Cloud Manufacturing as an Event-based Rescheduling Instrument in Multi-Site Production Networks: Models, Algorithms and Analysis

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Kurzfassung

Störungen in der Produktion können erhebliche negative Auswirkungen auf die betroffenen Unternehmen haben. Dementsprechend ist es entscheidend, dass im Falle einer Störung adäquate Maßnahmen ergriffen werden. In Produktionsnetzwerken erfordern die notwendigen Umplanungsmaßnahmen ein hohes Maß an Abstimmung mit den horizontalen und vertikalen Partnern im Wertstrom. In der Praxis gibt es jedoch kaum Planungswerkzeuge, die eine kurzfristige standortübergreifende Koordination unterstützen. Aufgrund der Komplexität und des resultierenden manuellen Aufwands werden die Potenziale im Netzwerk daher oft nicht so ausgeschöpft, wie es möglich wäre.

Ziel dieser Arbeit ist es, einen Cloud-Manufacturing (CM)-Ansatz zu entwickeln, der in Produktionsnetzwerken als kurzfristiges, standortübergreifendes Planungstool eingesetzt werden kann, um eine Umplanung im Störungsfall zu ermöglichen. Das Konzept basiert auf der Idee, im Netzwerk verfügbare Ressourcen (Maschinen und Materialien) zusammen mit verschiedenen von Spediteuren angebotenen Transportformen auf einer privaten CM-Plattform als nutzbare Services anzubieten, um mit diesen im Störungsfall einen Ad-hoc-Wertstrom erzeugen zu können, der in die bestehenden Produktionspläne im Netzwerk integriert werden kann, ohne diese ändern zu müssen.

Ausgehend von den Anforderungen eines deutschen Automobilzulieferers, der Robert Bosch GmbH, entwickeln wir in dieser Arbeit sowohl ein Framework, das beschreibt, wie die Plattform in verschiedenen Störungssituationen eingesetzt werden kann, als auch ein Konzept für die Funktionsweise der Plattform. Grundlage des Konzeptes ist ein umfassendes Datenmodell zur Beschreibung der Gegebenheiten im betrachteten Produktionsnetzwerk. Das Datenmodell bildet zusammen mit den Spezifikationen zur Systemarchitektur und zum Prozessablauf, das Rückgrat der Plattform. Kernaspekt der CM-Plattform ist das in diesem Rahmen zu lösende und in der Literatur als Service-Selection-Problem (SSP) bezeichnete Optimierungsproblem, das darauf abzielt, die angebotenen Ressourcen zeitlich und mengenmäßig so zu kombinieren, dass ein möglichst passender Wertstrom für den beauftragenden Kunden, d. h. das von der Störung betroffene Werk, erzeugt wird. Für die Modellierung des SSP wählen wir in dieser Arbeit eine bisher in der Literatur noch nicht verwendete Losgrößen-basierte Problemformulierung. Das entworfene Modell, welches wir in der vorliegenden Thesis als *Service-orientiertes Losgrößenproblem* (SLSP) bezeichnen, ist in seiner Grundversion ein multikriterielles gemischt-ganzzahliges lineares Problem (MOMILP). Ergänzend dazu stellen wir verschiedene Optionen zur Modellerweiterung, sowie eine auf linearer Programmierung (LP) basierende, vereinfachte Reformulierung, die eine deutliche Komplexitätsreduktion mit sich bringt, vor. Ziel des SLSP ist die Minimierung der Kriterien Kosten und Zeit aus Sicht des Auftraggebers.

Um die Praxistauglichkeit des Ansatzes nachzuweisen, wenden wir die entwickelten Methoden und Modelle in einer Fallstudie an, die auf realen Daten der Robert Bosch GmbH basiert. Ein Vergleich mit einer an die Vorgehensweise in der Praxis angelehnten Heuristik zum Umgang mit produktionsbezogenen Störungen zeigt, dass ein Einsatz bei Maschinenausfällen unterschiedlicher Größenordnung Vorteile liefern kann. Weiterhin wird gezeigt, dass auch bei mehrstufigen Produktionsprozessen und größeren Probleminstanzen eine für den Praxiseinsatz taugliche Lösungsgüte bei der Lösung des SLSP erzielt werden kann, wenn auf die eingeführten Modellerweiterungen verzichtet wird.

Zusammenfassend liefert die vorliegende Arbeit damit zum einen einen Beitrag zur Cloud-Manufacturing-Literatur, sowohl durch den Losgrößen-basierten Ansatz zur Modellierung des SSP als auch durch die Anwendung des CM-Konzepts als Umplanungsinstrument im Störungsfall in internen Produktionsnetzwerken. Der zweite Punkt trägt

darüber hinaus auch zur Störungsmanagement-Literatur im Kontext von Produktionsnetzwerken bei.

Abstract

Disruptions in production can have a significant negative impact on the companies affected. Accordingly, it is crucial that adequate measures are taken in the event of a disruption. In production networks, however, the necessary rescheduling measures require a high degree of coordination, both with the horizontal and the vertical partners in the value stream. In practice, though, there are hardly any planning tools that enable cross-site coordination at the short-term level. Due to the complexity and the resulting manual effort, the potentials in the network are therefore often not exploited as much as it would be possible.

This thesis aims to develop a cloud manufacturing (CM) approach that can be used in internal production networks as a short-term cross-location planning tool allowing for event-based rescheduling in cases of disruptions. The concept is based on the idea of using available resources (machines and materials) in the network, which are offered on a private CM platform together with different forms of transport provided by freight forwarders as services to be used to generate a short-term ad-hoc value stream that can be integrated into the existing production plans in the network without having to change them.

Based on the requirements of a German automotive supplier, the Robert Bosch GmbH, we develop in this thesis both a framework that shows how the platform can be used in different disruption situations and a concept for the functioning of the platform. The functional concept is built on a comprehensive data model representing the production network under consideration. Using this as a basis, a system architecture is developed, and process flows are defined, which form the backbone of the platform. The core aspect to be solved within this framework is the optimization problem referred to in the literature as the service selection problem (SSP), which aims to combine the resources offered in terms of time and quantity in such a way that the most suitable value stream possible is generated for the customer placing the order, i.e. the plant affected by the disruption. For the modelling of the SSP, we propose a lot-sizing-based problem formulation not yet used in the literature. The designed model, which we refer to as the *service-oriented lot-sizing problem* (SLSP), is a multi-objective mixed-integer linear problem (MOMILP). Complementing this, we present various options for extending the model, as well as a simplified reformulation based on linear programming (LP), which entails a significant reduction in complexity.

To demonstrate the practical applicability of the approach, we apply the developed methods and models in a case study based on real-world data provided by the Robert Bosch GmbH. A comparison with a heuristic approach, which follows the procedure typically employed by the automotive supplier when facing production-related disruptions, reveals that the use of the CM platform can be worthwhile in the event of machine breakdowns of different sizes. Furthermore, it is shown that it is possible to solve the SLSP with a solution quality suitable for practical use also in cases of larger problem instances if the model extensions introduced can be omitted.

To sum up, this work contributes, on the one hand, to the literature on cloud manufacturing, both through the lot-sizing-based approach for modelling the SSP as well as by applying the CM concept to an internal network in order to be used as an event-based rescheduling instrument. The second point furthermore provides a contribution to the literature on disruption management in production networks.

Contents

1 Introduction

The world of reality has its limits; the world of imagination is boundless.
J.J. Rousseau

Disruptions in production processes can lead to considerable negative effects for the companies affected. In an empirical study using the example of the automotive industry, Bendul and Brüning showed that for the majority of the companies interviewed, production-related disruptions caused significant problems (cf. Bendul and Brüning 2017). More than 99% of the surveyed companies were affected by a disruption in the last five years. The causes of disruptions can be very diverse and can have both an internal and external origin. Examples of causes are machine breakdowns, quality deviations, strikes and short-term increases in demand. A characteristic feature of these disruptions is the unforeseen deviation from an original plan (cf. Yang, Qi, and G. Yu 2005). As a consequence, additional costs are threatened with regard to extra shifts, special trips and shortages at the customer side (cf. Barthel 2006). With increasingly complex and interconnected processes in production networks, other locations can be impacted very quickly as well (cf. Schmitt and Singh 2012). In order to minimise those negative effects, it is important to react appropriately to a production-related disruption.

Possible measures include the holding of inventories and the use of reserve capacities, on which we will take a closer look in this work (cf. Schmitt and Singh 2012, Lücker, Seifert, and Biçer 2019). Reserve capacities can be maintained not only at the affected site but also at the other locations of a production network. Along with this, reserve capacities can result from planned backup capacities, e.g. shifts kept free, and from unscheduled gaps in the production plans if the capacity utilisation is less than 100%. In the further course of this work, we aim to use these reserve capacities in order to reschedule production orders affected by a disruption as quickly and at the same time cost-effectively as possible. As rescheduling in practice requires a high degree of coordination, we make the assumption that the existing production plan shall not be changed when leveraging those reserve capacities. Production orders not affected by a disruption shall therefore be manufactured as initially planned.

Based on the processes of the Robert Bosch GmbH, a German multinational automotive supplier, the system under consideration is a multisite production network consisting of several plants which jointly manufacture a single product with multiple customer-specific variants in a discrete batch production. The individual sites of the production network are able to perform specific production steps on available production resources. Those production resources are, to a large degree, redundantly available within the production network. The production process is characterised as a multi-stage flexible flow line. The production steps include both manufacturing and assembly tasks. During an assembly step, purchased components are added to the product. The finished products are finally called off by OEM customers within framework agreements.

In practice, the coordination of such a production network in the case of a disruption is difficult as data on reserve capacities from different locations and systems must be collected and evaluated in a timely manner. There are many dependencies that have to be taken into account by a planner working manually on the disruption management. In addition, there is often a only poorly coordinated production planning and control across locations even without any disruptions (cf. Kaphahn and Lücke 2006).

To solve the problem described, the concept of cloud manufacturing (CM) is proposed. Like current consumer-to-consumer (C2C) platforms such as AirBnB and Uber, cloud manufacturing is designed to make available resources exchangeable between suppliers and customers via a cloud platform. The centrally operated CM platform maintains the necessary data and intelligently mediates production resources and capacities among the partners involved (cf. X. Xu 2012). The aim is to enable temporary and reconfigurable on-demand production processes (cf. D. Wu et al. 2013). In general, four types of CM platforms are distinguished (cf. Tao, L. Zhang, Venkatesh, et al. 2011): Public CM platforms are open to all suppliers and customers and are operated by a third-party provider. Private CM platforms are operated by a company itself and are limited to its own production network. Hybrid and community platforms are mixtures that allow both restricted and public access (hybrid) or are operated jointly by several parties (community).

Transferred to the described problem, the idea of this thesis is to employ the concept of cloud manufacturing within a multi-site production network in order to create a temporary ad-hoc value stream that can be integrated into the existing production plans in the event of a production-related disruption. The private CM platform is intended to solve both the coordination of the required data as well as the underlying optimisation problem. Taking into account the available reserve capacities, it is the task of the optimisation model to allocate and schedule the production orders affected by a disruption to production resources offered on the platform as usable production services. Since this could lead to transport steps between the locations, the optimisation model additionally considers different forms of transport provided on the platform. Besides, it must be ensured that sufficient raw materials, mounting components and finished goods containers are available at the selected sites, e.g. by bringing them in from another plant first. We therefore include the material provisioning as a further service to be considered on the CM platform. The result of this service selection problem (SSP) is a temporary ad hoc value stream consisting of production and transport steps scheduled on allocated production and transport resources while making use of available materials. For the concrete realisation of this problem formulation, we will propose a lot-sizing-based model formulation, which we refer to in the further course of this work as the service-oriented lot-sizing problem (SLSP).

To sum up, the goal of this thesis is to develop a concept for a private CM platform that can be used to generate a temporary ad hoc value stream in the event of a production-related disruption in a multi-site production network. We will look at both the functioning of the CM platform, including the processes, architecture and data models required for it, and at the underlying optimisation problem. The intention of the present work is thus to contribute to the rescheduling-driven handling of disruptions as well as to the concept of cloud manufacturing and the service selection problem on which it is based. To ensure practical applicability, we will evaluate the concepts developed by the example of a real-world case study based on data provided by the Robert Bosch GmbH.

1.1 Research Questions

Based on the described problem setting and the derived research objective, we divide our research into three research segments.

The research in the **first segment** is guided by the following research question:

1. How can a private CM platform intended for usage as an event-based rescheduling instrument be designed?

The aim of the first segment is to develop a concept for the *design* and *use of the CM platform* based on existing approaches. On the one hand, this encompasses the functional aspects of the platform, including the data models and processes for solving the problem described. On the other hand, this segment also involves working out how the CM platform can be used in the event of disruption.

In the **second segment**, we address the core aspect of the CM platform, the service selection problem, which is reflected in the following research question:

2. How can the SLSP as the core aspect of the CM platform be modelled?

Thus, the goal of this segment is to *formally model* the SLSP, representing a subtype of the SSP, and to embed it in the conceptual framework of the designed CM platform. The starting point of this segment is a *requirements analysis* based on the network under consideration as to what needs to be considered in the optimisation model. Building on this analysis, a *literature review* on existing SSP approaches is conducted, which forms the basis for the modelling approach.

In the **third segment**, we focus on the evaluation of the developed models and methods, guided by the following research question:

3. How do the developed models and methods perform in a real-world use case?

The objective of the last segment is to investigate the use of the developed concepts both in terms of *practice-related* results and *runtime behaviour* based on real-world data from the production network introduced. With regard to the practice-related analysis, we aim to investigate the resulting time- and cost-related KPIs when using the CM platform in cases of simulated machine breakdowns, also in comparison to approaches currently employed in practice. As for the computation time analysis, a systematic analysis of influencing parameters is conducted. The overarching goal of the last segment is to derive *recommendations for action* for the use of the CM platform.

1.2 Structure of the Thesis

As summarised in figure 1.1, the thesis is divided into 7 chapters aiming to answer the formulated research questions.

Chapter 2 introduces the framework in which the thesis is embedded. To understand the studied system, we first present the theoretical fundamentals of production networks and classify the studied production network as a guiding example. Afterwards, basic concepts on production-related disruptions, which represent our problem to be solved, are introduced. In the last subsection, we outline the theoretical foundations of cloud manufacturing, which embodies our pursued solution approach.

In **chapter 3**, we first provide a structured overview of the requirements imposed on the SSP to be solved in this thesis, which result from the framework conditions presented in chapter 2. Building on this, we conduct a literature review on existing approaches in order to identify the research gap and to classify our approach - the SLSP.

Chapter 4 presents the developed concept for the CM platform, which is built on the aforementioned requirements. The subsections provide detailed descriptions of the data model as well as of the technical architecture and the processes in which the SLSP is embedded. Furthermore, the application of the CM platform in different disruption scenarios is discussed.

In **chapter 5**, we introduce the modelling of the SLSP in different modelling variants. The basic model of the SLSP is formulated as a multi-objective mixed-integer linear program (MOMILP). Besides, a linear programming (LP) based reformulation is introduced, which entails a significant reduction in complexity.

In **chapter 6**, we evaluate the developed models and methods in two separate case studies based on real-world data provided by the Robert Bosch GmbH. In the first study, we investigate the results of using the CM platform in different cases of simulated machine breakdowns in a single-stage production process and compare them to an existing practical approach. In the second study, we examine the computational time behaviour when solving the optimisation problems given a multi-stage production process.

Chapter 7 summarises the results of the thesis and gives an outlook on further research topics.

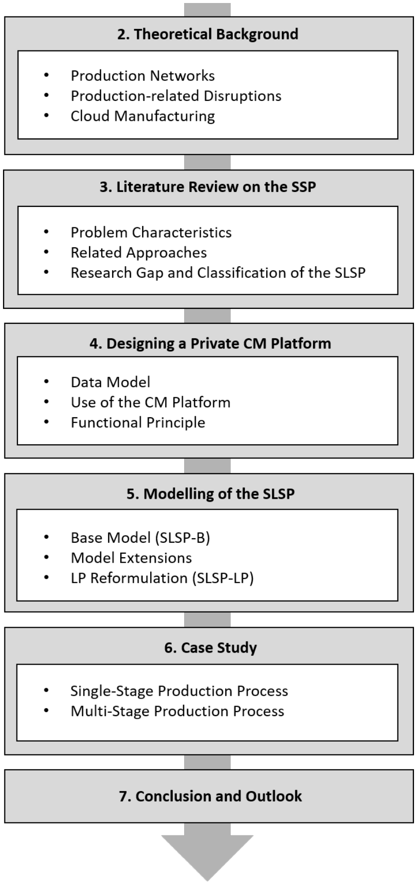

Figure 1.1: Structure of this thesis

2 Theoretical Background

Given one hour to save the world, I would spend 55 minutes defining the problem and 5 minutes finding the solution.
-A. Einstein

In the upcoming chapter, the fundamental concepts of the thesis are presented. In order to achieve a common understanding of the system and problem under consideration, we will first look at basic concepts of production networks and production-related disruptions. In chapter 2.1, several descriptive approaches used in the production network literature will be introduced with the aim of delineating and defining the system under consideration. Moreover, we will take a look at planning tasks and transport concepts in a production network in order to understand the framework of the approach of this thesis. Building on this, an overview of definitions and different types of production-related disruptions will be given in chapter 2.2. Furthermore, measures to disruptions described in the literature will be examined and classified. In section 2.3, we will finally discuss the concept of cloud manufacturing, which forms the basis of this work's proposed solution approach.

2.1 Production Networks

Nowadays, value creation processes are increasingly distributed across locations and companies (cf. Jacob and Strube 2008). Reasons for this development are, among others, the reduction of risk, closeness to the market, improved integration of individual competencies, cost advantages and agility, as stated by Eversheim, Schellberg, and Terhaag (2000). To describe those distributed activities, different terms have been established in scientific and general language use. The terms value creation network, (global) production network, logistics network or supply chain are often applied synonymously and are difficult to differentiate (cf. Schuh, Stich, and Schmidt 2008, Schönsleben 2016, Sturgeon 2001). In order to have an accurate understanding of the term and concept of production networks as used in this thesis, a characterisation of the system under consideration is made subsequently based on classification criteria used in literature (cf. subchapter 2.1.1). Building on this, we will afterwards look at different planning tasks in a production network and describe the production planning process in the studied network in order to classify the approach of this thesis (cf. subchapter 2.1.2). Due to the multi-site character of the pursued approach, we will conclude the chapter by presenting different transport concepts enabling inter-plant exchange (cf. subchapter 2.1.3).

