \\ \begin{pmatrix} 320 & 320 & 280 & 240 & 160 & 80 & 40 & 0 & 0 & 0 \\ 0 & 0 & 40 & 80 & 160 & 240 & 280 & 320 & 320 & 320 \end{pmatrix} \end{array} \tag{6.14}$$

The demand of all three products is still 10 per period. The capacity requirements of the products are also kept constant.

The results from the Displacement Heuristic reach low costs of 2464 in the capacity transfer scenario. This is a cost reduction of 34% compared to the sudden ramp-down and of 32% compared to the smooth ramp-down. Obviously, there is no holding necessary, as there is no capacity shortage, due to the seamless capacity transfer from facility 1 to facility 2. But the qualification costs of the seamless transfer of capacities are significantly higher, than in both of the ramp-down scenarios. Compared to the qualification costs of the sudden ramp-down scenario, the capacity transfer scenario requires 38% higher qualification costs. Compared to scenario 2 the qualification costs in this scenario raise by 37%. Altogether, the sudden ramp-down requires the least qualification effort. This is expectable, as there are not many periods left for buffering with qualification. The increase in qualification costs in scenario 3 by 294 compared to scenario 1 and 284 compared to scenario 2 is justified by the possible reduction of holding effort. Instead, the sudden ramp-down has to be buffered with holding effort. Still, the optimization model would reach 269 lower costs, as it does not plan iteratively. It would have managed the qualification of all products in facility 2. Instead of splitting the qualification effort to period 5 and 6 to cover the necessary demand in each period, the optimization model would foresee the necessity of an entire qualification of product portfolio $(1,1,1)$. Summarizing scenario 3, the Displacement Heuristic quantifies the benefit of transferring capacity instead of just ramping it down.

Scenario 4: Stable Reference

The last scenario of this experiment compares all the ramping scenarios to an equivalent situation without ramping actions. This fourth reference scenario includes one facility and three products. The facility has stable capacity of 320 each in every period. The demand is constantly 10 for all the products in every period. The capacity requirements of each product are the same, as in the other scenarios. The planning horizon still considers ten periods. Hence, the overall capacity is constantly at 3200.

The results attest the expected cost reduction in this stable scenario. The overall costs of this scenario are only 1165. No holding is necessary and only one major qualification is necessary in the beginning. The qualified product portfolio of $(1,1,1)$ is transferred throughout the entire planning

	Sudden Ramp-down	Smooth Ramp-down	Capacity Transfer	Stable Reference
Qual. Costs	2170	2180	2464	1165
Holding Costs	1810	1720	0	0
Overall Costs	3980	3900	2464	1165
△ to Sc1	0%	-2%	-38%	-71%
△ to Sc2	21%	0%	-37%	-70%
△ to Sc3	62%	54%	0%	-53%
△ to Sc4	241%	235%	112%	0%

Table 6.1: Cost Summary of Non-Steady State Scenarios

horizon.
Table 6.1 summarizes the costs of all the four scenarios of this non-steady state experiment:
This simple experiment with four scenarios assumes static demand, which is not a realistic assumption. But the demand is kept static to quantify influences on overall costs and holding as well as qualification policies, due to non-steady state capacity. The costs are extremely different, although the overall capacity in all the scenarios was 3200. The conclusion is that a Dynamic Supply Network Design may provide large benefits, if the flexibility is covering the market volatility. This experiment shows in simplified way, that capacity as well as performance problems lead to extreme cost increases, even if the markets are stable and the overall capacity per period and in the planning horizon is constant.
The next intuitive experiment turns the view back to market volatility. The main motivation of this work is the trend of increasing market volatility and shortening product life cycles. The effects of these trends are evaluated in the next experiment. Again, the experiment is structured in different scenarios of the same environment.

6.2.5 Experiment: Shortening Product Life Cycles

The experiment intends to examine the effects of shortening product life cycles. It is structured in two simplified scenarios. Both scenarios only consider two facilities with constant capacity of 300 each per period. Holding a lot for one period increases the overall costs by 10. The experiment assumes the same qualification cost and time parameters, as the other experiments. The two scenarios differ in number of products considered, as well as in demand of products. Each product has another demand structure. The different demand structures resemble the shortening product life cycle trend. The following capacity requirements are assumed for the products in the scenarios of this experiment:

$$\begin{array}{cccccc} & P_1 & P_2 & P_3 & P_4 & P_5 \\ M_1 & 1 & 2 & 0 & 0 & 3 \\ M_2 & 2 & 0 & 4 & 1 & 3 \\ M_3 & 1 & 1 & 4 & 2 & 0 \\ M_4 & 4 & 1 & 1 & 0 & 3 \end{array} \tag{6.15}$$

Scenario1: Long Life Cycles This first scenario serves as a reference for the second. Therefor, it assumes three products, which have constant demand of 6 (product 1) and 11 (products 2 and 3) in each period in the planning horizon. Altogether, during the planning horizon of 20 periods the overall demand of product 1 is 120, the demands of product 2 and 3 are 220, each. In this balanced demand scenario the capacity of facility 1 is enough in every period to fulfill the entire demand. Hence, facility 2 is left idle and does not require any qualification. Consequently, it does not generate any costs at all. As the demand is stable, the Displacement Heuristic maintains the initially qualified product portfolio $(1,1,1)$ in facility 1 for the entire planning horizon. It decides to produce not to stock, but fulfill demand just-in-time. Hence, the overall costs of this stable scenario consist of one major qualification of all three products in the first period for 1030 and 19 qualification maintenances throughout the other 19 periods for 15 each. Altogether, the scenario consequently costs 1315.