2.1.1 Classification

In scientific literature, various, in some cases overlapping, approaches can be found to describe and classify production networks. In general, the term production network describes geographically distributed production activities (cf. Neuner 2009). With regard to the range of those activities, most authors confine themselves to the value creation process (cf. Thomas 2013). Following this limitation, development, purchasing and distribution, for example, are not taken into account within this thesis. Furthermore, we study the production network of a single product group with similar products. This consideration is corroborated by Shi (2005): The idea is that the basic structure of a production network is based on a single product or product group. Therefore, companies may have several networks, e.g. for different business units, which together form the company network.

Subsequently, different literature approaches for a more precise description and classification of production networks will be presented. The objective is to define and delimit the network considered in this thesis. The specifications are based on the characteristics of the studied production network of the Robert Bosch GmbH. Additional considerations arise from the use of the CM platform. In this respect, a distinction can be made between restrictions that are necessary for later usage in practice and modelling assumptions that have been made. Following the classification scheme of Meyr and Stadtler (2008), we will, in a first step, look at structural literature approaches. Those approaches describe the structure and the basic configuration of a production network. Based on Thomas (2013), we will focus on criteria relevant for this work, including the participant structure, the geographical structure, the role structure and the network structure. Afterwards, the operating mode of the network will be addressed in a more detailed and holistic way applying the morphological feature scheme of Schuh, Gierth, and Schiegg (2006).

Structural Approaches

Classification based on the Participant Structure: In the work of Rudberg and Olhager (2003), production networks are classified according to the participant structure. Classification criteria are the number of participating organisations and the number of participating sites per organisation (see figure 2.1). This results in four types of networks (cf. Rudberg and Olhager 2003):

- Plant
- Intra-firm network
- Supply chain
- Inter-firm network

Implications for this Thesis: As introduced in chapter 1, we look at a production network based on the production structures of an automo-

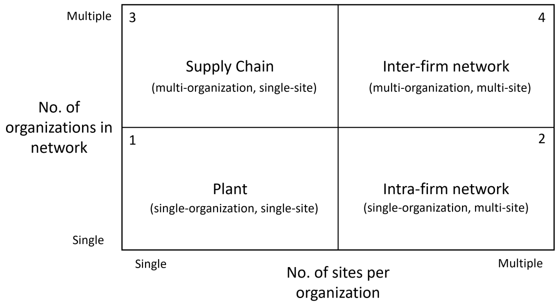

Figure 2.1: Classification of production networks based on the participant structure (Rudberg and Olhager 2003)

tive supplier company with multiple cooperating sites. In the sense of this classification, we thus refer to an **intra-firm network**.

This limitation is also grounded on considerations related to a practical usage of the CM platform. There are two reasons that play a decisive role. Since the parts to be manufactured are series products that require strict and time-consuming approvals in the automotive industry (cf. VDA Band 2 2012), it is difficult to integrate external companies into a CM platform operated in this context. If the necessary **approvals** and the accompanying qualifications are not present, production resources cannot be used and taken into account when generating an alternative ad hoc value stream in the event of a disruption. Furthermore, the issue of **data sovereignty** plays an important role (cf. Lu and X. Xu 2015). A company using the platform may want to prevent sensitive product details from getting into the hands of external companies. On the other, hand external companies may be reluctant to provide information about production details, e.g. capacities and cost rates, to a CM platform that is not operated by itself. Limiting the CM platform to internal sites thus provides more flexibilities for a deeper data and process integration than it would be in the case if external sites were added.

However, it should be noted that these findings do not exclude external companies in general. External sites, e.g. of closely connected suppliers, that meet the above-mentioned requirements in terms of approvals and data sovereignty may participate without loss of generality. This is also the case in the production network under consideration, where external sites are involved in several operations. But since the network in its entirety is operated and controlled by a single company, we stick with the term internal (or intra-firm) network.

Classification based on the Geographical Structure: Shi and Gregory (1998) classify production networks according to the geographical dispersion of the factories and the coordination mechanism applied between them. With regard to the geographical dispersion of the factories, a distinction is made between domestic, regional, multinational and worldwide networks. The coordination mechanism distinguishes between the multi-domestic and the globalized approach. The multi-domestic approach is only rarely coordinated, with more or less autonomous factories. The globalized approach is based on close cooperation between the sites. (cf. Shi and Gregory 1998)

Implications for this Thesis: The production network addressed in this thesis can be characterised as a **globalized, regional** network. That is, several factories working closely together within one region. More precisely, we refer to regions with free movement of goods that can be served by truck, in our specific use case, the EU.

The first part of the characterisation is based on the mode of operation in the considered internal production network, in which a close cooperation between the individual sites exists. Such a close cooperation is also highly advisable in terms of the practical usage of the CM platform, especially with regard to coordinated approvals and mutual data exchange. The second part of the restriction is based on a modelling assumption related to the CM platform. It aims to limit the complexity of transport planning and of further planning requirements, such as customs and legal regulations, that would arise from a worldwide exchange. This restriction is consistent with the use case under consideration. Although the regarded production network represents a worldwide network, the network structure is based on regionally cooperating clusters to which we refer.

Classification based on the Role Structure: Following up on the considerations in the previous section, plants can take on different roles in a production network based on their **responsibilities** and **vertical range of manufacture**. Schmenner (1982) distinguishes the following role types:

- Product Plants
- Market Area Plants
- Process Plants
- General Purpose Plants

Product plants and market area plants are responsible for producing a product or a product group for the world market, respectively, a specific geographical area. Process Plants are used only for specific process steps. General purpose plants can be utilised as flexible locations and are therefore particularly suitable for use in bottleneck situations. (cf. Schmenner 1982 and also Friedli and Schuh 2012)

A further possibility for classification is offered by the role model of Ferdows (1997). In this work, the locations of a production network are classified on the basis of **competence** and **strategic orientation**. The following role types are distinguished (cf. fig 2.2):

- Lead Factory
- Outpost Factory
- Offshore Factory
- Source Factory
- Contributor Factory
- Server Factor

Lead factories hold a strategic leadership role in a network. Outpost factories are used to provide access to information and knowledge. An offshore factory is intended to enable low-cost production. This is also the task of a source factory, but with more extensive competencies. Contributor and server factories produce for the local market, whereby the contributor factories provide a greater level of expertise. (cf. Ferdows 1997 and also Thomas 2013)

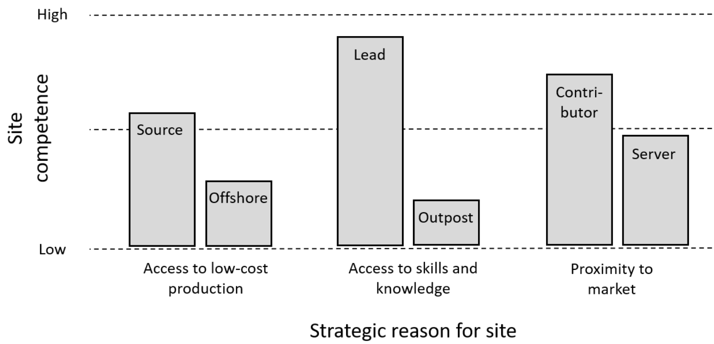

Figure 2.2: Role types in a production network (Ferdows 1997, graphic: Friedli and Schuh 2012)

Implications for this Thesis: The production network we are looking at consists of several plants within the same region that produce for both the local and global market. A lead factory assumes the strategic (global) leadership role and operates in parallel as a product and market area plant. It is supported by a source factory located in a low-wage country that can also be considered a product and market area plant. Furthermore, several process plants, able to perform single production steps, are integrated.

Classification based on the Network Structure: The following section presents several literature approaches that deal with material flow-related relationships between the locations of a production network.

Stremme (2000) differentiates on the basis of **internal material flows** between monocentric structures, in which a main site is supported by extended workbenches, island-like structures with mainly independent sites, and networked structures with multiple connections (cf. also Thomas 2013). Those patterns may occur both in their pure form as well as in combination, e.g. within a region (cf. Friedli and Schuh 2012).

T. Meyer and Jacob (2008) use the achievable **economies of scale** and the degree of **local adaptation** to categorize between world factory, hub and spoke, sequential, web structure, and local for local production.

Figure 2.3 summarises those two approaches based on an illustration of Friedli and Schuh (2012).

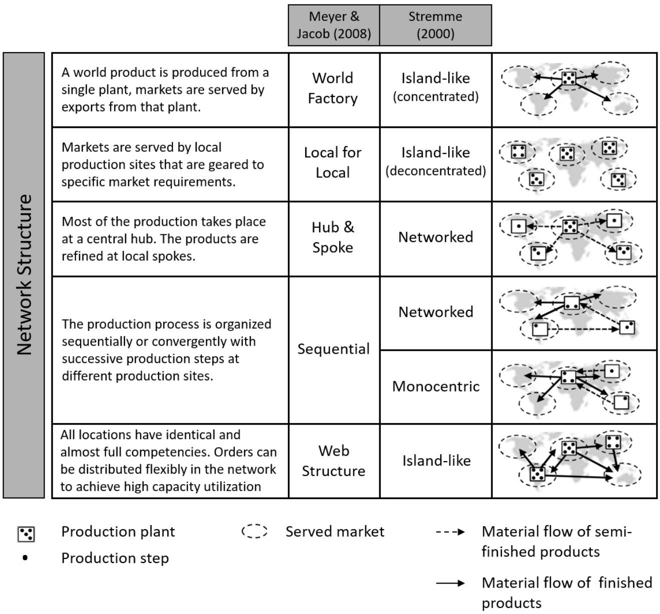

Figure 2.3: Approaches to describe the network structure of a production network (slightly adapted from Friedli and Schuh 2012)

Kaphahn and Lücke (2006) distinguish in a different approach horizontal and vertical connections between locations (see figure 2.4).

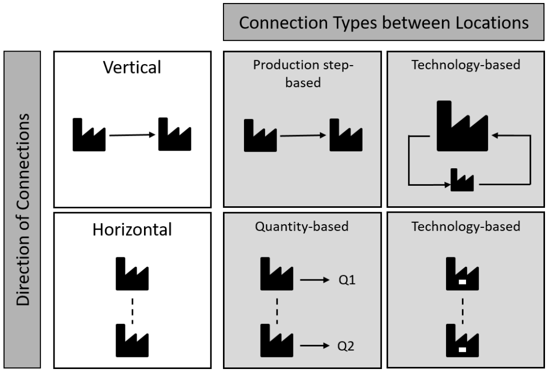

Figure 2.4: Basic operational connection types between locations (slightly adapted from Kaphahn and Lücke 2006)

Horizontal connections describe similar steps of value creation at distributed sites. Among others, the following basic horizontal connection types are described:

- Quantity-based horizontal connections
- Technology-based horizontal connections

Quantity-based connections indicate that the same products are produced at multiple plants. In technology-based connections, similar production technologies exist at different locations. In both cases, internal sourcing is possible. (cf. Kaphahn and Lücke 2006)

Vertical connections describe the allocation of successive production steps to different locations. The following connection types are distinguished:

- Production step-based vertical connections
- Technology-based vertical connections

Production step-related connections reflect an internal customer-supplier structure. In technology-based connections, a particular technology is only available at a specific plant, which means that the corresponding production steps must be outsourced to this location. (cf. Kaphahn and Lücke 2006)

Implications for this Thesis: The production network considered in this thesis is characterised by regional combinations of the approaches described above. In this way, the relationship between the lead factory and the source factory introduced in the last section can be characterised as an island-like web structure. Both plants, in the following termed as main plants, have almost identical production capabilities and are able to exchange orders due to parallel approvals. They supply both the regional market, i.e. the EU, and the world market in their double roles as local for local factories and world factories. In that regard, quantity-based and technology-based horizontal connections exist. The process plants are, in turn, integrated into the sequential monocentric structures of the two main plants in order to take over individual production steps. There are both vertical technology-based, horizontal quantity-based and horizontal technology-based connections between the main plants and the process plants. Individual steps are therefore outsourced either exclusively to the process plants or parallel to the main plants for flexible capacity control.

Summary: Figure 2.5 schematically summarises the considerations of the last sections on the structural set-up of the production network studied in this thesis: In the further course, we will restrict ourselves to an internal, regional production network of a product group with several cooperating manufacturing locations. Two main plants supply the regional and global market in their roles as lead and source factories. Several process plants contribute to individual production steps. In that regard, it is worth noting that the structure described seems to be suited for the usage of the CM platform as developed in this work due to parallel approvals of specific products at several locations of the production network. In this way, a short-term exchange of capacity and resources coordinated by a platform can be possible.

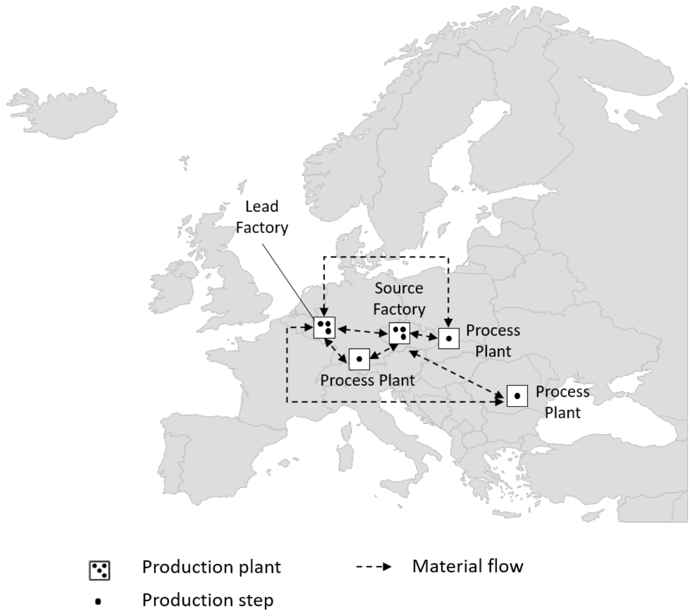

Figure 2.5: Schematic representation of the structural characteristics of the production network considered in this work

Mode of Operation

So far, we have focused on structural points coming from a macro perspective. In this section, we will take a closer look at operating principles. For a basic orientation, we will, in a first step, present a holistic classification scheme of Schuh, Gierth, and Schiegg (2006), in which ideal-typical production networks are described. Based on this, we will discuss selected aspects in more detail in order to classify the considered production network.

Schuh, Gierth, and Schiegg describe in their publication ideal-typical production networks by applying a morphological pattern. They differentiate between project network, hierarchical-stable chain, hybrid production network, development-based series network and externally determined supplier network based on product characteristics, the form of cooperation and network properties.

According to Schuh, Gierth, and Schiegg, a **project network** is intended to produce multi-part customer-specific products with complex structures based on the engineer-to-order principle in an intensively cooperating network. A typical example of this type of network is the mechanical engineering industry. **Hierarchical-stable chains** are characterised by long-term cooperation and are typically dominated by the demand side. Along with this, multi-part products with many variants are produced on the basis of production plans following the make-to-order or assemble-to-order principle. As a typical industry for this type of network, the authors name the automotive supplier sector. The **development-based series network** represents a variant of the hierarchical-stable chain. However, the products are more customer-specific and consist of fewer parts. The textile industry is mentioned as a typical example. The **externally determined supplier network** is a special variant of the project network, which produces less complex products consisting of fewer parts in a flexible network. A typical industry is the manufacturing of metal products in the context of general plant construction. **Hybrid production networks** are characterised by process manufacturing and stock production structures. Low-value standard products are produced in a long-term and program-based cooperation. The authors consider the chemistry industry as a typical example of this kind of production network. (cf. Schuh, Gierth, and Schiegg 2006)

Implications for this Thesis: As mentioned before, this thesis is based on the production network of an automotive supplier that can be classified as a hierarchical-stable chain. Figure 2.6 shows the morphological pattern of this ideal-typical network. We thus address a demand-dominated production network with constant and intensive cooperation, in which multi-part, multi-variant products are manufactured order-related on the basis of production plans. For a detailed description of all ideal-typical network types, attributes and characteristics, we recommend the publication of Schuh, Gierth, and Schiegg (2006).

	Attribute	Characteristics				
Product	Product Structure	Multi-part products with a complexe structure	Multi-part products with a simple structure	Products with few parts		
Product	Product Specificity	Products according to customer specifications	Typified products with customer-specific variants	Standard products with variants	Standard products without variants	
Product	Changed ongoing production orders due to changed customer requirements	> 25%	5- 25%	< 5%		
Product	Production Concept	Engineer-to-Order	Make-to-Order	Assemble-to-Order	Make-to-Stock	Continous/Batch Process
Product	New Product Release every	> 9 years	3 – 9 years	6 months – 3 years	1 – 6 months	< 1 month
Cooperation	Duration of cooperation	One-time order-related	Temporary recurring	Seasonal	Constant	
Cooperation	Stability of cooperation	Intensive-confident	Intensive-formal	Fragile-normal		
Cooperation	Coordination Mechanism	Personal directive	Self-coordination	Plan	Program	Market Mechanism
Network Properties	Substitut-ability	Flexible with low switching costs	Flexible with high switching costs	Limited with high switching costs		
Network Properties	Domination	Supply-side dominated	Demand-side dominated	Heterarchic		

Figure 2.6: Morphological pattern of a hierarchical-stable chain (translated from Schuh, Gierth, and Schiegg 2006)

Based on the above remarks, we will below take a more detailed look at selected product-, production- and order processing-related attributes relevant to this work. As in the previous sections, we will, in a first step, introduce basic principles and, on this basis, describe the characteristics of the production network under consideration.