Scenario2: Short Product Life Cycles

Based on this static scenario, the second scenario changes the demand structure of the three products, but keeps the overall demand constant. The product life cycles are now shortened, so that they start and end within the same planning horizon and concentrate the demand to only a few periods. The following matrix shows the demand structure of all the products in the shortened life cycle scenario:

$$
\begin{array}{c} \\ D_1 \\ D_2 \\ D_3 \\ D_4 \\ D_5 \end{array}
\begin{array}{c}
\begin{array}{cccccccccccccccccccc} t_1 & t_2 & t_3 & t_4 & t_5 & t_6 & t_7 & t_8 & t_9 & t_{10} & t_{11} & t_{12} & t_{13} & t_{14} & t_{15} & t_{16} & t_{17} & t_{18} & t_{19} & t_{20} \end{array} \\
\begin{pmatrix}
30 & 40 & 30 & 20 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 20 & 40 & 50 & 50 & 40 & 20 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 20 & 40 & 50 & 50 & 40 & 20 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 70 & 70 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 100
\end{pmatrix}
\end{array}
\tag{6.16}
$$

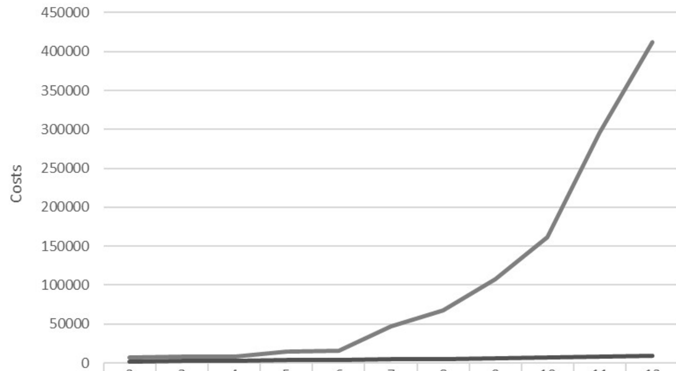
The demand is much more volatile. This structure resembles the market trend of shortening product life cycles, which is motivating this work. The second scenario considers the same three products as the first basic scenario. It assumes the first product in the second period to be on the peak of its life cycle with a demand of 40. In this second period the capacity of facility 1 is no more sufficient to produce it alone, hence additional qualification is necessary to enable facility 2 to support with product 1. The demand of product 1 decreases in period 3 and 4 with 30 and 20. In parallel, product 2 ramps-up and fills the reduced demand of product 1. Hence the capacity, which is left from product 1, can be utilized for the raising demand of product 2. But an additional qualification of product 2 is necessary in period 3. In period 5 the Displacement Heuristic decides to disqualify product 1 in facility 1 and 2 again, as there is no demand upcoming any more. After a ramp-up of 2 periods, product 2 reaches the demand peak of 50 in the periods 5 and 6. In periods 7 and 8 product 2 shows the same decrease pattern as product 1 before. In these two periods the set-free capacity is used for the production of the ramping-up product 3. In period 7 facility 1 is additionally qualified for product 3, while ramping-down product 2. Facility 1 is overwhelmed with the major qualification of product 3 and the ramping-up demand in addition to the ramp-down of product 2. Hence, facility 2 has to support the production of product 2, which requires an additional qualification. In period 8 facility 2 has to support additionally with the fulfillment of the raising demand of product 3. Product 2 can now be disqualified in both facilities, as the product life cycle ends. Facility 1 and 2 maintain their qualification of product 3 until demand starts to decrease in period 11. In period 12 it is possible and more efficient to disqualify facility 2 completely and maintain the remaining production of product 3 in facility 1. Finally in period 13, as all demand is fulfilled just-in-time, also facility 1 can be completely disqualified.

The demand is concentrated in this scenario, which may intuitively lead to economies of scale in production, for example due to the avoidance of long qualification maintenance in the last periods. But due to the punctual demand peaks capacity limits exceeded. This required expensive support by the second facility. The necessary coordination of qualifications leads to higher overall costs. The overall costs for fulfilling the same demand with a different structure raise by 214% from 1315 in the balanced case to 4128 in the case with short product life cycles. Although, the overall capacity is sufficient and no stock is necessary, the qualifications reacting on volatile demand lead to much higher costs. The costs are raising although there is no long qualification maintenance necessary after period 13, while in the balanced reference scenario the most expensive qualification state has to be

maintained throughout all 20 periods. The comparison of this scenario to a situation with long product life cycles and stable demand leads to the conclusion, that shortening product life cycles triggers to high challenges in the coordination of the right point of the individual qualification. Considering relationship of products, demand structure and qualification differentiation helps to design better and more performant dynamic supply networks, but leads to higher coordination requirement. Nevertheless, this higher coordination effort is assumed to be cheaper compared to a full production-to-stock policy. Especially in the current trend, where new demand is nearly impossible to predict, due to its volatile character.
This experiment shows that volatile demand and shortening product life cycles can extremely raise the overall costs, even though the overall demand can be fulfilled just-in-time and the revenue is exactly the same. Hence, the provided approach for coordination of these volatile demands on a mid-term level is absolutely beneficial and has to be fostered in the future.

6.2.6 Experiment: Cost Comparison in Volatile Markets

This final experiment concludes all the observations of the previous experiments. It incorporates 22 scenarios. Half of them are based on static demand and static capacity, the other half is based on volatile demand and capacity. Each scenario considers 8 facilities. The planning horizon is 20 periods for all scenarios. The difference between the scenarios is the number of products. The number of products is increased in 11 steps from two to 12. For each number of products there are two scenarios, one, which assumes volatile demand and the other, which assumes the average demand constantly in every period. Hence, for each number of products the costs of the dynamic supply network are compared between volatile and static demand environment. The demand and capacity is generated, as introduced in the experiment of subsection 6.2.3. The holding costs are 10 per lot and period. The qualification costs are calculated mix-dependently with the same



Products	2	3	4	5	6	7	8	9	10	11	12
CostsVolatileScenarios	6594	7912	8583	14695	16269	46973	67267	107610	161377	295586	412326
CostsBalancedSceanrios	1210	2315	2420	3550	3735	4800	5155	6260	7295	7725	9217

Products

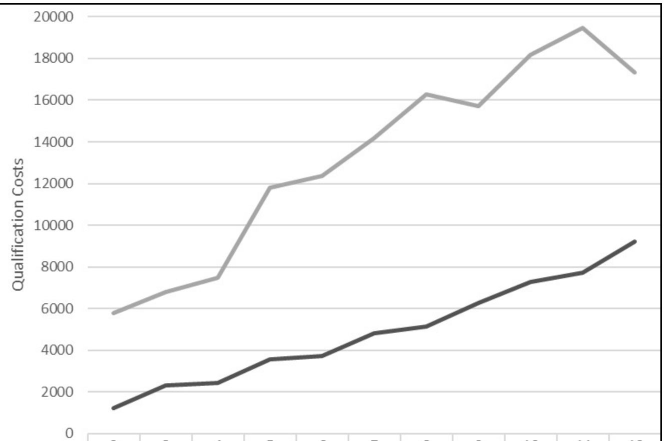
Figure 6.8: Heuristic Evaluation for Volatile vs. Stable Scenarios

parameters as in the previous experiments.

The scenarios are not analyzed in detail. This experiment supports the result evaluation of scenarios with realistic assumptions in an industrial problem setting. All possible effects have been already evaluated in the previous laboratory experiments.

The first two scenarios start with two products with volatile versus static demand and volatile versus static capacity in eight facilities. Figure 6.8 shows the resulting overall supply network costs for different number of products:

The figure compares the costs of the different volatile and stable scenarios. For each number of products there is one scenario, which assumes static demand and capacity, and one scenario, which assumes volatile demand and capacity. Both, static capacity and demand equal in every period the average capacity or demand of the volatile scenario. Hence, the conditions are the same. Both scenarios have to fulfill the same volume of demand and have the same capacity. Nevertheless, the costs of the scenarios with volatile demand increase exponentially, while the costs of the static demand and ca-



Products	2	3	4	5	6	7	8	9	10	11	12
QualCostsBalancedScens	1210	2315	2420	3550	3735	4800	5155	6260	7295	7725	9217
QualCostsVolatileScens	5794	6812	7483	11795	12369	14173	16267	15710	18177	19486	17326

Figure 6.9: Heuristic Evaluation of Qualification Cost in Volatile vs. Static Scenarios

pacity increases nearly linear. This means fulfilling the same demand but in a volatile structure, leads to an extreme increase in costs. In this experiment the major part of the costs originates from necessary holding. But also the qualification costs are significantly higher for the version with volatile demand and capacity. Figure 6.9 compares only the qualification costs of the volatile with the static scenarios:

Detailed analysis shows the stepwise fix costs of the facilities. Always, when an integrated new product exceeds the currently qualified facility, a new one has to be initially qualified with this product. As the first qualification in a facility is the most expensive one (least related), the qualifications for the first product portfolio in each facility are highly increasing the costs. This captures the realistic effect of stepwise fix costs.

This experiment shows again, volatile markets are a complex challenge and require extensive synchronous planning approaches, as this one. As products emerge and erase in much higher frequency and new markets build and

change much faster, the supply networks, which are bound to physical constraints, have to be much more dynamic. As the last experiment significantly shows, holding can not cover these effects efficiently. Facilities have to be emerged, qualified and adapted in higher flexibility and speed.
After this extensive evaluation of the Displacement Heuristic in various situations several insights can be derived. At first considering the Displacement Heuristic, itself, secondly considering planning decisions in complex dynamic supply networks and their design process. The subsequent chapter summarizes those managerial insights.

6.3 Managerial Insights

The Displacement Heuristic incorporates realistic assumptions and tradeoffs, such as qualification differentiation, mix-dependent qualification, multitasking resources, storage, stability versus flexibility strategy, volatile demand, volatile capacities etc. All these are derived in this thesis from industrial observations of facilities and supply networks. All of these are observed to influence the supply network. Therefore, for an accurate design of a dynamic supply network, capable for volatile demand, all of them have to be considered. The optimization model as well as the Displacement Heuristic have involved all of these practical assumptions to represent a suitable design approach for industrial supply networks. In the different experiments in section 6.2 the interaction of all of these assumptions has been analyzed. The single effects have been analyzed separately and in interaction in different experiments. During the experiments different practical observations have been made and different insights to the Dynamic Supply Network Design Problem have been gained. This section will summarize the managerial insights resulting from the evaluation phase of the Displacement Heuristic.
First of all, the Displacement Heuristic, other than the optimization model, follows the principle to minimize the storage costs. It does not integrate the storage costs into the optimization, as the optimization model does. But

it uses the option for storage to ensure feasibility of the plan. The reason for this is, that storage is handled as an expensive way to buffer unexpected volatility. The task of the dynamic supply network design phase is to develop dynamic networks, which may cope with the volatility with minimum buffers. The supply network design problem is located in the very beginning of the master planning level, where the physical supply network is not formed yet and the utilization is not planned yet. In this early tactical level, to design lean and flexible supply networks, buffering should not be considered as a tactical planning option. As buffering material is a corrective containment solution, it has to be left as an option for fine planning, where the other long and mid-term decisions have already been made. The optimization model considers pre-processing as a tactical decision, but as the holding costs can be adjusted, the planning policy can be aligned to this principle.

Additionally, the experiments showed, that the length of the planning horizon has some significant influences on the costs. Altogether, the optimal length of the planning horizon has to be treated in a separate tradeoff. If the length is chosen too short, the dynamic supply network does not have suitable enough choices to decide about the suitable qualification policies to efficiently cope with the given demand and capacity. On the other hand, if the planning horizon is chosen too long, the planning uncertainty is higher. The demand forecasts are vague and due to the shortening product life cycles even not all relevant products might be considered. Hence, the initial considerations in subsection 4.1.1 about suitable planning horizons of 1 to 2 years and monthly planning periods have been confirmed. The longer the planning horizon was, the more options the model had and the more efficient the dynamic supply network could be designed. Tradeoffs between stability and flexibility strategy could be solved optimally, re-qualification benefits could be gained, related production focus of the single facilities could be developed. Especially the last effect is related to the volatility of demand. Always, it requires some time to group the products with the displacement

routine to a stable and cost-efficient related production focus in every facility. But in all the experiments demand was given, even if it was volatile. Hence, if demand uncertainty is assumed to be increasing with longer planning horizons, the necessary planning horizon is suggested to be at least one year but better two years.
Especially the assignment and displacement routine of the Displacement Heuristic led to a further effect. The tradeoff between specialization and generalization of a facility. The heuristic as well as the optimization model are aiming to specialize each facility more and more, to gain scaling benefits of related products. However, the relationship of products has two sides of a coin. Clustering related products in one facility might be beneficial, when considering qualification costs. However, if market risk is considered on the other side, it is maybe advisable to limit this specialization strategy at some point. Otherwise, the single facilities in the dynamic supply network may suffer the market risk. It might be risky to focus the production portfolio only on the relationship of the products. To balance utilization, the correlation of demand has to be additionally taken into account, when specializing a facility on a certain group of products. Re-capturing the micro-economical concept of Marginal Rate of Substitution, mentioned in subsection 4.2.4, a change in price of one product might influence the demand of another product. The concept of product substitution has to be considered, when diversifying the risks. Clustering related products is beneficial for reduction of qualification costs, unless they are not complementary reacting to any change of market circumstances. Optimally the products clustered in a facility are related in production, according to the concept of relationship of products, but have negatively correlated demand. In this case the qualification benefits can be gained, while the utilization can be balanced. Such situations can occur, if two different products are related, but serve different applications for different markets. For example in semiconductor industry a Gyro Sensor can be applied in related, but different products to either stabilize an airplane, or a car, or a smartphone display. The product in those