Product: The purpose of a production network is to manufacture products in a distributed manner. The structure of a product is reflected by the **bill of materials** (BOM), which describes how the final product is composed of raw materials and components. Three basic forms, which can also occur in combination, are distinguished: If only the raw material is changed in several levels in its properties and appearance, it is referred to as a *serial* structure. In a *convergent* structure, several components are combined into a joint product. In a *divergent* structure, an incoming component is split into several output components. (cf. Meyr and Stadtler 2008)

Implications for this Thesis: The product group produced in the production network under consideration comprises different customer-specific variants of a standard product, which is characterised by a convergent multi-level product structure. The raw material is converted in several levels and assembled with purchased mounting components to a discrete final product. Figure 2.7 shows a schematic gozinto graph in which the nodes represent the part respectively the mounting component and the weights of the directed arcs indicate the number of source parts respectively mounting components that go into a sink part.[1]

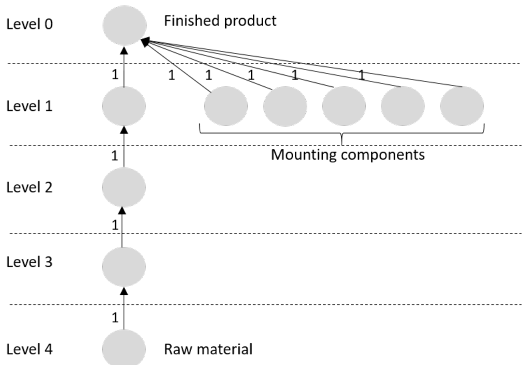

Figure 2.7: Schematic gozinto graph of the product group produced in the production network considered in this work

[1] In this regard, it should be noted that the figure only shows an abstract visualization of the product structure in order to illustrate the basic requirements for the model of this thesis. In fact, e.g. the number and types of mounting components vary for the different product variants. Also, there are some product variants that are already assembled with components in level 1.

Production: The product structure is closely related to the production process. A **production process** consists of one or more *production steps* in which changes are made to the item to be processed (cf. Seeanner 2013). A production step corresponds to a *production stage*, which represents a specific functionality offered by a machine or a manual workstation[2] (cf. Seeanner 2013). Multiple production steps are in a discrete production usually executed at multiple production stages[3] (cf. Seeanner 2013). The production process itself can be **organised** in different ways (cf. Meyr and Stadtler 2008): If all production orders pass through the production stages in the same order, the production system is referred to as a *flow shop* (cf. Meyr and Stadtler 2008). In this case, a serial production sequence is given (cf. Copil et al. 2017). In a *job shop* production, the production orders can move through the production in different sequences (cf. Meyr and Stadtler 2008). The material flow therefore might be cross-linked (cf. Copil et al. 2017). If there are multiple parallel resources at a production stage, which can be selected alternatively, a *flexible job shop*, respectively, a *flexible flow line*[4] is considered (cf. Chaudhry and Khan 2016, Quadt and Kuhn 2007). Another essential criterion with regard to the organisation of a production is the number of **repetitions of operations** (cf. Meyr and Stadtler 2008). A distinction can be made between mass production, batch production and one-of-a-kind-production (cf. Meyr and Stadtler 2008): In *mass production*, the same product type is produced permanently. In *batch production*, several identical items are combined into a batch or lot, which is processed in a continuous sequence on a resource. When switching to a new batch, a set-up operation usually becomes nec-

[2] In the following, we will generically speak of resources when referring to machines and manual workstations.

[3] It is also possible that a product undergoes a production step several times, e.g. for filtration in the process industry. In this case, we have a product that is processed in several production steps but only at a single production stage. (cf. Seeanner 2013)

[4] In the literature, several terminologies such as hybrid flow shop or flexible flow shop are used synonymously to the term flexible flow line (cf. Ribas, Leisten, and Framiñan 2010, Quadt and Kuhn 2007).

essary. In a *one-of-a-kind production*, customer-specific one-time orders are produced. (cf. Meyr and Stadtler 2008)

Implications for this Thesis: The production processes in the production network under consideration are organised as flexible flow lines. Fig. 2.8 schematically illustrates the serial production process using the example of the lead factory. The raw material is processed in several manufacturing steps, followed by a final assembly. The assembly involves combining the parts with mounting components as well as packing them into product-specific finished goods containers. All products of the product group pass through the multi-stage process in the same order in product-specific load carriers. As described in the previous chapter, individual stages are outsourced exclusively or in parallel to other sites of the production network. Furthermore, multiple parallel resources, which offer similar functionalities and which can therefore be used alternatively, are available at each stage. However, due to the required approvals, not all resources are accessible for all product types. Those parallel resources also differ in their properties, such as processing times and cost rates. Moreover, it is to be noted that the production stages are grouped together into several planning areas, each of them converting a part to a new product level. There are no substantial buffers within those planning areas. However, the planning areas are decoupled from each other by larger stocks. This structure is also referred to as a multi-level material flow (cf. Lödding 2019) and can be found among other 1-tier suppliers in the automotive industry as well, mostly due to the larger set-up times of the machining steps compared to the assembly (cf. Holweg 2003, Holweg 2005). With regard to the number of repetitions, a batch production is given. A batch of several parts is processed in a continuous sequence on a resource that must be set up for this purpose. Those batches do not proceed through the entire production process all at once, but are grouped together for each planning area separately.

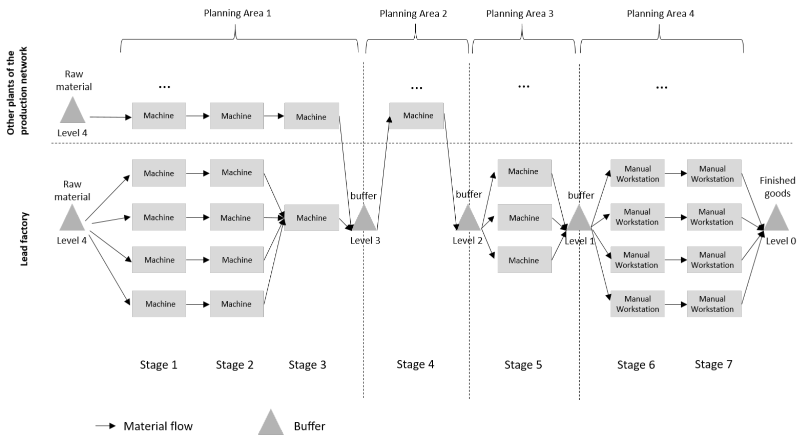

Figure 2.8: Schematic representation of the flexible flow line production in the production network considered in this work using the example of the lead factory

Order Processing: Schuh and Schmidt (2006) describe different ideal-typical order processing structures with the help of another morphological feature scheme. They differentiate between make-to-stock manufacturer, make-to-order manufacturer, variant manufacturer and call-off manufacturer. Using customer-anonymous sales forecasts, the ideal-typical *make-to-stock manufacturer* produces exclusively on stock, from which customer orders are fulfilled. The production process of a *make-to-order manufacturer* is triggered by an incoming order and carried out in an order-related one-time fashion. *Variant manufacturers* are characterised by a mixture of a customer-anonymous production process and order-related completion steps. A *call-off manufacturer* produces on the basis of orders placed within longer-term framework agreements. (cf. Schuh and Schmidt 2006)

Call-off manufacturers can especially be found in the automotive supplier industry (cf. Schuh and Schmidt 2006). In the following, we will therefore take a closer look at the order processing structures of this type.

Characteristic is the long-term cooperation based on framework agreements. A framework agreement defines a total quantity to be ordered and delivered in subsets over a longer period of time. The call-off mechanism is based on the principle of rolling planning and transmits long-term, medium-term and short-term order information in regular cycles. In doing so, the closer the planning period to production start, the more detailed and accurate the order information becomes. (cf. Schuh and Schmidt 2006)

Figure 2.9 shows the call-off mechanism of the German automotive industry. In a *delivery call-off* (VDA 4905), the supplier receives the planned quantities for the next 6-18 months in a weekly cycle. Typically, the upcoming eight weeks are shown on a daily basis. Periods beyond this are aggregated on a weekly or monthly basis. Suppliers with a closer logistical connection additionally receive in a weekly to daily cycle a *detailed call-off* (VDA 4915), which defines the quantities for the next 15 days on a daily scale. Beyond that, just-in-sequence suppliers get a *production-synchronous call-off* (VDA 4916) with exact quantities, dates and sequence information sent out several times a day. (cf. Klug 2010)

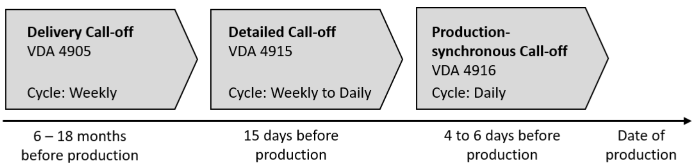

Figure 2.9: Call-off mechanism in the German automotive industry (slightly adapted from Kunert (2018))

The actual order quantities are thus called-off from logistically closely connected suppliers at such short notice that production planning at the supplier side is usually based on order-related previews (cf. Schuh and Schmidt 2006). This kind of a preview-based production is counted in the literature among the *build-to-order* strategies (cf. Braun 2012). Since these previews and also the production processes themselves are subject to uncertainties, the OEM is typically supplied from an additional stock to ensure the ability to deliver (cf. Holweg 2003, Holweg 2005).

Implications for this Thesis: Those considerations also apply to the automotive supplier under consideration, who delivers to several OEMs as a call-off manufacturer within the framework of a hierarchical-stable chain. The company receives its order information through delivery call-offs and short-term detailed call-offs and fulfils them from additional buffer inventory. Production planning is thereby carried out according to the *push* principle, i.e. by scheduling orders on the basis of demand previews (cf. Hopp and Spearman 2011). In that regard, the concept of *manufacturing resource planning* (MRP II) is applied. Based on this approach, production orders are distributed and scheduled within the production network, and second-tier suppliers[5] are assigned. To get a more detailed overview of the planning framework in which the approach of this thesis is integrated, we will take a closer look at the MRP II procedure applied at the regarded automotive supplier company in the next chapter.

Summary: In terms of operating principles, the production network under consideration in combination with its customers and suppliers can be described as a hierarchical-stable chain. This network type is characterised by long-term cooperation and a dominating customer, i.e. OEM side. The regarded production network manufactures a homogeneous product with customer-specific variants for different OEMs. The parts are processed in batches in a serial multi-stage production process, organised as a flexible flow line. The production steps are grouped into different planning areas, which are decoupled from each other by buffers. In the last planning area, the assembly takes place and purchased mounting components are added to the product. The order processing within the regarded production network follows the processing

[5] From the perspective of an OEM

structures of an ideal-typical call-off manufacturer, who produces on the basis of delivery previews within framework agreements. The quantities to be delivered are submitted to the automotive supplier in a multi-level rolling horizon based call-off system. The allocation and scheduling of orders in the production network and the assignment of suppliers are carried out according to the MRP II approach. Due to the short-term final call-offs in combination with existing process uncertainties, additional inventory buffers are kept, from which the OEMs are supplied.

2.1.2 Planning Tasks

After having discussed several concepts on structures and operating principles of production networks with the aim of classifying the network considered in this thesis in the last sections, we will take a closer look at the planning tasks in a production network in the upcoming chapter. For this purpose, we will first give an overview of different planning tasks referring to a frequently used planning matrix. Afterwards, we will describe the specific production planning process of the considered network, the MRP II process, which constitutes the planning framework for the approach of this thesis. In the last subchapter, and building on this planning framework, we will classify the approach of this thesis into the introduced planning matrix.

Planning Matrix

Since planning tasks in a production network not only affect the production process itself but also include upstream procurement and downstream customers, we will speak of supply chain planning in the following. The job of planning is to support decision-making by identifying and selecting suitable alternatives for taking action (cf. Fleischmann, Meyr, and Wagner 2008). Planning tasks in a supply chain can be classified according to the dimensions **planning horizon** and **type of process**, as stated by Fleischmann, Meyr, and Wagner (2008), on which the following explanations are based. With regard to the **plan-**

ning horizon, long-term, medium-term and short-term tasks can be distinguished. *Long-term planning* comprises strategic decisions which typically deal with the design and structure of the network. The effects are long-term. *Mid-term planning* covers a planning horizon of 6-24 months and is used for a rough planning of regular operations. *Short-term planning* refers to the detailed scheduling of activities and encompasses a planning horizon of a few days to 3 months. With regard to the **type of process**, a distinction between procurement, production, distribution and sales can be made. *Procurement* includes all tasks related to the provision of resources required for production, such as materials and personnel. The available resources are used as input for the *production* process. The *distribution* is responsible for bringing the produced goods to the customer. The entire process described is triggered by the customer demand determined by *sales*. (cf. Fleischmann, Meyr, and Wagner 2008)

Fleischmann, Meyr, and Wagner represent the outlined remarks in a **planning matrix**, which depicts typical planning tasks in a supply chain (cf. figure 2.10):

The long-term planning tasks affect all processes and are therefore usually addressed in a comprehensive manner. The decisions to be made include the definition of the product program, i.e. which markets are to be served with which products, based on long-term sales forecasts. Depending on the defined product program, materials and suppliers - if helpful within a strategic cooperation - must be selected for the most important components. In addition, decisions have to be made with regard to locations, capacities and production systems of the plants. The distribution structure, e.g. the number and locations of warehouses, depends on these decisions and is therefore often planned together with the plants. (cf. Fleischmann, Meyr, and Wagner 2008)

The starting point for the mid-term planning is the mid-term sales forecast. This forecast is calculated, for example, on a weekly basis for a period of one year or less. The resulting sales plan is compared to the available capacity and translated into a *master production schedule*

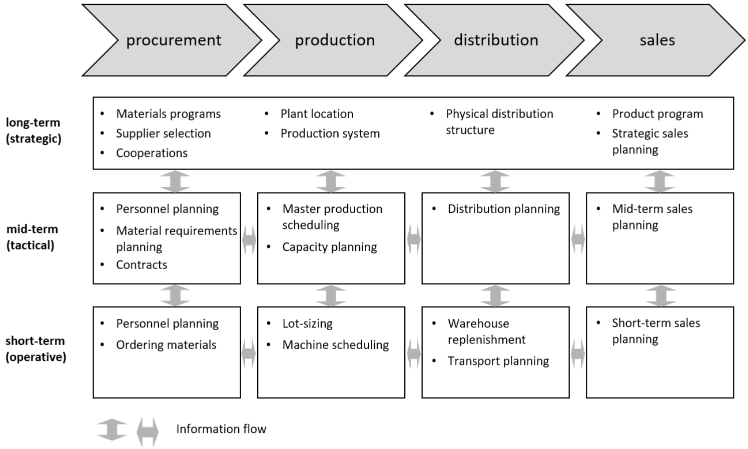

Figure 2.10: Planning matrix of a supply chain (slightly adapted from Fleischmann, Meyr, and Wagner (2008))

(MPS). The MPS specifies the end product quantities to be produced, e.g. in weekly time buckets. Based on the MPS, the required materials and semi-finished products are planned with regard to the BOM. This is done, for example, by applying *material requirements planning* (MRP) or stochastic inventory policies. Suppliers must be assigned accordingly. Furthermore, the personnel capacities for the production steps conducted in-house need to be considered. A possible decision to be taken in this respect is whether additional part-time staff is needed. In addition, transport quantities are determined within the distribution planning. This is accompanied by the planning of warehouse stocks and the question of whether third-party carriers need to be assigned. (cf. Fleischmann, Meyr, and Wagner 2008)

Within short-term planning, sales planning has the task of examining whether and when customer orders can be fulfilled from stock (*available-to-promise* (ATP)) or from the production process (*capable-to-promise* (CTP)). Building on this, short-term production planning determines the lot sizes and schedules them on the production lines. Depending on the resulting short-term production plan, personnel is allocated, and the required materials are called up from the suppliers. Furthermore, distribution planning creates a detailed transport plan for supplying the warehouses and customers. (cf. Fleischmann, Meyr, and Wagner 2008)

As shown in the above explanations, there are strong vertical and horizontal dependencies between the planning tasks (cf. Fleischmann, Meyr, and Wagner 2008). Due to its complexity, however, **simultaneous planning** of the entire supply chain is mostly unrealistic (cf. Stadtler 2008, Vogel 2014). A further approach is therefore referred to as **hierarchical planning** originally proposed by Hax and Meal (1973), which involves breaking down the overall problem into smaller sub-problems that are interconnected via coordination mechanisms (cf. Stadtler 2008). In doing so, the higher planning level provides the frame for the vertically lower level (cf. Stadtler 2008). Through anticipation, the higher level estimates the behaviour of the lower level, which in turn sends back feedback (cf. Schneeweiß 1994, Stadtler 2008). Following this logic, the hierarchical planning approach forms the basis of modern *advanced planning systems* (APS) (cf. Fleischmann, Meyr, and Wagner 2008). The planning structure described in the planning matrix is represented in such a system through different modules in which individual or several planning tasks are combined (cf. Fleischmann, Meyr, and Wagner 2008). APS modules thereby may supplement ERP systems and solve specific optimisation tasks (cf. Fleischmann, Meyr, and Wagner 2008). A special case of hierarchical planning is **successive planning**, which transfers planning tasks from an upstream to a downstream planning level without anticipation (cf. Schneeweiß 1994). An example for this kind of planning is the MRP approach frequently used in practice [6] (cf. Fleischmann, Meyr, and Wagner 2008).

Irrespective of the planning method, the extent of detail typically decreases the longer the planning horizon (cf. Fleischmann, Meyr, and Wagner 2008). For example, products are aggregated to product groups,

[6] With regard to the points of criticism related to successive planning we refer to Drexl et al. (1993) and Hopp and Spearman (2011)

resources to capacity groups, and time periods to longer-term time spans, the higher the planning level (cf. Fleischmann, Meyr, and Wagner 2008). Along with this, a *rolling horizon* based approach is often chosen due to the uncertainty associated with planning - especially for more distant time frames (cf. Fleischmann, Meyr, and Wagner 2008). In this respect, the planning horizon is divided into periods, which are replanned in regular cycles and updated by one period each (cf. Fleischmann, Meyr, and Wagner 2008). Accompanying, the frequency of planning increases the shorter the planning horizon (cf. Vogel 2014). Alternatively, *event-based planning* is conducted, which is triggered by specific events, such as major changes in customer demand (cf. Fleischmann, Meyr, and Wagner 2008).

Manufacturing Resource Planning

Current standard production planning systems are mostly built on the logic of MRP II (cf. Stadtler 2008). Also in the production network under consideration, production planning is carried out by means of this planning logic.