three cases is quite related in production, but the destination markets are diversified. Hence, clustering products according to the concept developed in this work might tremendously reduce the qualification costs, but it has to be applied with care to the market risk diversification to avoid making the facilities cost-efficient but vulnerable due to their specialization. The best strategy is to combine substitution products, which are related, according to the approach of this work. This makes the supply networks efficient and resilient against market volatility at the same time.
The realistic concept of qualification differentiation leads to several insights. Firstly, an initial qualification should be always more expensive, as it captures the fix costs, which occur at an initial qualification, but maybe avoided, when the product is re-qualified. This is one way to express the long-term experience of the facility. The short term experience can be expressed by the basic re-qualification costs. The short-term experiences are expressed with the even lower qualification maintenance costs. This assumption leads to the tradeoff of stability versus flexibility strategy, which is present in modern multitasking facilities. The question is, how long to maintain an unused qualification state to be flexible, when the product is required again. In this approach, this tradeoff is intuitively solved with the minimization criterion of qualification costs. If it is cheaper to maintain a qualification to bridge a certain time without demand, this is suggested, else a re-qualification is suggested, once the product is required again. This tradeoff is strongly influenced by the relationship of the products, as the re-qualification is depending on the product relationship but the maintenance is not. In a facility, which is focussed on a close group of very related products the gap between re-qualification and maintenance is comparably low. Hence, this facility is suggested by the Displacement Heuristic as well as by the optimization model to more follow the flexibility strategy and faster drop a qualification state and re-qualify it again, when needed. The cost delta between mix-independent maintenance and mix-dependent re-qualification is comparably low. Hence, the Displacement Heuristic will faster decide to dis-

and re-qualify. This effect results from the interaction of several realistic assumptions and is quite intuitive. With this background again it is advisable to integrate as many periods as possible to the planning horizon. The more information about future demand can influence the qualification decision, the more stable the decision will be.
Beyond the qualification differentiation, important insights can be summarized from the relationship of products. The suggested cost structure considers stepwise fix costs, when opening a new facility. No matter how unrelated the existing product portfolio in a specific facility is, it should always be better to additionally qualify a new product to a mature facility and exploit the installed capacity even more, instead of opening a new facility. This is precisely represented by the structure of the mix-dependent qualification costs. The first product in an empty facility triggers the highest qualification costs possible, as there is no portfolio installed, which provides benefits. Hence, it is economically much more efficient to increase the capacity of one facility, instead of opening a new one. Due to the mix-dependent structure of the qualifications as well as the gained experience, a mature facility always provides benefits for the qualification. Due to the mix-dependent qualifications and the experience-based differentiation of qualifications, mature facilities are suddenly strategically higher valued, than expected by conventional business depreciation methods. Rather than just cash cows, mature facilities can be of strategic value, when kept flexible. Recent examples show this in semiconductor industry: Economies of scale on increasing required production volume motivated the semiconductor industry for development of 300mm or even 450mm wafer technologies in the last decades. But markets develop differently. The large scale, low mix, high volume production is a luxury, which is often risky to rely on. Markets become manifold. Final products are more and more customized. Specialized niche products play an increasingly important role. But the major 300mm or even 450mm fabs require huge lotsizes to be utilized and are highly automated. Hence, it is an increasing challenge to react on fast changing markets with those huge

size static facilities. To increase economies of scale the lotsizes have been increased tremendously with 300 and 450mm wafer technology. These facilities have been build for low-mix high volume product portfolios with constantly high demand. But as markets require more and more customized solutions, flexible production in smaller volumes is required. In these situations mature 200mm or even 150mm facilities should get higher value and higher attention again. Those facilities can handle small lotsizes much more flexible, which is required for volatile markets. Due to their long history and high experience, the machines and equipment can be managed quite flexible. This is exactly the upcoming trend. Flexibility as well as capability for small lotsizes is turning out to be a competitive advantage in volatile markets. This conclusion can directly be derived from the developed approach for Dynamic Supply Network Design. The hardware and knowledge is existing and evolved through decades. The capabilities of the equipment experienced through years. It now has to be used for a new kind of production in volatile small-volume, high-mix markets. To profit from these new opportunities, mainly the mindset for dynamic production environments has to develop. Dynamic supply networks with lean, central planning and control instruments and decentral flexible production units is a challenging but promising architecture to serve volatile markets.
The subsequent section concludes this thesis and gives a scientific outlook to motivate further work in the field of dynamic supply network design.

7 Conclusion and Scientific Outlook

This thesis proposes the Dynamic Supply Network Design approach as an answer for serving more and more volatile markets with static, capacitated facilities. The subsequent section summarizes and concludes the thesis and the final section motivates further research in this new field with the direct industrial requirement.

7.1 Conclusion

The Dynamic Multi-Product Multi-Facility Supply Network Design Problem is one major challenge in modern supply chain management. To efficiently serve the volatile markets the supply networks have to be more dynamic. Especially, facing shortening product life cycles and aggravated prediction of future demand, makes the ability of the network for fast and dynamic reaction on changing environment inevitable. The observation is thereby, that classical stable supply chains, have to converge to dynamic networks, which have to be able to change flexibly on a mid-term basis. Due to physical constraints the capacities of each facility have already been fixed for the mid-term level. But due to modern market requirements, the real supply network has to be designed right in the mid-term level in the Supply Network Design Problem. This is necessary to react in unstable markets in time. Hence, with given facilities and given capacities new dynamic supply networks can be developed and changed efficiently. This is possible by considering tactical capacity qualification as a decision objective. In the modern

Dynamic Supply Network Design Problem, the qualification policies of the static capacities are optimized considering demand satisfaction under minimum overall costs. Qualifying a facility triggers qualification costs. But also holding finished goods for future demand peaks creates holding costs. The proposed MILP optimization model of the DSNDP minimizes these supply network costs, by choosing the efficient policy of qualification and storage. Thereby, the optimization model sets the capacitated facilities in a dynamic supply network structure. It assumes, that the facility resources can qualify and produce an entire product portfolio, instead of only single products. Further, the qualification structure is mix-dependent and the costs for a specific qualification depend on the current qualification state. Additionally, it assumes, that a facility collects experiences and gains benefits, if the same product portfolio has ever been qualified there. With this modelling approach a dynamic supply network can be built to satisfy the volatile markets, using the static capacities and the dynamic qualification option. As the optimization model is only capable for small, but not realistic problem sizes, the additionally proposed Displacement Heuristic supports finding a good solution for the DSNDP in acceptable time. The extensive validation shows, that with the Displacement Heuristic realistic industrial problem sizes can be solved very fast. Due to the iterative character of the heuristic, optimality can not be guaranteed. The Displacement Heuristic leads to a loss of goodness of $\sim$4% to 6%. In the context of mix-dependent qualification structures, qualification differentiation, multitasking resources, this is a very satisfying result.

Altogether, this work closes the research gap, to find a way to use qualification as a tactical decision variable to design dynamic supply networks with given facilities. Thereby, cost-efficient adaptation of static supply chains to dynamic supply networks is enabled. This is necessary, to efficiently answer the volatility of the markets and the planning uncertainty, due to shorter product life cycles.

In concrete terms, the four research questions, motivating this thesis, have been answered step by step.

1. How can a supply network be designed dynamically for the volatile markets? In chapter 2 resource qualification decisions are introduced as enabler to dynamic supply networks in static capacitated environments. In chapter 4 the approach is detailed and the structure of qualifications is described in detail. This leads to the mathematical formulation of the MILP for the cost-optimal design of the dynamic supply network, to answer market volatility.

2. How and where can the dynamic supply network design process be integrated to the conventional hierarchical planning system? The sections 3.1 and 3.2 of the literature review point out, that the DSNDP has to be located in the tactical mid-term Master Planning Level with a planning horizon of 1-2 years, quarterly planning frequency and monthly period buckets, to answer mid-term market volatility with the generation of dynamic supply networks on a tactical level with given capacitated resources.

3. How can overall costs be minimized in a dynamic supply network? Chapter 4 specifies the structure of facility resources as well as supply networks. On this basis cost-efficient solutions for the supply network of every period can be found by the optimization model as well as the Displacement Heuristic.

4. How can realistic sizes of the DSNDP be solved in acceptable time? The proposed optimization model can only solve small problem sizes. The Displacement Heuristic, proposed in Chapter 5, provides the solutions for realistic problem sizes in acceptable time.

As the literature review shows, this field of flexibilizing supply networks with the right choice of resource qualification is poorly researched, up to now. This is the reason, this thesis does not claim to have completely closed the topic, but rather make a scientific call for further research in the field of Dynamic Supply Network Design. The subsequent final section will give some concrete suggestions for further scientific research, but also for industrial implementation.

7.2 Scientific Outlook

The field of Dynamic Supply Network Design is quite new, as it is motivated by the recent trend of shortening product life cycles. Finally, this thesis can suggest three further working areas in this field.
Firstly, the optimization model is not able to cover realistic problem sizes. This issue has to be solved either with different programming proposals or with different hardware. Otherwise, optimality can not be guaranteed for industrial solutions.
Secondly, the Displacement Heuristic captures a very promising relaxation idea of ignoring the capacity constraint to find better solutions, which are made feasible afterwards. This challenging approach provides two ways of further research: On the one hand, the Displacement Heuristic itself can be optimized to reduce the loss of goodness even more. On the other hand, the Displacement Heuristic can be transferred to other domains. As the approach is quite generic, it can be applied in other areas too.
Thirdly, not only research should be motivated to continue in this area. Also industry is strongly suggested to take the challenge serious and to adapt and implement solutions, carefully provided by research. Otherwise, the static character of mature locally optimized supply chains is inhibiting the exploration of new markets and business solutions. Future business will uncompromisingly turn to higher volatility, requiring higher dynamics.
"It is not the strongest of the species that survives, nor the most intelligent that survives. It is the one that is most adaptable to change." [Charles Darwin, Evolutionary Biologist].

Glossary of Notations

Abbreviations

ASIC	Application-Specific Integrated Circuit	8
cf.	conferatur - compared to	48
CLSP	Capacitated Lotsizing Problem	32
DSNDP	Dynamic Supply Network Design Problem	3
e.g.	exempli gratia - for example	48
ECU	Electronic Control Unit	12
LP	Linear Program	13
MAE	Machine and Equipment	27
MES	Manufacturing Execution System	54
MILP	Mixed Integer Linear Programming	40
MIT	Massachusetts Institute of Technology	24
OEM	Original Equipment Manufacturer	2

Parameters and Variables

b_m	Capacity buffer of machine m	56
$BigM$	Big number near infinity	49
C	Linear Capacity Program Matrix	61
C_m	Capacity of machine m	61
$ci_{f,i,j}$	Initial qualification costs for portfolio j from i in facility f (transferred from mix-dependent $cq_{f,i,j}$)	74

$cq_{f,i,j}$	Basic qualification costs for portfolio j from i in facility f 67
$cq_{f,j}$	Basic qualification costs for portfolio j in facility f 49
$cq_{n,f}$	Simplified qualification costs of product n in facility f .. 98
$cr_{f,i,j}$	Re-qualification costs for portfolio j from i in facility f ($cr_{f,j,j}$ thereby resembles the qualification maintenance costs) 74
$cr_{f,i,j}$	Re-qualification costs for portfolio j from i in facility f 74
Dim_j	Dimension of product portfolio j 66
$Fxy_{f,j,t}$	Extended subtour restriction counter variable for qualification differentiation 49
$Fy_{f,j,t}$	Simple subtour restriction counter variable 49
mdc	Mix-dependent qualification costs factor 64
mdt	Mix-dependent qualification time factor 64
$NumConstr_{f,t,n}$	Number of constraints with f facilities, t periods and n products 83
$NumVar_{f,t,n}$	Number of variables with f facilities, t periods and n products 83
$P_{j,n}$	Binary product mix assignment matrix of all products n to all product mixes j 66
PT_n	Process time of product n (with product $n \in$ portfolio j) 67
$Q_{f,t,n,j}$	Lotsize of product n in product portfolio j at facility f in period t 49
qmc	Qualification maintenance cost constant 64
qmt	Qualification maintenance time constant 64
R	Product portfolio relationship matrix 61
r	Product relationship matrix 61
$R_{i,j}$	Relationship of portfolio j with portfolio i 61
$r_{k,n}$	Relationship of product n with product k 59
r_{max}	Maximum product relationship matrix 62