MRP II has evolved from the successive MRP approach introduced by Orlicky in the 1960s, which is used to plan the required materials coming from internal production and external suppliers (cf. Hopp and Spearman 2011). One of the aims of the ongoing development from MRP to MRP II starting in the 1970s was to include capacities in the planning process that were not considered in MRP (cf. Hopp and Spearman 2011).

In the literature, various approaches describing MRP II can be found (cf. Hopp and Spearman 2011). In the subsequent section, we will present a basic successive four-step model. The explanations are based on Stadtler (2008) and Hopp and Spearman (2011), to whom we refer for a more comprehensive overview.

1. **Master Production Scheduling**:

   On the basis of existing orders and sales forecasts, this step aims to determine the production quantities on a finished product level for each period within the planning horizon. In doing so, the primary requirements are calculated and scheduled in order to create the MPS. To support this, some systems offer rough capacity planning, which employs product-specific capacity profiles to estimate the rough capacity requirements that can be compared to the available capacity of a bottleneck resource. However, this is rarely done in practice, so that the MPS often corresponds to the sales program.

2. **Material Requirements Planning**:

   Using the MPS in combination with available stocks and scheduled receipts, dependent requirements (raw materials, components and semi-finished products) are planned. For this purpose, the BOM is exploded iteratively in order to create and (roughly) schedule in-house production orders and purchase orders on the basis of predefined lead times and simple lot-sizing heuristics.

3. **Capacity Requirements Planning**:

   In this step, the individual production steps belonging to a production order are scheduled. The start and end dates determined by MRP define the planning framework. The scheduling process can be based on forward or backward scheduling and is initially carried out without taking into account any capacities. After completing lead time scheduling, the capacity requirements are compared with the available capacities for the resources affected. In the event of a capacity bottleneck, a possible reaction could be to add additional shifts. In practice, however, these capacity levelings are often carried out manually.

4. **Short-Term Control**:

   Short-term control represents the last step of the MRP II process. The period under consideration is kept short and covers the next

1-2 weeks. The purpose of this step is to transmit the production orders to the shop floor. To do so, the availability of the required materials is first checked. If this is ensured, a production order is released. The status changes from planned to scheduled. In the subsequent dispatching step, the sequence of the released orders at the work stations is determined. The progress of work is finally monitored by shop floor control.

Implications for this Thesis: In the production network considered in this work, the MRP II process is carried out separately at each of the main plants producing the finished product. The delivery call-offs of the customers serve as input from sales side. In the course of a monthly reconciliation procedure coordinated by the lead factory, it is tried to achieve a balanced capacity utlilisation between the plants of the network. For this purpose, a manual levelling of volumes at the finished product level and at the bottleneck stage (planning area 1) is undertaken. The volume exchange is carried out on the basis of the MPS, which is updated in a rolling manner. The planning horizon of the MPS covers several months, whereby the level of detail decreases from daily to weekly to monthly, the more distant the start of production.

With regard to the MRP step, event-triggered runs are carried out iteratively for the individual levels of the BOM. Also suppliers of raw materials and of mounting components are contracted through backward-scheduled MRP runs within the framework of a call-off system.

In the short-term planning and scheduling, the concept of levelling is utilised. In doing so, production orders are smoothed at the assembly line, being the pacemaker process to compensate for fluctuations in demand. The levelled production plan forms the basis for the subsequent MRP runs and is recorded in a levelling board. The aim of levelling is to reduce the variability in the preceding production steps by leveraging order and inventory buffers. In our specific case, we are dealing with a so-called push-levelling principle, which, in contrast to pull-levelling (heijunka levelling), does not involve a closed kanban circuit with a defined overflow. For a more detailed introduction to the concept of levelling, we refer, for example, to Veit 2010.

The levelling performance is measured at the Robert Bosch GmbH by the ratio of the number of lots correctly executed in terms of sequence and quantity and the number of all planned lots in a fixed levelling period. The objective is thus to have as few reschedulings as possible in the short term horizon, which goes hand in hand with the concept of this work.

Figure 2.11 schematically shows the interaction of MRP planning and levelling using the example of the lead factory. As shown in the value stream, a further levelling of the MRP data is carried out in planning area 1 due to significantly deviating set-up times. Within the planning areas, the parts are pushed to the subsequent steps according to the FIFO principle.

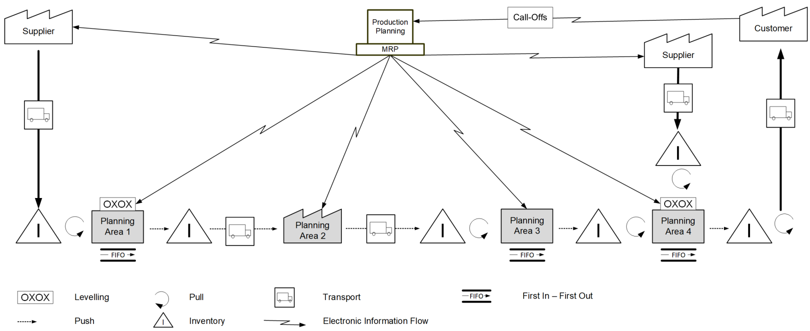

Figure 2.11: Schematic representation of the value stream of the lead factory

Classification of the Approach of this Thesis

After having described the planning framework, we classify the approach of the present work into the introduced planning matrix (cf. figure 2.12). The CM concept of this thesis represents an event-driven bottom-up approach. This means that a replanning process is triggered by production-related disruptions detected during execution, i.e. at the short-term control level. The idea is to respond to such a disruption within the short-term planning. By using the CM platform at this level, a targeted cross-plant rescheduling of *affected production orders* shall be made possible. In this way, we can help to avoid a complete rescheduling of an existing - often frozen - short-term production plan, aiming to minimise the planning nervousness.

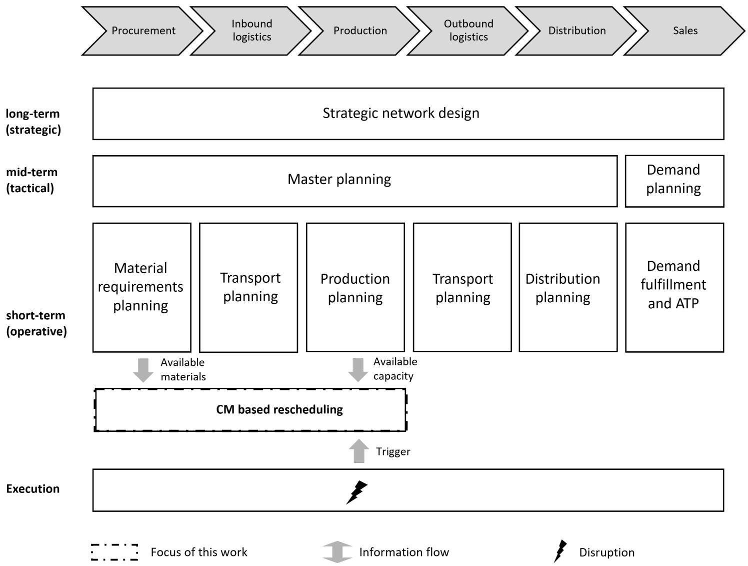

Figure 2.12: Classification of the approach of this thesis into the planning structure of a supply chain. The illustration is based on Fleischmann, Meyr, and Wagner (2008), supplemented by two additional columns for inbound and outbound transport planning. The planning tasks described in the supply chain planning matrix are summarised in this figure in modules that typically represent the basic structure of an APS (cf. Fleischmann, Meyr, and Wagner 2008).

The approach of this thesis is integrated into the hierarchical planning structure. The higher-level planning, which includes the long-term planning of locations, mid-term master production scheduling and material requirements planning, as well as short-term lot-sizing and machine scheduling, has consequently already been carried out and forms a given framework. The pursued approach aims to facilitate the short-term exchange of capacities across locations by applying the concept of CM. By using the available capacities in the existing production plans throughout the production network, a production order affected by a disruption shall be rescheduled to available resources. The main task of the CM platform thus consists of assigning the affected production order to the available resources with regard to quantity and time. Since these distributed activities create transport and material requirements, we simultaneously integrate the short-term transport planning and material planning into the decision-making. As such, it must be ensured that the required materials are on hand at the selected workstations at the right time. We therefore need to consider the available stocks throughout the network when creating a plan, which may first have to be transferred to the corresponding plant prior to start the processing. With regard to transport planning, we note that only inbound transport steps between plants are considered. Possible transport steps to be planned include the shipping of required materials (raw materials, mounting components and finished good containers), of semi-finished products between subsequent production steps, and of finished products to the ordering plant. A subsequent outbound distribution to the end customer is not taken into account. In order to gain a common understanding of different possibilities for carrying out those transport steps, we will present fundamental transport concepts in the succeeding chapter.

To sum up, the approach of this thesis integrates on a short-term level transport, production and material planning with the aim of rescheduling a production order affected by a disruption by using existing resources and capacities in the network. Along with this, a cross-location planning at the operative level becomes possible, breaking down the planning silos that usually exist in a production network, especially at the near-term planning horizon (cf. fig. 2.13).

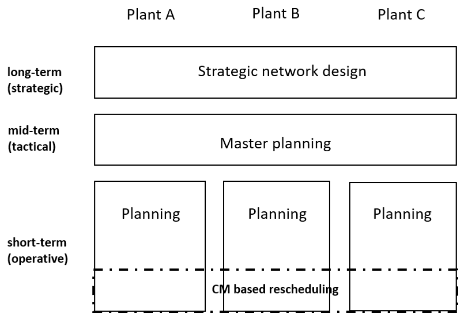

Figure 2.13: Classification of the approach of this thesis into the planning structure of a production network

2.1.3 Transport Concepts

As mentioned in the previous chapter, the cross-site planning approach of this work involves transport steps. We will therefore give an overview of inter-plant transport concepts in the following section. In line with the limitation to a regional production network and based on the transport concepts applied in the production network under consideration, we will focus on road transport. In this context, transport steps are carried out by motor vehicles, e.g. transporters, light trucks or articulated trucks (cf. Cardeneo 2008). We will first look at the logistics service providers (LSPs) conducting a transport step, subsequently describe the most relevant forms of transportation and finally transfer the findings to the approach of this thesis.

Logistics Service Provider

A basic distinction can be made between whether a company owns its own fleet and carries out transport steps by itself or if an external logistics provider is contracted in order to handle those tasks. Below, we will refer to the commissioning of external LSPs, which corresponds to the general trend in freight forwarding in Europe (cf. Krajewska 2008). In this respect, an LSP undertakes a logistics activity for another company (cf. C. Geiger 2013). The following types of LSPs are distinguished in the transport sector (cf. C. Geiger 2013):

- **Carrier**: Carriers are transport companies that are specialised in the pure transport of goods with usually company-owned transport vehicles (cf. C. Geiger 2013).
- **Freight Forwarder**: It is the task of a freight forwarder to organise the transport. The freight forwarder thus assumes the planning and controlling position and acts as an intermediary between customers and carriers. Alternatively to commissioning an external transport company, the freight forwarder may also operate as a carrier by himself and provides transportation services using his own vehicles. (cf. C. Geiger 2013)

  In the transportation market typically shaped by medium-sized companies, it is rarely possible for the individual freight forwarders and carriers to achieve area coverage with their own vehicle fleet. Therefore, cooperations and subcontractor structures are often found. (cf. Gleissner and Femerling 2008)
- If individual or several logistical tasks are completely taken over by an LSP within a long-term cooperation between LSP and customer, one speaks of a **Third Party Logistics Provider (3PL)**. The range of tasks can include both transport and warehousing, right up to the complete takeover of a logistical chain. If an LSP designs, builds and optimises a logistical chain of a customer and operates it without its own resources, the term **Fourth Party Logistics Provider (4PL)** is used. (cf. Gleissner and Femerling 2008, C. Geiger 2013)

Forms of Transportation

The first criterion for differentiating between different forms of transportation refers to the loading of the transport vehicle. If a single shipment is filling up a whole truck, we speak of a *full truck load* (FTL) shipment. Otherwise, if a single shipment does not fill up a truck, we speak of *less than truck load* (LTL) shipments. (cf. Kunert 2018)

The German Association of the Automotive Industry (VDA) describes three standard transportation forms (cf. VDA 5010 2008). In the case of a *direct transport*, a single FTL shipment is brought from a starting point to a destination as a direct point-to-point transport without any transshipment. The second form is the *groupage service*, in which LTL transports are carried out within a geographically limited area by an area freight forwarder. Characteristic is the consolidation of shipments collected via preliminary legs in consolidation centres (e.g. cross-docks) and the subsequent distribution via main legs and optional subsequent legs. The last standard transportation form described by VDA are *milk runs*. With these, LTL shipments of several supplying plants are collected on pre-defined transport routes with fixed volumes and then brought to the receiving plant with or without transshipment. Specialised transports and courier, express and parcel services (CEP) are not included in the VDA guidelines. (cf. VDA 5010 2008, Kunert 2018)

Building on the standard transportation forms of the VDA, A. Meyer (2015) presents in her dissertation a detailed classification scheme for the characterisation of physical transports under the consideration of the planning aspect. Since the classification scheme of A. Meyer refers to inbound transports from suppliers to a consignee, we have slightly reworded it in order to reflect the inter-plant traffic considered in this work as well. Furthermore, we have included stopovers and the transport load as further classification criteria in order to describe the routing characteristics and to be able to distinguish between FTL and LTL shipments. Therewith, the following classification criteria are applied (cf. A. Meyer 2015):

1. **Planning Horizon**: Is a transport planned *ad hoc* or do we have a *regular* transport?
2. **Tour Planning**: Does the *company ordering the transport* itself take over the planning of a specific tour or is this done by the *freight forwarder*?

3. **Consolidation**: Is a transport exclusively *dedicated* to the shipments of the ordering company or is it possible for the freight forwarder to form *mixed tours* with third party shipments?
4. **Transshipment**: Is a transport carried out with transshipments (*indirect*) or without transshipments (*direct*)?
5. **Routing**: Are there any *stopovers* during a transport (i.e. to pick up or drop off load or to tranship) or do we have a *non-stop* transport?
6. **Load**: Does a transport comprise *full truck load* (FTL) or *less than truck load* (LTL) shipments?

In a first stage, A. Meyer (2015) distinguishes between ad hoc and regular transport forms. Since the approach of this work is embedded in a disruption-related ad hoc context, we will take a closer look at those kinds of transports (cf. figure 2.14). By combining the introduced classification criteria, the following ad hoc transport forms can be identified (cf. A. Meyer 2015):

1. **Dedicated direct non-stop transport**: The ordering company plans a dedicated direct non-stop transport of a single shipment and assigns a freight forwarder for carrying out. The shipment either fills a truck completely (FTL) or not completely (LTL).
2. **Dedicated direct stopover tour**: The ordering company plans a dedicated direct tour with stopovers in order to carry several LTL shipments and assigns a freight forwarder for executing.
3. **Dedicated pre-, main- and sub-leg tour**: The ordering company plans a dedicated tour with pre-, main- and an optional sub-leg in order to carry several LTL shipments and assigns a freight forwarder to execute the transport steps and to transship the load in consolidation centres.
4. **Direct stopover tour with third party shipments**: The ordering company plans a direct tour for several LTL shipments and assigns a freight forwarder for carrying out. The freight forwarder is allowed to add or consolidate with shipments from third parties.

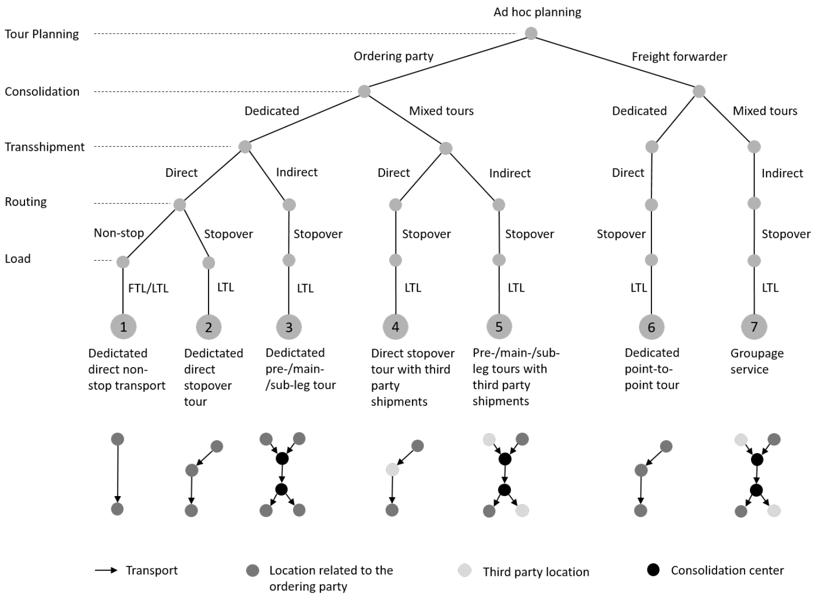

Figure 2.14: Ad hoc transport forms (adapted from A. Meyer (2015))

5. **Pre-, main- and sub-leg tour with third party shipments**: The ordering company plans a tour with pre-, main- and an optional sub-leg for several LTL shipments and assigns a freight forwarder to carry out the tour and to tranship the load in consolidation centres. The freight forwarder is allowed to add or consolidate with shipments from third parties.
6. **Dedicated point-to-point tour**: The ordering company schedules several LTL point-to-point transports from sender to receiver, taking into account - as much as possible - the vehicle capacity and assigns a freight forwarder for planning and executing a dedicated direct stopover tour.
7. **Groupage service**: The freight forwarder plans a tour including third party shipments and carries out the transport steps using its consolidation centres.

For a detailed overview of regular transport forms such as milk runs, we refer to A. Meyer (2015).

Tariff Systems

When planning a transport step, we need to consider the resulting transport costs. For this purpose, A. Meyer (2015) describes three common tariff systems from the perspective of an ordering company (cf. figure 2.15).