$ti_{f,i,j}$	Initial qualification time for portfolio j from i in facility f (transferred from mix-dependent $tq_{f,i,j}$)	74
$tq_{f,i,j}$	Basic qualification time for portfolio j from i in facility f	67
$tq_{f,j}$	Basic qualification time for portfolio j in facility f	49
$tr_{f,i,j}$	Re-qualification time for portfolio j from i in facility f ($tr_{f,j,j}$ thereby resembles the qualification maintenance time)	74
$Vol_{(t,preproc)}$	Non-product-specific lotsize to be pre-processed in period t	104
$x_{f,t,i,j}$	Binary re-qualification variable indicating a re-qualification of portfolio j from i in facility f in period t	74
$y_{f,t,i,j}$	Binary qualification variable indicating a qualification of j from i in f in t (initial qualification variable in qualification differentiation extension)	67
$y_{f,t,j}$	Binary qualification variable indicating a qualification of j in f in t	49
$Y_{t,n}$	Stock size of product n in the end of period t	49
$z_{f,t,j}$	Binary qualification maintenance variable indicating a qualification maintenance of portfolio j in facility f in period t	74

Indices

F	Number of Facilities	48
i	Product portfolio index ($i \in 1..2^N$)	48
j	Product portfolio index ($j \in 1..2^N$)	48
k	Product index ($k \in 1..N$)	48
n	Product index ($n \in 1..N$)	48

Terminology

Basic Cost Fix qualification cost factor, not dependent from the qualified product portfolio 14

Capacity Provided dimension of the resource in time [15] 9

Classical Term, to describe conventional approaches, similar to traditional 15

Evaluation Used to analyze the behavior of a model in specific experiments 15

Experiment Constructed planning use case to test specific modelling effect 15

Facility Local resource containing set of machines 9

Final Product Output, which satisfies demand of the end customer 7

Hierarchical PlanningSystem System of hierarchical planning levels for coordination of specific planning decisions in specific planning horizons with given planning input [59] 12

Holding Costs Costs for holding a lot in stock for one period [97] 13

Initial Qualification Type of qualification, if product has never been qualified on particular resource 15

Initial Qualification Costs Costs generated in initial qualification 15

Initial Qualification Time Time required in initial qualification 15

Investment Extension of production capacity 11

Linear Capacity Program Linear Program describing capacity requirements of product on resource 13

Long – Term Planning Planning horizon ≥ 2 years for resource investment [118][3] 13

Machine Most granular resource unit to perform an operation 9

Mid – Term Planning Planning horizon 6 months to 2 years for production portfolio planning [118][3] 13

Mix – Dependent Cost Qualification cost factor, which depends on the previous product portfolio . . . 14

Mix – Dependent Qualification Qualification effort depends on already qualified product portfolio . . . 14

Multitasking Facility Capability of a facility resource to produce multiple products in parallel . . . 14

Operation Single production step and greatest level of granularity in the transformation process . . . 8

Overall Costs Sum of qualification costs and holding costs of a supply chain [97] . . . 13

Planning Buckets Periods in the planning horizon to be planned [97] . . . 12

Planning Horizon Time scope of a specific planning level [114] . . . 12

Planning Level [114] . . . 12

Process Time Time an operation requires from the resource . . . 8

Procurement Time Time to receive and activate a resource . . . 11

Product Output of a transformation process [52] . . . 7

Product Component Output, which serves as an input for further transformation . . . 7

Product Groups Technological cluster of familiar products . . . 8

Product Life Cycle Structures the limited lifespan of a product to specific stages [10] . . . 9

Product Mix Equivalent of Product Portfolio . . . 10

Product Portfolio Set of products a facility is able to produce [65] . . . 10

Production Costs Variable cost, occurring in production of a lot [53] . . . 13

Production Location Equivalent of Facility . . . 10

Production Partner Active facility involved in the supply chain with production responsibility for one or more production stages 12

Production Site Equivalent of Facility . . . 10

Production Stage Sequence of work plan for product component . . . 7

Qualification Generates the capabilities to perform an operation or production stage [29] . . . 10

Qualification Costs Costs occurring, when generating the capabilities to perform an operation or production stage 11

Qualification Maintenance Qualification state transfer from one period to another 15

Qualification Maintenance Costs Costs generated, if a qualification state is transferred to the next period 15

Qualification Maintenance Time Time required, if a qualification state is transferred to the next period 15

Qualification Time Time required to generate the capabilities to perform an operation or production stage 11

Re − Qualification Type of qualification, if product has already been qualified in the past on particular resource 15

Re − Qualification Costs Costs generated in re-qualification 15

Re − Qualification Time Time required in re-qualification 15

Relationship of Product Portfolios To express the similarity of two product Portfolios 14

Relationship of Products To express the similarity of two products 14

Resource Limited entities required to produce a product [106] 9

Scenario Specific parameter setting in an experiment 15

Short − Term Planning Planning horizon < 6 months for lotsizing and production fine planning [118][3] 13

Supply Chain Chain-oriented collaboration of production partners to produce a final product [110] 11

Supply Network Network-oriented collaboration of production partners to produce different final products [114] 12

Validation Used to assess the goodness of heuristic results compared to the optimum in specific experiments 15

Work Plan Specifies the sequence of transformation operations which result in the final product 7

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A Appendix

A.1 Proof by Mathematical Induction

Proof by mathematical induction:

$$2^N = \sum_{k=0}^{N} \binom{N}{k} \qquad \forall N \in \mathbb{N} \tag{A.1}$$

Base case:

$$2^0 = \sum_{k=0}^{0} \binom{N}{k} = \binom{0}{0} = 1 \tag{A.2}$$

Inductive step:

$$2^{N+1} = \sum_{k=0}^{N+1} \binom{N+1}{k} = 2^N * 2 \tag{A.3}$$

$$= \sum_{k=0}^{N} \binom{N}{k} * 2 \tag{A.4}$$

$$= \sum_{k=0}^{N} \binom{N}{k} + \sum_{k=0}^{N} \binom{N}{k} \tag{A.5}$$

$$= \sum_{k=1}^{N} +1 \binom{N}{k-1} + \sum_{k=0}^{N} \binom{N}{k} \tag{A.6}$$

$$= \sum_{k=1}^{N} \binom{N}{k-1} + \sum_{k=1}^{N} \binom{N}{k} + \binom{N}{0} + \binom{N}{N} \tag{A.7}$$

$$= \sum_{k=1}^{N} \left[\binom{N}{k-1} + \binom{N}{k} \right] + 1 + 1 \tag{A.8}$$

$$= \sum_{k=1}^{N} \binom{N+1}{k} + 1 + 1 \tag{A.9}$$

$$= \sum_{k=1}^{N} \binom{N+1}{k} + \binom{N+1}{0} + \binom{N+1}{N+1} \tag{A.10}$$

$$2^{N+1} = \sum_{k=0}^{N+1} \binom{N+1}{k} \qquad \textbf{q.e.d} \tag{A.11}$$

A.2 Capacity and Demand for Evaluation Experiment 6.2.3

The following table A.1 shows the periodic capacities as well as the average and overall capacity of every facility:

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	D_1	D_2	D_3	D_4
t_1	1000	1000	1000	1000	1000	1000	1000	1000	16	0	11	0
t_2	5	5	163	167	5	5	5	122	0	15	0	0
t_3	5	5	5	193	5	165	5	150	2	0	17	0
t_4	5	167	5	189	5	5	176	5	6	0	0	0
t_5	146	150	5	166	5	5	5	5	11	0	0	0
t_6	167	5	5	5	5	150	117	118	16	0	0	0
t_7	151	5	138	5	5	131	151	162	0	0	10	14
t_8	139	5	135	5	5	177	5	5	0	11	0	17
t_9	181	5	183	152	5	180	176	183	0	10	0	0
t_{10}	121	5	5	5	5	5	5	168	18	13	0	1
t_{11}	5	172	5	149	5	5	169	142	0	20	6	20
t_{12}	5	5	119	202	5	139	157	5	0	18	0	18
t_{13}	217	5	92	171	151	167	178	5	0	0	0	19
t_{14}	5	5	140	159	139	170	130	151	0	20	0	8
t_{15}	149	159	5	190	164	5	148	5	0	0	6	14
t_{16}	149	5	5	150	168	149	5	149	0	0	16	3
t_{17}	5	5	168	5	5	149	193	137	0	0	19	0
t_{18}	5	5	138	5	5	5	134	151	0	0	0	0
t_{19}	5	5	160	183	189	140	160	5	13	2	0	0
t_{20}	200	124	164	5	183	148	159	151	18	0	20	2
Avg	133,25	92,1	132	155,3	102,95	145	153,9	140,95	5	5,45	5,25	6,1

Table A.1: Volatile Capacity and Volatile Demand of Scenario1

A.3 DSNDP Model Performance Evaluation Scenarios

The following table A.2 specifies the 43 evaluation scenarios performed and shows the resulting overall costs as well as the resulting computation time for the optimization model as well as the pre-calculation:

ID	Scenario	N	F	T	*#Var.*	*#Constr.*	*Costs*	T_{opt}	T_{pre}
1	Ref. Scen.	3	3	3	1449	1491	2481	1	0
2	Inc. t	3	3	4	1932	1980	2606	2	0
3	Inc. t	3	3	5	2415	2469	2716	9	0
4	Inc. t	3	3	6	2898	2958	2858	15	0
5	Inc. t	3	3	7	3381	3447	3002	47	0
6	Inc. t	3	3	8	3864	3936	3152	111	0
7	Inc. t	3	3	9	4347	4425	3302	69	0
8	Inc. t	3	3	10	4830	4919	3452	89	0
9	Inc. t	3	3	11	5313	5403	3602	348	0
10	Inc. t	3	3	12	5769	5892	3752	811	0
11	Inc. t	3	3	13	6279	6381	3902	949	0
12	Inc. t	3	3	14	6762	6870	4052	623	0
13	Inc. t	3	3	15	7245	7359	4202	1106	0
14	Inc. t	3	3	15	7245	7359	4202	1106	0
15	Inc. t	3	3	16	7728	7848	4352	1775	0
16	Inc. t	3	3	17	8211	8337	4502	19851	0
17	Inc. t	3	3	18	8694	8826	4652	10268	0
18	Inc. t	3	3	19	9177	9315	4852	21517	0
19	Inc. t	3	3	20	9660	9804	4952	44994	0
20	Inc. f	3	4	3	1929	1985	2481	7	0
21	Inc. f	3	6	3	2889	2973	2481	6	0
22	Inc. f	3	8	3	3849	3961	2481	10	0
23	Inc. f	3	10	3	4809	4949	2481	13	0
24	Inc. f	3	12	3	5769	5937	2481	14	0
25	Inc. f 10	3	14	3	6729	6925	2481	16	0
26	Inc. f	3	16	3	7689	7913	2481	66	0
27	Inc. f	3	18	3	8649	8901	2481	79	0
28	Inc. f	3	20	3	9789	9913	2481	95	0
29	Inc. n	2	3	3	393	432	1321	0	0
30	Inc. n	4	3	3	5340	5406	2642	23513	0
31	Inc. n	5	3	3	20175	20289	failed	100917	0
32	Inc. n	6	3	3	77778	77988	failed	failed	failed
33	Inc. n	7	3	3	511381	761651	failed	failed	failed
34	Inc. n	8	3	3	null	null	failed	failed	failed
35	Inc. n	9	3	3	null	null	failed	failed	failed
36	Inc. n	10	3	3	null	null	failed	failed	failed
37	Inc. n	11	3	3	null	null	failed	failed	failed
38	Inc. n	12	3	3	null	null	failed	failed	failed
39	Inc. n	13	3	3	null	null	failed	failed	failed
40	Inc. n	15	3	3	null	null	failed	failed	failed
41	Inc. n	19	3	3	null	null	failed	failed	failed
42	Inc. n	21	3	3	null	null	failed	failed	failed
43	Inc. n	25	3	3	null	null	failed	failed	failed

Table A.2: Evaluation Scenario Table

A.4 Pseudo Code of the Displacement Heuristic

To even go a bit more in detail, the following paragraphs introduce the pseudo code of the Displacement Heuristic.

Pre-check if plan is executable (A.12)

$for\ (periods : t = 1 \rightarrow T)$

$\quad for\ (products : n = 1 \rightarrow N)$

$\quad\quad sumDemand = sumDemand + D_{n,t}$

$\quad closeLoop(products)$

$\quad for\ (facilities : f = 1 \rightarrow F)$

$\quad\quad sumCapa = sumCapa + C_{f,t}$

$\quad closeLoop\ (facilities)$

$closeLoop(periods)$

$if\ (sumDemand > sumCapa)\ then$

break –> not executable

$else \rightarrow continue$

$\quad for\ (periods : t = T \rightarrow 1)$

$\quad\quad for\ (products : n = 1 \rightarrow N)$

$\quad\quad\quad Utilization_t = Utilization_t + D_{n,t} * PT_n$

$\quad\quad closeLoop\ (products)$

$\quad\quad for\ (facilities : f = 1 \rightarrow F)$

$\quad\quad\quad sumCapa_t = sumCapa_t + C_{f,t}$

$\quad\quad closeLoop\ (facilities)$

Determine necessary pre-processing (A.13)