In case (a), payment is made on a tour basis, whereby the transport costs increase with the distance or duration of the tour, typically depending on the vehicle size and subject to a minimum cost rate. This form of billing is typical for direct tours. In case (b), costs are calculated on a vehicle basis. Regardless of the activity, a vehicle is paid for a whole period, e.g. one day. This kind of cost structure can be found, for example, among freight forwarders and their subcontractors. In the case of order based payments (c), costs are usually determined on the basis of tariff tables, taking into account the weight or volume and the distance of an order. The costs typically follow a degressive, piecewise linear pattern. This form of cost calculation is common for groupage services. (cf. A. Meyer 2015)

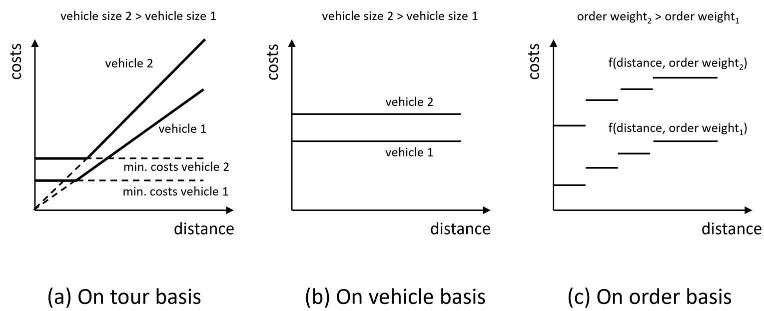

Figure 2.15: Different tariff systems for transport services (slightly adapted from A. Meyer (2015))

Inclusion into the Approach of this Thesis

Below, we will transfer the previously described transport concepts to the approach of this thesis.

As described in the preceding chapter, this work's planning approach involves ad hoc transport steps between the locations of a production network. With regard to the transport form of those transport steps, we will consider, on the one hand, *direct non-stop tours*, i.e. dedicated ad hoc transports that are carried out for FTL or LTL shipments by direct means and by exclusive assignment of a vehicle (transport form 1). Compared to the other above-mentioned transport forms, a dedicated direct non-stop tour offers the advantage of a fast, controllable, reliable and flexible plannable transport combined with a high process and cost transparency, which seems to be suited for time-sensitive disruptions (cf. A. Meyer 2015). In addition, the planning effort is lower compared to other approaches under which the transport ordering company takes over the transport planning by itself. However, it has to be taken into account that the ordering company - in our specific case, the CM platform - bears the risk of insufficient capacity utilisation if LTL shipments are to be transported (cf. A. Meyer 2015). It is therefore of relevance to plan the necessary transports efficiently, i.e. with a high capacity utilisation considering different available vehicle classes - from small transporters to standard articulated trucks.

Furthermore, we will look at the *groupage service* (transport form 7). With this form of transport, the freight forwarder plans and executes a consolidated tour with pre-, main- and sub-legs. The main advantage of this transport form is that the freight forwarders can achieve a high utilisation rate, enabling them to offer a more cost-effective transport to the ordering company (cf. Beilhammer 2017). This is accompanied by the fact that the risk of inefficient tours is outsourced to the freight forwarder (cf. A. Meyer 2015). For the CM platform, this type of transport is therefore easy to plan and suitable for all shipment sizes (cf. A. Meyer 2015). However, longer transport times are required due to longer distances and necessary transshipment steps (cf. Beilhammer 2017). In addition, the ordering company has less process control and also bears a higher process risk due to the involvement of third party shipments (cf. A. Meyer 2015). Groupage services thus seem to be suited for less time-sensitive disruptions, where a more cost-effective transport is desired.

Following that, the transport planning task to be performed within the present work includes to plan the necessary transport steps in terms of *quantity*, *time* and *transport form*. With regard to the transport form, it must be decided whether and with which vehicle type the rather fast but more expensive direct non-stop transport should be chosen, taking into account the capacity and characteristics of different vehicle classes. Or alternatively, whether the slower but more cost-effective groupage service should be selected.

2.2 Production-related Disruptions

Having taken a closer look at the studied system and the related planning tasks and transport concepts in the last chapter, the following sections will address the problem of production-related disruptions occurring in it.

Disruptions can arise within a production network at various points: Machines break down, interruptions in transport, suppliers deliver too late, to name just a few examples. One of the reasons for the lack of resilience to disruptions is the streamlining of production systems resulting in fewer possibilities to decouple through capacity, time and quantity buffers. Especially in production networks with closely interlinked processes, there is a high vulnerability to disruptions. In particular, the automotive industry provides a suitable example for such a sensitive system due to the high degree of shared work and high requirements on the timing of processes. (cf. Fischäder 2007)

In the following chapters, theoretical concepts of production-related disruptions will be addressed. In the first subchapter, we will look at relevant definitions. Based on this, we will afterwards discuss how different types of disruptions can be distinguished. In the last section, different measures to handle disruptions will be outlined.

2.2.1 Definitions on Disruptions

Despite the long tradition of scientific investigation of production-related disruptions, it is difficult to find a uniform terminological base, as this heavily depends on the object of investigation (cf. Fischäder 2007, Kim, Y.-S. Chen, and Linderman 2015). In general, disruptions represent unforeseen deviations from an original plan (cf. Yang, Qi, and G. Yu 2005). A characteristic element is the uncertainty and randomness of events, which leads to unanticipated effects on the production environment (cf. Fischäder 2007). Furthermore, disruptions are limited in time (cf. Xia et al. 2004).

Fischäder (2007) provides a system theoretical definition seeing disruptions as "temporary influences on the intra- and inter-plant based value creation caused by the occurrence of a disturbance variable." According to the author, those influences can be related to the resource side, the production process, and the production program. For a more detailed specification, Fischäder introduces the following characteristics:

- Disruptions describe a multi-stage **cause-and-effect relationship**. The causal dimension refers to the stochastic influence of a disturbance variable on the value creation, which leads to process- or result-related deviations: A disturbance variable (e.g. a machine failure) affects the controlled system (e.g. a production system). The resulting disturbance effect represents the deviation of a controlled variable (e.g. a delay of a production start). (cf. Fischäder 2007)

- A **disturbance variable** influences the system over a limited period of time.[7] This period must be distinguished from the duration of the **disturbance effect**. The disturbance effect is also limited in time, with the time span depending on the characteristics of the production system and the measures taken. It is therefore possible that there is no disturbance effect at all despite an existing disturbance variable. (cf. Fischäder 2007)

Based on the above-mentioned, a disruption can be divided into different phases (cf. fig. 2.16). Fischäder defines the period from the appearance of the disturbance to the occurrence of the disturbance effect as the **latent phase**. During this phase, the disruption does not yet show an effect, e.g. due to buffering. The subsequent phase from the beginning to the end of the disturbance effect is called the **manifest phase**, in which appropriate measures are planned and implemented (cf. Fischäder 2007). This time period can be divided into the reporting and diagnosis phase and the subsequent recovery phase (cf. Fischäder 2007, Sheffi and Rice 2005 and Cauvin, Ferrarini, and Tranvouez 2009). Specifying this, Ivanov (2019) proposes a further detailing by distinguishing within the recovery phase between the period in which the disturbance is still present and the subsequent post-disruption phase. During the post-disruption phase, Ivanov calls this phase the revival phase, the system operates properly again and reduces possible shortages that may have arisen.[8]

Furthermore, it should be noted that disruptions may propagate within a production system and also across a production network. As such, disruptions can spread both in and against the direction of the material flow (cf. Fischäder 2007). If, for example, a resource breaks down, the succeeding stations will most likely also have to stop their production processes after a certain delay due to a lack of materials. Similarly, the

[7] This includes a discrete event as well, as it is assumed in the definition of Sheffi and Rice (2005), for example.

[8] In the supply chain risk management literature, the ability of a supply chain to return to its original state or to an even improved state is also referred to as *resilience* (cf. Heckmann, Comes, and Nickel 2015).

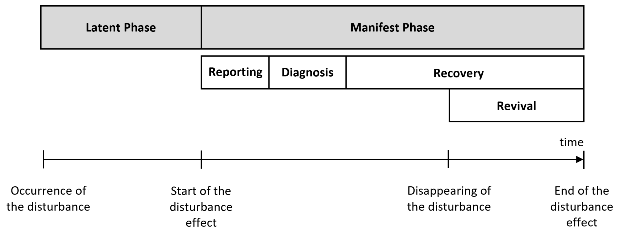

Figure 2.16: Phases of a disruption (based on Fischäder 2007 and Ivanov 2019)

stocks of the previous stations may pile up since there are no call-offs. Those propagation phenomena are subsumed by Ivanov, Sokolov, and Dolgui (2014) as **ripple effect**.

2.2.2 Types of Disruptions

There are different approaches in the literature to classify disruptions. For example, Ivanov, Dolgui, et al. (2017) distinguish within supply chain disruptions between production disruptions, transport disruptions and supply disruptions. Following Paul, R. Sarker, and Essam (2015), we will restrict ourselves to disruptions that affect the production environment, which does not exclude the possibility that those kinds of disruptions were originally caused by transport, supply or demand (cf. C. S. Tang 2006, Cauvin, Ferrarini, and Tranvouez 2009).

Building on the work of Fischäder (2007), we classify the different types of production-related disruptions in this thesis by means of the *cause dimension* based on the impact point of the disturbance variable (cf. fig. 2.17). In the first level, internally and externally induced causes of disruptions can be distinguished (cf. Cauvin, Ferrarini, and Tranvouez 2009 and Fischäder 2007). In the case of internal causes, the problem lies in the system itself; in the case of external causes, the disruption is induced from outside. As mentioned in the previous section, disturbance variables can affect in a more detailed view both the resource side, the production process and the production program (cf.

Fischäder 2007). In the first case, the elementary **resources** - manufacturing equipment, materials and/or human labour (cf. Gutenberg 1951) - are not available as planned. An example of such a disruption is the internally induced breakdown of a machine. An example of an externally induced disruption of this category is a delayed delivery of components from a supplier. However, it should be noted that the examples mentioned do not represent the primary causes, which could, for instance, be a traffic jam, but a more aggregated level in the cause-effect chain. Looking at the **production process**, typical examples of disruptions are quality failures and slower processing times. Disruptions related to the **production program** are caused by changes in the orders to be produced. An example of this category is a short-term quantity increase in a sales order.

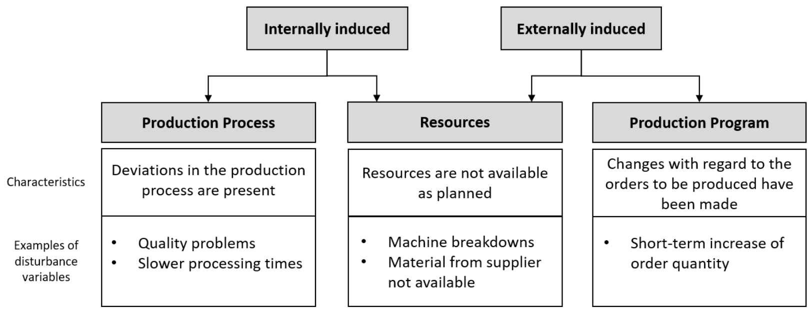

Figure 2.17: Classification of disruptions based on the impact point of the disturbance variable (based on the work of Fischäder (2007))

The three categories form an abstract and aggregated descriptive approach, which is able to represent specific causes of disruptions. We use this approach as a modelling input for the CM platform and will therefore come back to it in chapter 4. In chapter 6, we will take a closer look at the disturbance effects (*impact dimension*). Our aim is to examine the effects that arise when reacting to different disruptions by applying the CM logic.

2.2.3 Measures to Disruptions

After having introduced basic concepts of production-related disruptions, we will below give an overview of existing approaches to addressing them, followed by a classification of the approach of this work.

Overview of Measures

When coping with disruptions, a general distinction can be made between **proactive** measures taken in advance and **reactive** measures during the event of a disruption (cf. Tomlin 2006, Snyder et al. 2016). Furthermore, a distinction can be made between measures to **prevent** disruptions and measures to **overcome** disruptions (cf. Fischäder 2007). Within the scope of this thesis, we will focus on production-related measures, which we will discuss in more detail below. Measures to adress the supply, the transportation process or the demand, e.g. through backup suppliers, suitable sourcing strategies or demand switching strategies, will therefore not be considered. For a more detailed introduction to these topics, we refer to the comprehensive review paper of Snyder et al. (2016).

Measures to *prevent* disruptions *proactively* focus on the cause of the disruption aiming to reduce the probability of occurrence (cf. Fischäder 2007). Exemplary principles for this, such as the TQM approach, can be found in the publication of Kleindorfer and Saad (2005). Measures to *overcome* disruptions in the case of occurrence can be designed both proactively and reactively. *Proactive* measures of this type are referred to as *mitigation strategies* and aim to mitigate the effects of disruptions through measures taken in advance (cf. Tomlin 2006, Fischäder 2007). This can be done by maintaining additional time, capacity and inventory buffers based on the anticipated impact of a disruption (cf. Fischäder 2007). Time buffers are created, for example, by scheduled surcharges on processing times. Additional capacity is provided by not fully utilising resources or blocking certain time slots. Inventory buffers represent safety stocks. These buffers are available immediately in the event of a disruption and do not have to be activated first (cf. Fischäder 2007). Another mitigation strategy is to make use of preparatory measures, such as tracking procedures to detect disruptions at an early stage, trainings for the handling of disruptions, as well as preparations for a quick collaborative exchange of information in the case of a disruption (cf. Ivanov, Dolgui, et al. 2016). *Reactive* measures to overcome disruptions are classified as *contingency strategies* (cf. Tomlin 2006). These include adjustment measures that provide additional capacities to be activated in the event of a disruption by means of quantity, intensity or time-related alignments (cf. Gutenberg 1983, Fischäder 2007). Quantitative adjustments refer to the activation of additional resources, e.g. a decommissioned machine. Intensity-based adjustments enable more throughput to be processed at the same time, for example by accelerating the machining time. Time-based adjustments try to extend the available working time, e.g. by using night shifts (cf. Hansmann 2006). However, the strategies mentioned so far do not yet include an active replanning of the processes; this is subsumed in the literature under the term *rescheduling*. Rescheduling describes the process of adapting an existing plan due to a disruption (cf. Vieira, Herrmann, and E. Lin 2003). With regard to possible rescheduling strategies, Vieira, Herrmann, and E. Lin (2003) differentiate between predictive-reactive rescheduling, in which a generated schedule is repaired periodically, event-driven or in a hybrid approach by partial, complete or right-shift-based rescheduling, and dynamic approaches that are not based on production schedules and which respond to uncertainties by applying dispatching rules or pull policies.

Classification of the Approach of this Thesis

The measures introduced above are primarily used in combination rather than individually (cf. Tomlin 2006). That is also the underlying idea of this thesis. Using available, proactively planned buffers, this work aims at enabling a reactive, cross-location rescheduling based on the concept of CM. The proactively determined capacity and material buffers represent the input data of the model for generating an ad hoc value stream. In this respect, we keep in mind that not only the free capacities and material buffers at the affected location are considered for rescheduling, but also those of the entire production network. As those capacity buffers may still not be sufficient for a short-term reaction if the network is highly utilised, time-related adjustments, i.e. the decision whether additional, often costly, extra shifts should be planned , may become necessary. For this reason, we see extra shifts as further usable capacity buffers that can be taken into account in the decision making if necessary. Since extensive and frequent changes to an existing production program reduce the scheduling stability and lead to scheduling nervousness, which may have a negative impact on the performance of a system (cf. Pujawan 2004, Schuh, Prote, et al. 2019), one objective of this thesis is to change the existing plan as little as possible. We therefore follow the idea of using the CM concept to reschedule only those production orders that are directly affected by a disruption (e.g. an additional short-term order to be executed or an order that has been put on hold due to a machine breakdown) by making use of available capacity buffers. In this way, a complete rescheduling of the production program shall be avoided. The approach of this thesis can thus be classified into the rescheduling scheme of Vieira, Herrmann, and E. Lin (2003) as an event-driven partial rescheduling approach within a dynamic flow shop environment.

To sum up, the method of this thesis is built on a CM based reactive rescheduling approach, in which proactively planned buffers across sites and, if beneficial, additional reactively utilised extra shifts are used to overcome a disruption by creating an ad hoc value stream with the aim of changing the existing production plan as little as possible (cf. fig. 2.18).

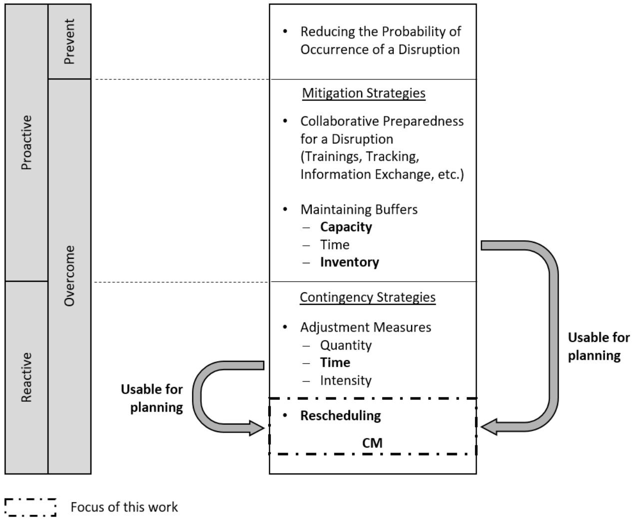

Figure 2.18: Classification of production-related measures to disruptions and positioning of the approach of this work (bold) (based on the contributions of Ivanov, Dolgui, et al. (2016), Tomlin (2006) and Fischäder (2007))

2.3 Cloud Manufacturing

After having introduced the regarded system and the problem occurring in it, we will now take a closer look at the conceptual framework of our solution approach - cloud manufacturing. We will look at definitions, operation modes, proposed architectures and processes.

2.3.1 Definition

Cloud manufacturing is a service-oriented manufacturing principle first mentioned in 2010 by the research group of B.-H. Li et al. (2010) (cf. Adamson et al. 2015). The basic idea is to make production resources exchangeable as services over a cloud platform, as described in the definition of Adamson et al. (2015):

> ” Cloud Manufacturing is a networked manufacturing model in which locally and globally distributed manufacturing resources for the complete product life-cycle are made available by providers for satisfying consumer demands, and are centrally organised and controlled as manufacturing cloud services. The model supports unified interaction between service providers and consumers, for trading and usage of configurable resources/services, as well as dynamic and flexible cooperation and collaboration in multi-partner manufacturing missions. Distinct characteristics for the use of services are that they are scalable, sold on demand, and fully managed by the provider.”

Hence, the objective is to share manufacturing resources as services on a cloud platform which maintains the necessary data and is capable to create temporary on-demand manufacturing lines (cf. Fisher et al. 2018). As such, a service describes the provision of a single resource or of combinations of resources (cf. Adamson et al. 2015). Based on X. Xu (2012), two main classes of *manufacturing resources* can be classified: physical manufacturing resources and manufacturing capabilities. *Physical manufacturing resources* can be distinguished in hard resources (e.g. manufacturing equipment, materials or vehicles) or soft resources (e.g. simulation software or personnel). *Manufacturing capabilities* are intangible and describe the ability to perform a specific task with a physical manufacturing resource (e.g. executing a milling operation with a machine). Both physical resources and capabilities are virtualised and offered as services on the cloud platform. (cf. X. Xu 2012, Adamson et al. 2015)

With regard to the range of resources offered as services on a CM platform, most authors refer to the entire product life-cycle (cf. X. Xu 2012, Fisher et al. 2018, Ren et al. 2017, Adamson et al. 2015). Based on these considerations, services can include both the primary production process and related upstream and downstream activities such as design, simulation or testing, enabling together Manufacturing-as-a-Service (cf. Ren et al. 2017).

Implications for this Thesis: In the further course of this work, we will refer to the primary production process in which products are manufactured and processed, as stated in chapter 2.1.1. In this respect, we consider the physical manufacturing equipment (i.e. machines and assembly facilities) as *production resources*. Those production resources, together with the required personell and the resulting capability to perform a specific task with them, are shared as services on a cloud platform. Furthermore, the transport side is taken into account, as it is done, for example, in the works of Lartigau et al. (2015), Zhou, L. Zhang, and Fang (2020) and Akbaripour et al. (2018). The basic idea is that a freight forwarder offers different *transport forms* on the CM platform in order to make them available as on-demand services. The platform therefore not only matches appropriate production resources to an order, but also takes care of the planning and allocation of any transport steps that may arise. As described in chapter 2.1.3, we consider both direct non-stop transports with different vehicle classes and groupage services. The freight forwarder offers those transport forms on the platform in order to carry out the necessary transport steps through its cooperation network with subcontracted carriers and geographically distributed consolidation centres. Furthermore, the required materials, i.e. (raw) materials, mounting components and finished good containers, are integrated as *material resources* provided on the CM platform. To carry out a production step on a production resource, the required materials must be available. For this purpose, they may first have to be brought from another location that offers them on the platform by commissioning a transport. It is the task of the CM platform to arrange material supply, production and transport in an ad hoc value stream in order to fulfil a customer demand. CM is thus summarised in this thesis as a service-oriented production principle that combines suppliers of production resources, transport and material resources on a centrally coordinated cloud platform in order to provide an on-demand supply chain to a customer.

2.3.2 Operation Mode

As shown in fig. 2.19, three different **platform roles** are distinguished: The *customers* are the consumers of the platform who would like to have something produced. They have a need, which they want to satisfy by sending a request with specific requirements to the platform. The *providers* offer available resources on the platform and provide the relevant information to virtualise them. The cloud *operator* runs the platform and acts as a mediator between supply and demand. To satisfy demand, it is the task of the platform to evaluate the request of the customer and to compose the services offered by the providers as intelligently as possible to fulfil the request. (cf. D. Wu et al. 2013, Ren et al. 2017, Cheng et al. 2012, Liu, L. Wang, X. V. Wang, et al. 2019, Tao, L. Zhang, Venkatesh, et al. 2011)

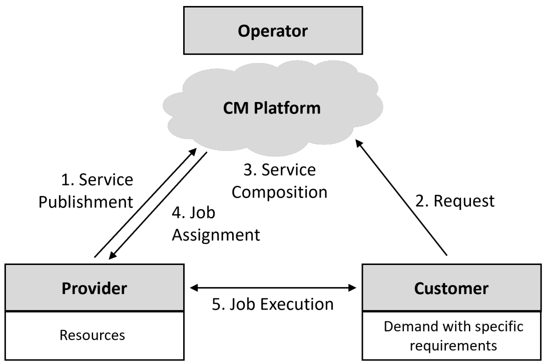

Figure 2.19: Roles and basic principle of cloud manufacturing (adapted from Ren et al. (2017), Cheng et al. (2012) and Liu, L. Wang, X. V. Wang, et al. (2019))

As described in chapter 1, a further distinction can be made between public, private, community and hybrid **platform types**, which in the two extreme cases are either open to all providers and customers, being operated by a third-party operator (*public*) or are designed and operated by a single company in order to exchange in-house resources (*private*). *Community* platforms are operated by a group of companies with common interests. In *hybrid* platforms, non-critical services are publicly accessible, business critical services remain private. (cf. Tao, L. Zhang, Venkatesh, et al. 2011, Adamson et al. 2015)

Implications for this Thesis: This thesis's approach is based on the idea that the different sites of an internal production network share information about their available production resources and material resources on a private CM platform. Furthermore, a freight forwarder is included who offers different modes of transportation for carrying out the necessary transport steps (cf. fig. 2.20). In contrast to the public approach, the basic data configurations required to describe the network are made in advance. The corresponding data model is explained in chapter 4. The providers are then able to supplement and update their provided information accordingly. As such, they can offer a production resource for usage if there are unused reserve capacities. Material resources can be made available on the platform if stocks exist that have not yet been scheduled. The site impacted by a disruption acts as a customer and orders the affected products in order to reschedule them. The platform evaluates the order and assigns the jobs to the providers. The aim is to be able to react to the disruption by means of a demand-driven, temporary, flexibly reconfigurable and scalable supply chain (cf. Fisher et al. 2018, D. Wu et al. 2013) of independently acting units orchestrated by the CM platform (cf. Fisher et al. 2018).

2.3.3 Architecture

In the literature, numerous approaches describing the architecture of a CM system can be found. For a more detailed overview, we refer to the comprehensive review of Adamson et al. (2015). Analogous to cloud

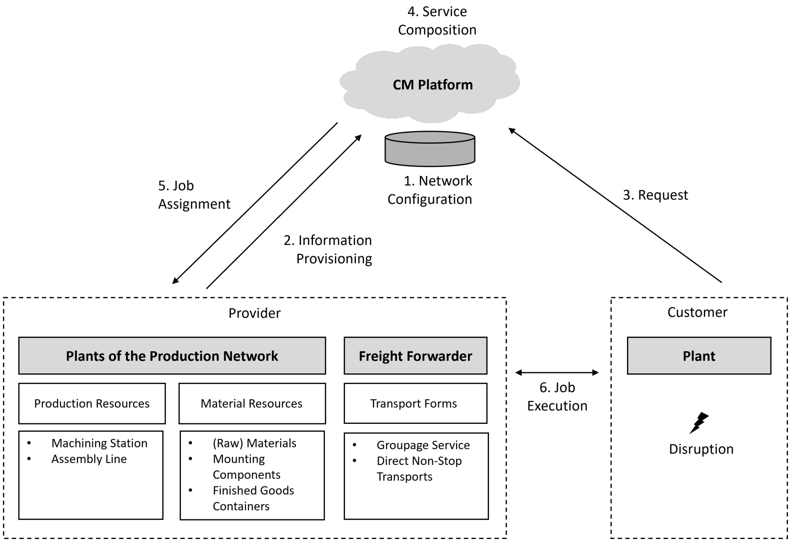

Figure 2.20: Roles and basic principle of the cloud manufacturing approach of this thesis

computing, which represents a source of inspiration and an important basic technology for CM (cf. X. Xu 2012, Tao, L. Zhang, Venkatesh, et al. 2011), most approaches are based on a layered architecture varying in the number and granularity of the individual levels. In the further explanations, we orientate ourselves on the 5-layer architecture of L. Zhang, Luo, et al. (2014), partly extended by the considerations of X. Xu (2012), Tao, L. Zhang, Venkatesh, et al. (2011) and Fisher et al. (2018) (see fig. 2.21). The *resource layer* represents the bottom level of this architecture and comprises the physical manufacturing resources and manufacturing capabilities (cf. L. Zhang, Luo, et al. 2014). The next higher level is the *perception layer*, which is responsible for sensing the resources in order to connect them to the network (cf. L. Zhang, Luo, et al. 2014). Identification and sensing based on real-time data can be provided, for example, by internet of things (IoT) technologies (cf. L. Zhang, Luo, et al. 2014, X. Xu 2012, Fisher et al. 2018). In the *service layer*, the manufacturing resources are virtualised by abstracting them into logical resources, which are encapsulated into services using suitable description languages, such as ontologies (cf. L. Zhang, Luo, et al. 2014, X. Xu 2012). The services form a so-called service pool (cf. L. Zhang, Luo, et al. 2014). The *middleware layer* represents the backbone of the system and is in charge of operating the cloud (cf. L. Zhang, Luo, et al. 2014, Fisher et al. 2018). Its tasks include the selection of services in the case of an incoming order (service composition), and other activities such as monitoring, evaluation, failure response, fee calculation, user administration and service management (cf. L. Zhang, Luo, et al. 2014, Tao, L. Zhang, Venkatesh, et al. 2011, Fisher et al. 2018). The uppermost level is referred to as the *application layer*, in which the users interact with the multi-tenant system through interfaces (cf. L. Zhang, Luo, et al. 2014, Fisher et al. 2018). A further crucial element of CM architectures is the aspect of *security and safety*, which must be guaranteed throughout the system (cf. Tao, L. Zhang, Venkatesh, et al. 2011, Fisher et al. 2018). Additionally, a seamless and interoperable exchange of *knowledge* is required (cf. L. Zhang, Luo, et al. 2014, Adamson et al. 2015, Tao, L. Zhang, Venkatesh, et al. 2011). In this way, a data-driven decision making can be ensured (L. Zhang, Luo, et al. 2014, Fisher et al. 2018), and a fast reaction to a disruption, which was named in chapter 1 as a critical point in disruption handling in practice, becomes possible.

Implications for this Thesis: Within the present work, we address the service and middleware layer. More precisely, the focus lies on the preliminary processing of an incoming order and the subsequent selection of services on the basis of a service description model. The service composition process (cf. Bouzary and Frank Chen 2018), which represents the core functionality of the CM platform, will be discussed in more detail in the following section.

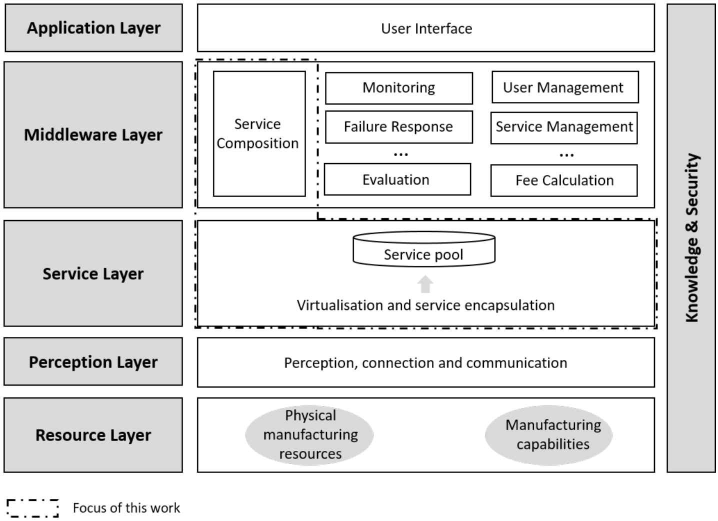

Figure 2.21: Architecture of cloud manufacturing (adapted from L. Zhang, Luo, et al. (2014), Fisher et al. (2018), Tao, L. Zhang, Venkatesh, et al. (2011) and X. Xu (2012))

2.3.4 Service Composition Process

The service composition process describes the workflow from order entry to the assignment of jobs to the resources of the providers. In our explanations, we follow a 4-step approach based on the contributions of Bouzary and Frank Chen (2018), Akbaripour et al. (2018), Tao, L. Zhang, Liu, et al. (2015), Liu, L. Wang, X. V. Wang, et al. (2019) and Cao et al. (2016) (see fig. 2.22).

In the first step, the customer order - in the literature referred to as task - is evaluated. Within the present work, we call this step **requirements engineering**. This process step aims to capture the functional and non-functional requirements of a task (cf. Liu, L. Wang, X. V. Wang, et al. 2019). For this purpose, the task is *analysed* and *decomposed* into separate subtasks (ST), e.g. single production steps, which are connected in sequential, parallel, selective and/or loop-based structures (cf. Liu, L. Wang, X. V. Wang, et al. 2019, Akbaripour et al. 2018).

In the next step, the **service discovery**, all service candidates (SC) suitable for the individual subtasks are searched for and grouped together as candidate sets (cf. Bouzary and Frank Chen 2018, Akbaripour et al. 2018). This is usually done by a *semantic matching* of the service descriptions to the requirements of the subtask (cf. Bouzary and Frank Chen 2018).

The next step addresses the **service evaluation**. However, this step is only partially listed in the literature and can be considered optional, depending on the communication model between operator and provider and the service data already available. A possible task at this point is to *enquire* service candidates for confirmation and for providing more detailed job-related information (cf. Cao et al. 2016). In addition, the selected candidates may need to undergo further subtask-related *analysis* in preparation for the final selection (cf. Tao, L. Zhang, Liu, et al. 2015).

In the last step of the process, the **service selection** is carried out. The aim is to *assign* the services from the candidate set to the subtasks in order to find the best possible solution for the entire task, taking into account the given restrictions and characteristics of the services at hand (cf. Tao, LaiLi, et al. 2013). If the services are additionally planned in terms of time, service *scheduling* is performed.

Implications for this Thesis: Within this work, the service composition process forms the basis of the designed CM platform and will be taken up again in chapter 4. The problem of service selection [9] to be solved in this process represents the fundament of the modelling in chapter 5. As a preparatory step, we will take a closer look at the literature on this problem class in the next chapter in order to classify the solution approach of this thesis.

[9] Within this thesis termed as service selection problem (SSP)

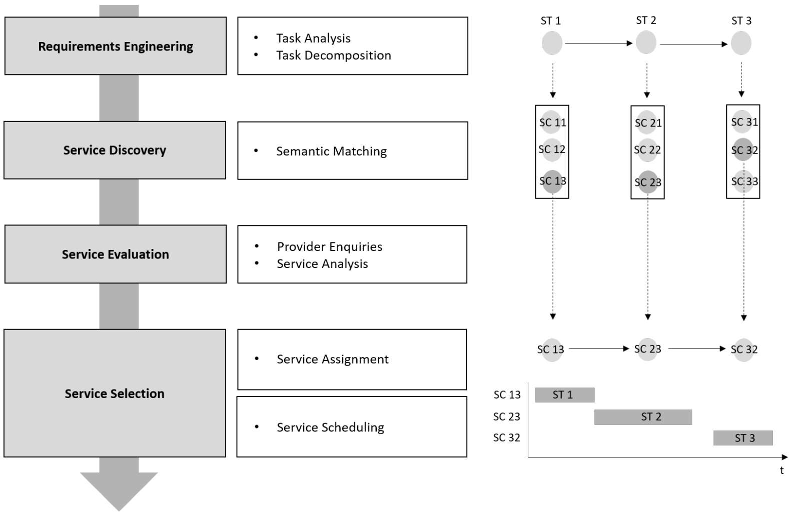

Figure 2.22: Service composition process (consolidated from the contributions of Akbaripour et al. (2018), Bouzary and Frank Chen (2018), Liu, L. Wang, X. V. Wang, et al. (2019), Cao et al. (2016) and Tao, L. Zhang, Liu, et al. (2015))

3 Literature Review on the Service Selection Problem

In order to understand the
world, one has to turn away
from it on occasion.
-A. Camus

Having addressed the field of application, the regarded problem, and the solution framework in the last chapter, we will now focus on the methodological core of this work. For this purpose, we will have a closer look at the related literature on the service selection problem (SSP) addressed in this paper. In a first step, we will describe the characteristic features of the pursued approach based on the previous remarks, which will serve as guidelines for the literature search (cf. sec. 3.1). We will then look at the relevant literature streams that form the basis of the modelling: Related models in production planning and CM based models. Accordingly, we will look at lot-sizing and scheduling problems presented in the production planning literature in chapter 3.2. Subsequently, we will discuss different service selection models of the CM literature in chapter 3.3. Based on these elaborations, we will define the research gap and classify our approach, the SLSP, in the last subchapter.

3.1 Problem Characteristics

In the following sections, the underlying characteristics of the SSP to be solved within this work will be described. Those characteristic features are based on the properties of the production network, the disruption-related use case and the solution framework of cloud manufacturing, as presented in chapter 2. In short, the problem consists of putting together the best possible value stream for an incoming order using available resources. Decisions to be made therefore include the selection of appropriate **production resources** (i.e. machines or manual working stations) and a time-based allocation of production quantities. During a production step, materials - i.e. (raw) materials, mounting components and finished goods containers - are being consumed. For this reason, the required **material resources** available at the network locations are to be allocated in terms of quantity and time and must be made available at the processing plants. To enable an exchange of goods between the network locations, transport planning decisions are required: A **transport form** needs to be selected, and transport quantities are to be assigned time-wise.

Below we will take a more detailed look at demand-, production-, transport-, material- and objective-related properties of the regarded problem. The classification criteria applied are adapted from the lot-sizing and scheduling classification schemas of Meyr (1999), Z.-L. Chen (2010) and Karimi, Fatemi Ghomi, and Wilson (2003) and combined with own considerations relevant for this work:

- **Demand**:
  - **Number of Orders**: We consider a planning problem in which a *single order* is to be planned. The order results from a disruption and includes the production quantity affected.
  - **Order Entry**: The order is provided as a *deterministic* input triggering the planning. We are thus looking at a planning problem with a *statically* given order which is due at

planning start and represents the demand to be satisfied via the platform.

  - **Number of Customers**: The given order originates from a *single customer* to whom the requested items are to be delivered. More precisely, the plant affected by a disruption is acting as the customer aiming to reschedule a production order with the help of the CM platform.
  - **Number of Products**: An order may include *multiple products* with different order quantities. This is the case if several product types are affected by a disruption. Those products represent different variants of a product group.
  - **Product Structure**: The product structure of the considered products is characterised by a *multi-level converging* BOM. A product is thus transformed in several levels and assembled with further components.