$\quad\quad if\ (sumCapa_t < Utilization_t) then$

$if\ (t=1)\ then$

break –> not executable

$else$

$while\ (Utilization_t > sumCapa_t)$

$for\ (products\ n = 1 \rightarrow N)$

$$if\ (minCosts > ch_n * roundUp\frac{(Utilization_t - sumCapa_t)}{PT_p} andD_{n,t} > 0)\ then$$

$n \rightarrow cheapest\ product\ to\ preprocess$

$necessary\ cheapest\ preprocess\ lotsize =$

$$roundUp\frac{(Utilization_t - sumCapa_t}{PT_n})lots$$

$endIf$

$closeLoop\ (products)$

$$lotsize_{n,preproc} = min(D_{n,t}; roundUp\frac{(Utilization_t - sumCapa_t)}{PT_n})$$

$Utilization_t = Utilization_t - lotsize_{n,preproc}$

$Utilization_{t-1} = Utilization_t + lotsize_{n,preproc}$

$overallCosts = overallCosts + ch_n * lotsize_{n,preproc}$

$closeWhile$

$endIf$

$endIf$

$closeLoop\ (periods)$

Find costs in cheapest alternative (A.14)

$for\ (periods: t = 1 \rightarrow T)$

$while\ (there\ are\ lots\ to\ be\ assigned)$

$for\ (facilities: f = 1 \rightarrow F) check\ costs\ for\ assignment$

$if\ (n\ already\ qualified)\ then$

$$costs = cm_{f,n}$$
$$elseIf\ (n\ was\ once\ qualified)\ then$$
$$costs = cr_{f,n}$$
$$elseIf\ (n\ was\ never\ qualified)\ then$$
$$costs = ci_{f,n}$$
$$endIf$$
$$if\ (minCost > cost)\ then$$
$$minCost = cost$$
$$facility\ for\ assignment = f$$
$$endIf$$
$$closeLoop\ (facilities)$$

Assign to facility ignoring capacity limit (A.15)

$$minCost = cost$$
$$productionQuantity_{f,t} = productionQuantity_{f,t} +$$
$$lotsizeToBeAssigned_{n,f}$$
$$C_{f,t} = C_{f,t} - lotsizeToBeAssigned_{n,f} * PT_n$$
$$qualify\ product\ to\ productmix_{f,t}$$

Cost-driven displacement (A.16)

$$while\ (lotsize_{n,t,b} > 0 in\ any\ facility \neq f)$$
$$for\ (facilities : b = 1 \rightarrow F)$$
$$if\ (remainingCapacity_{f,t} \geq (lotsize_{n,t,b} * PT_n))\ then$$
$$lotsize_{n,t,f} = lotsize_{n,t,f} + lotsize_{n,t,b}$$
$$remainingCapacity_{f,t} =$$
$$remainingCapacity_{f,t} - (lotsize_{n,t,b} * PT_n)$$
$$remainingCapacity_{b,t} =$$
$$remainingCapacity_{b,t} + (lotsize_{n,t,b} * PT_n)$$

$qualification_{b,t,n} = 0$

$overallCosts = overallCosts + additional\ qualification\ costs$

$endIf$

$closeLoop\ (facilities)$

$closeWhile$

Capacity-driven displacement (A.17)

$while\ (remainingCapacity_{b,t} < 0)$

$minCosts = 99999$

$for\ (products : k = 1 \rightarrow N)$

$for\ (facilites : f = 1 \rightarrow F)$

$if\ (k\ already\ qualified)$

$costs_{b,t} = cm_{b,k}$

$elseIf\ (n\ was\ once\ qualified)\ then$

$costs_{b,t} = cr_{b,k}$

$elseIf\ (n\ was\ never\ qualified)\ then$

$costs_{b,t} = ci_{b,k}$

$endIf$

$if\ (minCosts > costs_{[}b,t]andb \neq f\ and\ b\ is\ qualified\ for\ k)$

$minCosts = costs_{b,t}$

$displacementProduct = k$

$endIf$

$closeLoop\ (facilities)$

$closeLoop\ (products)$

$displace\ roundUp(min(lotsize_{k,t,b}, \frac{|remainingCapacity_{b,t}|}{PT_k})$

$remainingCapacity_{b,t} = remainingCapacity_{f,t} -$

$(roundUp(min(lotsize_{k,t,b} * PT_k, |remainingCapacity_{b,t}|)$

$remainingCapacity_{f,t} = remainingCapacity_{f,t} +$

$(roundUp(min(lotsize_{k,t,b} * PT_k, |remainingCapacity_{b,t}|)$

$lotsize_{b,t,k} = lotsize_{b,t,k} -$

$(roundUp(min(lotsize_{k,t,b} * PT_k, |remainingCapacity_{b,t}|)$

$lotsize_{f,t,k} = lotsize_{f,t,k} +$

$(roundUp(min(lotsize_{k,t,b} * PT_k, |remainingCapacity_{b,t}|)))$

$qualificationb, t, k = min(1, lotsize_{b,t,k})$

$overallCosts = overallCosts + additional\ qualification\ costs$

$closeWhile$

$closeWhile$

$closeLoop\ (periods)$

Reoptimization of maintaining vs. requalifying (A.18)

$for\ (facilities : f = 1 \rightarrow F)$

$for\ (products : n = 1 \rightarrow N)$

$for\ (periods : t = 1 \rightarrow T)$

$if\ (qualification_{f,t,n} = 1)\ then$

$startPeriod = t$

$endIf$

$for\ (periods : t = startPeriod + 1 \rightarrow T)$

$while\ (qualification_{f,t,n} = 0)$

$endPeriod = t$

$closeWhile$

$closeLoop\ (periods)$

$if\ ((endPeriod - startPeriod) * cm_{f,n} > cr_{f,t,n})\ then$

$for\ (period : t = startPeriod \rightarrow endPeriod)$

$$
\begin{aligned}
&\qquad\qquad qualification_{f,t,n} = 1\\
&\qquad\quad closeLoop\ (periods)\\
&\qquad\quad overallCosts = overallCosts - cr_{f,t,n} +\\
&(endPeriod - startPeriod) * cm_{f,n}\\
&\qquad endIf\\
&\quad closeLoop\ (products)\\
&closeLoop\ (facilities)
\end{aligned}
\tag{A.19}
$$

The Displacement Heuristic is implemented in JAVA using Eclipse IDE 2019 based on this pseudo code.