- **Production**:
  - **Production Stages**: The products are manufactured in a *multi-stage* production process.
  - **Production Sequence**: All products are passing through the production process in the same order, i.e. according to the principle of a *flow line*.
  - **Resources per Stage**: Each production stage contains multiple *non-identical parallel resources* that can be used by the CM platform. Differences between those production resources may exist, e.g. in terms of cost rates or processing times.
  - **Capacity of Resources**: The capacity of the production resources is *limited*. In addition to the maximum available working time, the production program already scheduled represents a capacity restriction. Therefore, only the remaining free capacities are available for dispatching an order via the CM platform.

  - **Time-Dependency**: The properties of the production resources are time-dependent and therefore considered to be *dynamic*. For example, the production cost rates can vary over time since weekend shifts are often more expensive than normal shifts during the week. Depending on the existing production program, also the available capacities can fluctuate with time.
  - **Number of Plants**: The production network available for the fulfilment of a CM order includes *multiple plants*. The individual plants are able to carry out one or more production steps on available resources.
  - **Set-up Time**: The products are manufactured in a batch process. When changing to a new lot, i.e. to a different product type, we assume a *sequence-independent* set-up time.
  - **Lot-size**: During the production process, the parts are handled in specific load carriers. The lot-size is therefore required to be a *multiple* of a predefined *discrete* container filling quantity. Due to the availability of parallel production resources with limited capacity distributed across different locations, the quantity ordered via the CM platform may be *split* into several lots per stage, both in terms of time and between different production resources.

- **Transport**:
  - **Transport Steps**: Due to the cross-location perspective, there are several transport steps between the plants that need to be considered. Those transport steps involve transporting the required *materials to the plants*, the transport of *semi-finished products between production steps* and the delivery of *finished parts to the customer*, i.e. to the ordering plant.
  - **Transport Forms**: A transport step is either carried out as a *dedicated direct non-stop transport* with FTL or LTL shipments being forwarded by direct means and with the

CM platform selecting an appropriate vehicle class. Alternatively, a *groupage service*, in which the planning is delegated to the freight forwarder, can be used to exchange the goods between the locations of the network.

- **Vehicle Characteristics**: In order to carry out a direct non-stop transport, *multiple vehicle classes* can be selected. The vehicles of the different vehicle classes are *capacitated* in terms of load quantity and have *non-identical* characteristics, such as size, speed and cost rates. Within a vehicle class, it is assumed that the vehicles are identical. In the case of groupage services, the vehicle level is not taken into account since the planning is being conducted by the freight forwarder.
- **Availability of Transports**: Due to vacations and driving bans for different vehicle classes, such as on Sundays, we consider a *limited availability* of the different transport forms. On days when transports are possible, we assume an unlimited number of available vehicles and transports since freight forwarders typically cooperate with various geographically distributed subcontractors and partners.

- **Materials**:
  - **(Raw) Materials**: In order to start the production process, the required raw materials must be available at the processing location. The raw materials are taken from available stocks in the production network and, if necessary, brought to the work site from other locations. The same considerations apply to semi-finished parts in the subsequent production steps, which must be on hand at the processing plant when starting production.
  - **Mounting Components**: As with raw materials and semi-finished parts, the required mounting components must be available at the processing location to perform an assembly

step. Likewise, the components are provided from available stocks in the production network.

  - **Finished Good Containers**: After assembly, the finished parts are packed in defined batch sizes into end customer-specific containers, which must be on hand at processing time as well.

- **Objective**:
  - **Scope and Direction**: In line with the service and customer-oriented idea of CM, the primary goal when solving the described problem within this work is to put together the best possible value stream from the perspective of the customer using the CM platform. We are accordingly looking at an *order-based* and *customer-oriented* problem.
  - **Criteria**: With regard to the target triangle of costs, time and quality, the aim is thus to find order-based a cost-effective, fast and high-quality process chain for a customer. In doing so, we focus on the criteria *costs* and *time*, considering them as the optimisation criteria of a multi-objective optimisation problem. Adherence to quality requirements, on the other hand, is assumed to be given at all sites due to the fact that an internal production network is taken into account. Other possible objectives from the point of view of the providers or the platform operator, such as improving capacity utilisation at the plants offering resources or distributing orders evenly, are not explicitly modelled.

Figure 3.1 summarises the results of the characterisation of the SSP to be solved within this work. In the following, we will discuss the literature streams relevant to this problem type. We will first give an overview of fundamental concepts from classical production-related lot-sizing and scheduling research. Building on this, we will take an in-depth look at approaches and relevant works from the service-oriented

CM literature stream considering the demand-, production-, transport-, material- and objective-related properties presented above.

Demand	• Number of Orders:	Single Order
	• Order Entry:	Planning Start
	• Number of Customers:	Single Customer
	• Number of Products:	Multiple Products
	• Product Structure:	Converging
Production	• Production Stages:	Multiple Stages
	• Production Sequence:	Flow Line
	• Resources per Stage:	Parallel Resources
		Non-identical
	• Capacity of Resources:	Capacitated
	• Time-Dependency	Dynamic
	• Number of Plants:	Multiple Plants
	• Set-up Time	Sequence-independent
	• Lot-size	Discret
		Lot-splitting
Transport	• Transport Steps:	Materials to Plants
		Semi-finished Parts between Plants
		Finished Parts to Customer
	• Transport Forms:	Direct Shipment
		Groupage Service
	• Vehicle Characteristics:	Multiple Vehicle Classes
		Capacitated
	• Availability of Transports:	Limited
Materials	• Material Types:	(Raw) Materials
		Mounting Components
		Finished Goods Packaging
Objective	• Criteria:	Cost
		Time
	• Scope:	Order
	• Direction:	Customer-oriented

Figure 3.1: Summary of the characterisation of the SSP to be solved within this thesis

3.2 Scheduling and Lot-Sizing

This section aims to give an overview of basic concepts from classical scheduling and lot-sizing literature. According to a definition of Fandel, Trockel, and Quadt (2004), *lot-sizing problems* address the question of when to produce which quantities and *scheduling problems* relate to the assignment and exact sequence of production jobs on machines. In this respect, the scheduling problem concretizes the planning within a lot-sizing period (cf. Fandel, Trockel, and Quadt 2004). Figure 3.2 illustrates this relationship. Since the planning of the two problem classes may influence each other, they are also considered simultaneously within integrated lot-sizing and scheduling models (cf. Copil et al. (2017)). In the following, we will first take a look at lot-sizing problems and afterwards focus on scheduling problems.

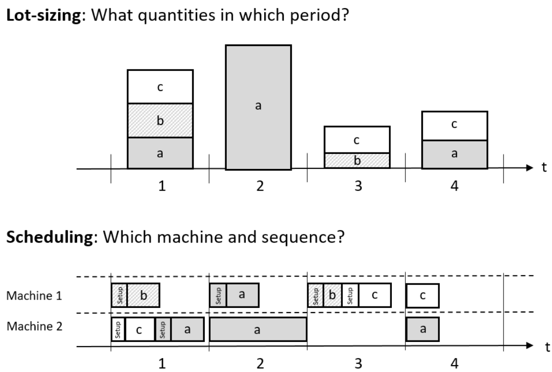

Figure 3.2: Illustration of the difference between lot-sizing and scheduling (Fandel, Trockel, and Quadt 2004)

3.2.1 Lot-Sizing Problems

Lot-sizing models are based on future demand quantities that are to be satisfied by production lots to be planned in time, considering existing stocks (cf. Tempelmeier 2020). The objective of such planning problems is to determine the lot-sizes for the individual planning periods in such a way that the resulting costs are minimised (cf. Tempelmeier 2020). The most relevant cost types include set-up costs and inventory holding costs (cf. Haase 1994). Other cost elements, such as production costs and penalty costs for unsatisfied customer demand, are added depending on the planning situation (cf. Seeanner 2013).

Lot-sizing models can be classified according to different criteria, which have partly already been introduced in section 3.1. For example, Haase (1994) distinguishes on the basis of the criteria **degree of information** between *deterministic* and *stochastic* models, on the basis of the **temporal development of parameters** between *static* and *dynamic* models, on the basis of the **planning horizon** between *finite* and *infinite* models, by the **time scale** between *continuous* and *discrete* models, by the **number of items** between *single-item* and *multi-item* models, by the **number of levels (stages)** between *single-level* and *multi-level* models, on the basis of **resource constraints** between *capacitated* and *uncapacitated* models, by the **number of parallel machines** between *single-machine* and *multi-machine* models which include machine assignment decisions, and on the basis of the **service policy** between models that *allow* or do *not allow shortages*.

With regard to the accuracy of the modelling, big bucket and small bucket models are distinguished. In a **big bucket model**, the planning periods are large enough to produce multiple products in one period. Only the product-specific production quantity per period is determined. The sequence within the period is not considered. In the case of **small bucket models**, the periods are kept short in order to allow a maximum of two products - including the set-up process - to be produced within one period. In addition to the product-specific production quantity, the sequence is determined in this case as well. Small bucket models are therefore used for simultaneous lot-sizing and scheduling. (cf. Tempelmeier 2020)

In the following, we will introduce the **Capacitated Lot-Sizing Problem (CLSP)**. The CLSP is the best-known big bucket model for dynamic, capacitated lot-sizing in the case of multiple items and represents the starting point for many extensions - also for the approach of this thesis (cf. Tempelmeier 2020, Seeanner 2013):

Indices:

$k =$ Products, $k \in \{1, ..., K\}$
$p =$ Periods, $p \in \{1, ..., P\}$

Parameters:

a_k = Capacity needed to produce one item of product k
h_k = Holding costs per item of product k for one period
s_k = Set-up costs for product k
$d_{k,p}$ = Demand for product k in period p
$I_{k,0}$ = Initial inventory of product k
C_p = Available capacity in period p
M = Large number

Decision variables:

$I_{k,p}$ = Inventory of product k at the end of planning period p
$x_{k,p}$ = Production quantity of product k in period p
$z_{k,p}$ = Binary set-up variable of product k in period p

$$\min \quad \sum_{k,p} h_k \cdot I_{k,p} + \sum_{k,p} s_k \cdot z_{k,p} \tag{3.1}$$

$$\text{s.t.} \quad I_{k,p} = I_{k,p-1} + x_{k,p} - d_{k,p} \quad \forall k, p \tag{3.2}$$

$$x_{k,p} \leq M \cdot z_{k,p} \quad \forall k, p \tag{3.3}$$

$$\sum_{k} a_k \cdot x_{k,p} \leq C_p \quad \forall p \tag{3.4}$$

$$I_{k,p} \geq 0 \quad \forall k, p \tag{3.5}$$

$$x_{k,p} \geq 0 \quad \forall k, p \tag{3.6}$$

$$z_{k,p} \in \{0, 1\} \quad \forall p, t \tag{3.7}$$

Formula 3.1 defines the objective function, which aims to reduce set-up costs and inventory holding costs. Condition 3.2 represents the inventory equation. Condition 3.3 says that production can only take place if a set-up has been made. Condition 3.4 ensures that the available capacity is not exceeded during a planning period. Formulas 3.5 - 3.7 describe the permissible value range of the decision variables.

The CLSP formulated as a mixed-integer program (MIP) is NP-hard, which is why many researchers have dealt with different kinds of solution methods (cf. Karimi, Fatemi Ghomi, and Wilson 2003). Karimi, Fatemi Ghomi, and Wilson (2003) distinguish in their review between exact methods, common-sense or specialised heuristics and mathematical programming-based heuristics. *Exact methods* are, for example, based on reformulation approaches of the MIP to solve the CLSP with standard solvers using branch & bound type procedures (cf. Karimi, Fatemi Ghomi, and Wilson 2003, Gicquel, Minoux, and Dallery 2008). *Common-sense or specialised heuristics* can be divided into period-by-period heuristics, which work through each period one after another in order to construct a solution, and improvement heuristics, which generate a feasible solution from an initial solution, which is then improved (cf. Karimi, Fatemi Ghomi, and Wilson 2003). Typically, greedy principles are applied in this regard (cf. Buschkühl et al. 2010). *Mathematical programming-based heuristics* use optimum seeking procedures to find a solution (cf. Gicquel, Minoux, and Dallery 2008, Karimi, Fatemi Ghomi, and Wilson 2003). Those kinds of heuristics are often based on relaxations aiming to reduce the complexity of the problem (cf. Gicquel, Minoux, and Dallery 2008, Karimi, Fatemi Ghomi, and Wilson 2003). Moreover, *metaheuristics* such as tabu search, simulated annealing, genetic algorithms, ant colony optimisation and variable neighbourhood search, and *decomposition and aggregation*-based approaches are employed (cf. Buschkühl et al. 2010).

Lot-sizing problems have been and are still intensively investigated in scientific literature, which is why we point the reader to specific review and overview articles. For a more detailed overview of different solution methods for the CLSP, we refer to Karimi, Fatemi Ghomi, and Wilson (2003). A comprehensive review of solution approaches to dynamic capacitated lot-sizing problems based on the multi-level capacitated lot-sizing problem (MLCLSP) can be found in the publication of Buschkühl et al. (2010). In the publication of Copil et al. (2017), simultaneous lot-sizing and scheduling models are discussed. Simultaneous multi-level lot-sizing and scheduling problems are furthermore addressed in the dissertation of Seeanner (2013). An overview of simultaneous lot-sizing and scheduling models focussing on secondary resources can be found in the dissertation of Wörbelauer (2018). Nascimento, Yanasse, and Carvalho 2018 give an overview on multi-plant lot-sizing problems (MPLSP). For a more general and comprehensive survey on lot-sizing models, we refer to Tempelmeier (2020).

3.2.2 Scheduling Problems

Scheduling problems deal with the question of assigning tasks to resources and sequencing them on the resources. In the context of manufacturing-related literature, tasks are called jobs and resources are called machines. A job may consist of several operations. (cf. Baker and Trietsch 2018)

A distinction is made between *static* models, where all information is available at the planning start, and *dynamic* models, where information is partly unknown at the start of planning [1], as well as between *deterministic* models, where information is known with certainty, and *stochastic* models, where information is only known with a certain probability. (cf. Baker and Trietsch 2018)

To classify scheduling problems in more detail, an $\alpha \mid \beta \mid \gamma$ classification scheme is usually used (cf. Pinedo 2016).

The first field α describes the **machine environment**. A distinction is made for single-stage manufacturing processes between *single machines* and *parallel machines*, which are either identical or non-identical, and for multi-stage manufacturing processes between *flow shop, flexible flow*

[1] Those types of models are also referred to as online scheduling models (cf. Pinedo 2016)

shop, job shop, flexible job shop and *open shop* problems (cf. Pinedo 2016).

The field β specifies **processing constraints**. Exemplary constraints are *precedence conditions* between jobs, the possibility of *preemptions*, i.e. the allowance to interrupt the processing of a job, the integration of *release dates* and *due dates* of jobs, the incorporation of *additional resources* (e.g. materials) necessary for production, the integration of *no-wait conditions* ensuring a job has no waiting times between subsequent stages, the integration of *sequence-dependent set-up times*, the integration of *machine eligibilities*, possible *breakdowns* of machines, a possible *blocking* of jobs due to limited buffer, the possibility to *recirculate* a job, i.e. to process a job more than once at the same machine, *permutation conditions* ensuring the same sequence of jobs throughout the process as well as *transportation* steps between machines. (cf. Pinedo 2016, Framinan, Leisten, and Ruiz García 2014, Blazewicz et al. 2019)

Furthermore, there are two standard assumptions for classical scheduling problems: A job is only processed by one machine at a time, and one machine is only processing one job at a time (cf. Blazewicz et al. 2019). These assumptions are relaxed in two extensions. If a machine is able to process multiple jobs simultaneously, several jobs can be combined into a *batch* and be processed at once (cf. Framinan, Leisten, and Ruiz García 2014). On the other hand, if *lot streaming* is considered, a job is split into several sub-lots that can be handled in an overlapping manner (cf. Framinan, Leisten, and Ruiz García 2014).

The last field γ characterises the **objective** of the optimisation problem. Most scheduling problems are based on a time-related objective function (cf. Framinan, Leisten, and Ruiz García 2014). Examples of target criteria are the maximum completion time (makespan), the total or average completion time, the maximum lateness and the total or average lateness of the jobs to be planned (cf. Framinan, Leisten, and Ruiz García 2014). Besides, there are some studies considering multi-criteria objective functions (cf. Pinedo 2016).

Scheduling models are a special case of combinatorial optimisation problems, with many problem classes being NP-hard. To solve those problems, more or less simple **dispatching rules** for scheduling jobs to machines, such as first-come, first-served (FCFS), are still frequently used in practice. On the other hand, when calculating a schedule algorithmically, a distinction is made between exact and approximate methods, analogous to the solution methods of lot-sizing problems. **Exact methods** determine a solution either *constructively* or *enumerative*, for example with branch & bound or dynamic programming-based approaches. **Approximative methods** include *constructive problem-specific heuristics* which generate a solution from scratch often based on iterative greedy approaches, *problem-specific improvement heuristics* which, for example, improve an existing solution by limited enumeration or local search, and *metaheuristics* such as simulated annealing, tabu search, genetic algorithms, ant colony algorithms and particle swarm optimisation algorithms. Furthermore, approximate approaches based on *mathematical programming based heuristics* such as relaxation as well as *decomposition and aggregation* approaches are applied. (cf. Framinan, Leisten, and Ruiz García 2014)

Due to the great variety of literature on scheduling problems, we refer to specialised publications for a more detailed insight into different problem classes and solution methods. For a general introduction to the topic of scheduling, we recommend the publications of Pinedo (2016), Framinan, Leisten, and Ruiz García (2014) and Blazewicz et al. (2019).

3.3 Service Selection in Cloud Manufacturing

After having reviewed concepts from classical production planning literature in the previous sections, we will now look at models that come from the service-oriented CM research. We will first look at basic principles and subsequently present relevant studies in order to relate them to the characterisation scheme described in chapter 3.1.

3.3.1 Fundamental Concepts

As described in chapter 2.3.4, the focus in this literature stream is on selecting service candidates within the service composition process to best fulfil a task request. Two classes of service selection problems are discussed in the literature (cf. Akbaripour et al. 2018): The *service composition and optimal selection* (SCOS) problem is about assigning services from the candidate set to the subtasks so that the objective value of the entire process is optimised (cf. Tao, LaiLi, et al. 2013, Akbaripour et al. 2018). However, the services are only allocated to the subtasks; no scheduling under temporal constraints is performed. Any such scheduling can be done afterwards (cf. Tao, L. Zhang, Liu, et al. (2015)). As an extension to the SCOS, the *service selection optimisation and scheduling* (SSOS) problem simultaneously selects and schedules the services based on available time frames (cf. Akbaripour et al. 2018).

Most publications in both problem classes are built on the *quality of service* (QoS) principle (cf. Liu, L. Wang, X. V. Wang, et al. 2019). Under this principle, the service candidates are characterised by different QoS values, e.g. cost, time and quality factors (cf. Akbaripour et al. 2018). Usually, those multiple criteria are simultaneously mapped into a single objective function by *simple additive weighting* (SAW) in order to optimise the aggregated QoS value of the entire process (cf. Bouzary and Frank Chen 2018, Liu, L. Wang, X. V. Wang, et al. 2019). The formulas for determining the aggregated QoS value depend on whether a sequential, parallel, selective or loop-based process structure is given (cf. Bouzary and Frank Chen 2018). Furthermore, a distinction can be made as to whether a single task or multiple tasks are to be planned simultaneously (cf. Liu, L. Wang, X. V. Wang, et al. 2019).

Based on the notation of Tao, LaiLi, et al. (2013), Bouzary and Frank Chen (2018) and Akbaripour et al. (2018), we will below present the standard SCOS model, which forms the starting point for many investigations and extensions. It is a model for assigning a single task with, in the simplest case, a serial process structure to suitable resources.

We, therefore, take up the example from figure 2.22 and describe the service selection step. With regard to QoS, we illustrate the example using the criteria time, cost and quality as it is done, for example, in the publication of Akbaripour et al. (2018).

Described generally, a task $TK = \{ST_1, ST_2, ..., ST_i, ..., ST_r\}$ consists of several subtasks $ST_i, i \in \{1, ..., r\}$, which in our example are to be executed in a three-step sequential process. For the ith subtask ST_i, m_i service candidates are available for selection. $S_i = \{S_{i,1}, S_{i,2}, ..., S_{i,j}, ..., S_{i,m_i}\}$ represents the set of candidates for subtask ST_i. The problem to be solved now is to select a service candidate from each candidate set in order to find the optimal *composite service execution path* (CSEP). Let $X = \{x_1, x_2, ..., x_i, ..., x_r\}$ be a CSEP in which x_i represents the number of the selected service candidate for subtask ST_i. Then the QoS values of X are given by the following formulas in the case of a sequential process[2] (cf. Akbaripour et al. 2018):

$$U^C(X) = \sum_{i=1}^{r} C(S_{i,x_i}) \tag{3.8}$$

$$U^T(X) = \sum_{i=1}^{r} T(S_{i,x_i}) \tag{3.9}$$

$$U^Q(X) = \frac{1}{r} \cdot \sum_{i=1}^{r} Q(S_{i,x_i}) \tag{3.10}$$

$C(S_{i,x_i})$ represents the resulting costs when performing subtask ST_i with service candidate S_{i,x_i}. $T(S_{i,x_i})$ indicates the time required by service candidate S_{i,x_i} to perform subtask ST_i. $Q(S_{i,x_i})$ represents the quality value of service candidate S_{i,x_i} when performing subtask ST_i.

[2] For the formulas for parallel, selective and loop-based processes, we refer to Akbaripour et al. (2018). Furthermore, it should be noted that in the literature, other approaches for the calculation of the aggregated QoS values can be found, e.g. for the aggregated quality value by multiplicative linking the quality values of the individual services candidates.

The resulting costs, time and quality values to perform the entire task TK with CSEP X are reflected by $U^C(X), U^T(X)$ and $U^Q(X)$.

Most commonly, SAW is used to turn the multi-criteria problem into a mono-criterion problem (cf. Bouzary and Frank Chen 2018): The QoS values are weighted and added together in a single objective function. Due to different dimensions and sizes, the QoS values are usually normalised first to do so (cf. Bouzary and Frank Chen 2018). A frequently used normalisation method is the *upper-lower-bound approach* which transforms a value to the range between 0 and 1 using its maximum and minimum values[3] (cf. Marler and Arora 2005):

$$Norm(U^q(X)) = \begin{cases} \frac{U^q(X) - U^{q,min}}{U^{q,max} - U^{q,min}} & , U^{q,max} \neq U^{q,min} \\ 1 & , U^{q,max} = U^{q,min} \end{cases} \tag{3.11}$$

$$Norm(U^q(X)) = \begin{cases} \frac{U^{q,max} - U^q(X)}{U^{q,max} - U^{q,min}} & , U^{q,max} \neq U^{q,min} \\ 1 & , U^{q,max} = U^{q,min} \end{cases} \tag{3.12}$$

$Norm(U^q(X))$ represents the normalised value of $U^q(X)$. In this respect, the variable q serves as a proxy for different QoS criteria - in our example, cost (C), time (T) and quality (Q). $U^{q,max}$ and $U^{q,min}$ indicate the maximum and minimum values of $U^q(X)$ among all possible CSEP X. For QoS criteria to be minimised, i.e. time and costs, eq. 3.12 applies. For values to be maximised, i.e. quality, eq. 3.11 is to be selected.

As a result, the following problem formulation is obtained (cf. Bouzary and Frank Chen 2018):

[3] The upper and lower bounds can be determined, for example, by solving the mono-criterion objective functions described in 3.8, 3.9 and 3.10 and taking then for each dimension the maximum and minimum objective function values out of all solutions found in this regard (cf. Marler and Arora 2005).

$$\max_X \quad \sum_q Norm(U^q(X)) \cdot w_q \tag{3.13}$$

$$\text{s.t.} \quad \sum_q w_q = 1 \tag{3.14}$$

Formula 3.13 represents the objective function in which the normalised and weighted QoS values of a CSEP X are added together. Constraint 3.14 states that the sum of the weights for the individual QoS criteria needs to equal 1. In addition, further constraints are usually included to guarantee a predefined minimum ($U^{q,min,0}$) or maximum value ($U^{q,max,0}$) for the different QoS criteria (cf. Bouzary and Frank Chen 2018):

$$U^q(X) \geq U^{q,min,0} \tag{3.15}$$

$$U^q(X) \leq U^{q,max,0} \tag{3.16}$$

The presented SCOS model forms the basis for numerous extensions, such as the inclusion of transport time and costs which leads to dependencies between the subtasks. A large number of publications deal with methods to solve the described NP-hard problem, usually by using metaheuristics (cf. Liu, L. Wang, X. V. Wang, et al. 2019). For a comprehensive overview of existing publications, we refer to the literature reviews of Bouzary and Frank Chen (2018), Liu, L. Wang, X. V. Wang, et al. (2019) and Akbaripour et al. (2018).

Building on the basic model introduced, we will below present several research papers related to the approach of this thesis. We are focusing on approaches within the CM literature stream that include both service selection and service scheduling (SSOS). The starting point for the literature search has been the review on selection and scheduling in CM of Akbaripour et al. (2018). In order to include more recent articles, a supplementary search was carried out with Scopus. We used the search string ”Cloud AND Manufacturing AND Scheduling” to find articles with a release date later than 2017. The search was performed on July 06, 2020 and has been updated on April 01, 2023. A total of 368 articles were found, which shows the actuality of the topic. In a second step, we screened the total amount of articles coming from the existing review and the supplementary Scopus search to find the approaches relevant for this work. For this purpose, it was checked whether real scheduling is carried out, i.e. it is determined where and when a task is executed, taking into account limited availability. In this respect, limited availability may result from external tasks already scheduled or multiple tasks to be scheduled. Furthermore, we limited ourselves to multi-stage approaches considering transport steps between the services. Taking these filter criteria into account, 28 articles remained, which we will present in the following.

3.3.2 Related Approaches

Cao et al. (2016) developed a model for the assignment and simultaneous scheduling of a single task consisting of several subtasks to suitable service candidates. A task involves producing a specific quantity of similar parts that need to be picked up at a pickup location and be brought to a destination point after completing the process chain. Time, costs, quality and service rating are considered as QoS criteria that are summed up in a weighted and normalised objective function with the help of SAW in order to generate the best possible CSEP for a customer. The total processing time of a CSEP consists of the manufacturing time of the selected service candidates and the distance-dependent transport time between the involved locations. Analogously, the total costs comprise the manufacturing costs and the distance-dependent transport costs. The quality value and the service rating of the CSEP are calculated as the sum of the quality and service values of the selected service candidates. As a limiting constraint for the selection of the service candidates, occupied time slots are included. The described problem is solved using an adapted ant colony optimisation (ACO) algorithm.

Liu, X. Xu, et al. (2017) also developed a simultaneous selection and scheduling model. In contrast to Cao et al. (2016), however, this approach considers multiple tasks. The tasks are sorted according to their workload and scheduled sequentially. In addition to the criteria regarded from the customer side - processing time, costs and reliability of a task - criteria related to the overall system, such as the system utilisation, are included in the normalised SAW-based objective function. With regard to the processing time of a task, the approach includes not only transport and manufacturing times but also waiting times that occur in the case of occupied resources. Different from the above model, which is based on a continuous time structure, a discrete period-based time structure is utilised. The authors analyse the model behaviour on an example instance, applying an exhaustive search-based algorithm.

Akbaripour et al. (2018) developed a model for simultaneous assignment and scheduling of a single task. In contrast to the previous two approaches - which are based on direct transports - this approach integrates the decision on which transport route a transport step is to be executed. Both direct transports and hub-spoke-based transports are selectable. Analogous to the aforementioned approaches, the costs, the processing time and, as a third QoS criterion, the quality of a generated process chain are assessed in a normalised SAW-based objective function from a customer perspective. The total processing time of a task is calculated analogously to Liu, X. Xu, et al. (2017) out of manufacturing, transport and waiting time, but based on a continuous time structure. The authors solve and analyse the problem based on mixed-integer programming (MIP) using the standard solver CPLEX.

Liu, L. Wang, Y. Wang, et al. (2018) developed an agent-based model in which the selection and scheduling of services to fulfil multiple dynamically arriving tasks is solved by negotiations between agents. Broker agents act as intermediaries in order to assign and schedule the subtasks of a task agent sequentially to service agents. The decision to assign a subtask to a service agent is based on their offers, which include the QoS criteria processing time, service costs, reliability and reputation. The processing time comprises the distance-dependent transport time, manufacturing times and waiting times. The service costs are calculated out of the production costs and the distance-dependent transport costs. In a further publication, the authors describe an extended agent-based model in which logistics providers are included as agents as well, and the subtasks of a task are scheduled simultaneously (cf. **Liu, X. Zhang, et al. 2019**). In more recent approaches, the research group makes use of reinforcement learning to solve the selection and scheduling problem in cloud manufacturing environments (cf. **X. Wang, L. Zhang, Liu, F. Li, et al. 2022**, **X. Wang, L. Zhang, Liu, Zhao, et al. 2022**, **Ping et al. 2023**, **Z. Chen et al. 2023**).

Zhou, L. Zhang, B. R. Sarker, et al. (2018) describe an approach in which subtasks are scheduled sequentially and event-triggered in a centrally coordinated manner. Triggering events are the occurrence of a new task or the completion of a subtask. The services are selected on the basis of the shortest processing time considering transport times, manufacturing times and waiting times.

Ghomi, Rahmani, and Qader (2019b) developed a model for a simultaneous planning of multiple tasks. The subtasks are assigned to the available service candidates with the objective of minimising the accumulated costs and processing times, striving for a balanced load among the services. Simultaneously integrated into the decision-making is the question of sequencing the subtasks assigned to the services. The multi-criteria problem is formulated as a mixed-integer linear program (MILP) using goal programming. The authors solved the problem with a particle swarm optimisation (PSO) algorithm. In a further publication, the research group applies a genetic algorithm (GA) to address the problem (cf. **Ghomi, Rahmani, and Qader 2019a**). A very similar approach, but with the objective of minimising the makespan and the resulting transport costs of all tasks, is described by **Elgendy, Yan, and M. Zhang (2019)**. The problem is solved with a GA as well. Another simultaneous multi-task model for selecting service candidates and sequencing the subtasks was developed by **F. Li, L. Zhang, et al. (2019)**. This model aims to optimise the makespan, the total costs and the total quality value. The processing times and associated costs are composed out of sequence-dependent set-up times, manufacturing times and transport times. The multi-criteria problem is solved with a multi-objective ACO algorithm and a multi-objective non-dominated sorting genetic algorithm (NSGA II). The same research group is addressing the selection and sequencing problem in a second publication with the aim of minimising the makespan (cf. **F. Li, Liao, and L. Zhang 2019**). The problem is solved with a two-level scheduling method based on the ACO algorithm. In this approach, scheduling is first done at the task level and then at the subtask level. Three steps are performed consecutively: Sequencing the tasks, allocating resources to the subtasks and subsequently sequencing the subtasks. **L. Zhang, C. Yu, and Wong (2019)** present a constraint programming model for a simultaneous assignment and sequencing of multiple tasks. Taking available time slots into account, the model aims to minimise the makespan. The problem is solved using the solver CPLEX. **Salmasnia and Kiapasha (2023)** developed a model for simultaneous assignment and scheduling of multiple tasks with different arrival times and with consideration of set-up times. Based on a normalized SAW-based objective function, the problem is solved with a GA with the goal of optimising makespan, total costs and quality. In the paper of **LaiLi, S. Lin, and D. Tang (2020)**, a multi-layer optimisation approach is described. The decisions to be made include the assignment of priorities to tasks, the assignment of subtasks to production lines at different sites, the sequencing of atomic process steps of a subtask within a production line and the assignment of material resources to the atomic steps. The multi-criteria problem is solved simultaneously, applying different types of multi-objective evolutionary algorithms (MOEA). **L. Wang et al. (2018)** address the selection and scheduling of services in the case of multiple tasks with a distributed GA. They convert the multi-criteria problem into a single objective function using SAW. In the approach of **He et al. (2019)**, the multi-criteria multi-task assignment and sequencing problem is solved with a two-phase optimisation method based on a GA. In the first phase, a lower bound for the different normalised target dimensions is determined. In the second phase, the difference between the target dimensions is optimised depending on the customer priorities in order to examine different Pareto optimal solutions. In the work of **Xiao et al. (2019)**, the allocation and sequencing of tasks is based on a non-cooperative game in which the customers want to maximise their utility. The problem is solved with an extended biogeography based optimisation (BBO) algorithm. **Q. Wu, Xie, and Zheng (2022)** developed a centrally controlled optimisation model for simultaneous assignment and scheduling of multiple tasks, whereby transportation is modelled via capacitated vehicle resources that also need to be scheduled. The problem is solved with an improved shuffled frog-leaping algorithm (SFLA) trying to minimise total costs. In the paper of **Zeynivand et al. (2021)**, a multi-task model that considers alternative process routes is described. Different forms of transportation and production resources are selected and scheduled simultaneously. The presented MILP model aims at cost optimisation and is solved with CPLEX. The authors also investigate the effect of including the last transport step to the customer in the optimisation. A more generic multi-user approach for simultaneous selection and scheduling of production resources considering sequence-independent set-up times is presented in the work of **T. Wang et al. (2022)**. The authors are mentioning that the multi-task models described above can be considered as special cases of the developed multi-user model, where each user has one task. The presented model aims at optimising the total makespan and the resulting costs and is solved with an improved NSGA II. In the work of **Tong and Zhu (2022a)**, a multi-task model that aims at minimising the total energy consumption and the deviation to the reguested customer delivery dates is introduced. The problem is solved with a hybrid artificial bee colony (ABC) algorithm. In a further paper, the same research group extends the model by adding the total costs as a further goal to be minimised and by considering available time windows of the production resources to be scheduled as planning constraints (cf. **Tong and Zhu 2022b**).

S. Zhang, Y. Xu, and W. Zhang (2021) developed a two-stage multi-task model under uncertainty. The uncertainty of service attributes is modelled by using triangle fuzzy numbers. In the first stage, a simultaneous selection and scheduling problem is solved. In the second stage, a rescheduling is conducted due to an urgent task arrival, with the goal of minimising the changes from the solution obtained in the first stage. Both problems are solved with a genetic based hyper-heuristic algorithm (GA-HH).

J. Wang et al. (2019) transfer the selection and scheduling problem into a directed graph structure. The service candidates of the subtasks represent the nodes of the graph that are connected to all service candidates of the upstream and downstream subtasks. The edge weights refer to the logistics time between the connected nodes plus the manufacturing time and waiting time of the receiving node. The waiting time results from already scheduled tasks. Beginning at a start node, the objective is to find the shortest route through the network to an end node. The problem is solved with an adapted Bellman-Ford algorithm. The tasks are scheduled sequentially, and the route of a task is updated each time a subtask is completed due to stochastically changing manufacturing times.

Summary:

In the following, we will summarise the presented state of literature using the categories described in section 3.1.

Demand: In most approaches, several tasks coming from different customers are taken into account. The tasks are either available at planning start or arrive dynamically. Only two papers examine single tasks problems. The individual tasks usually differ in their requirements and process flow. With regard to the process structure, most approaches consider sequential processes. Only a few publications focus on combinations of parallel, selective and loop-based processes.

Production: The approaches shown are based on multi-stage production processes in which a task is processed according to the above-mentioned process structures in several subtasks. Multiple non-identical, capacitated, parallel resources, distributed over multiple plants, are available as services to conduct the subtasks. However, a single subtask is always processed as a whole. Discrete lot sizes due to predefined container filling quantities and the splitting of a subtask for parallel processing are not considered. Furthermore, only four publications consider set-up times in their models. With regard to the dynamical properties of the resources, some approaches assume a limited and time-dependent availability of free time slots for planning. Other properties, such as cost rates, are not dynamically varied over time.

Transport: All approaches presented consider the transport steps between the services. In most cases, the additional transport steps from and to the customer are also taken into account. Only Akbaripour et al. (2018) and Zeynivand et al. (2021) distinguish between different transport forms. All other approaches are based on dedicated direct non-stop transports employing a distance-dependent tariff system. Except for the approaches of Liu, X. Zhang, et al. (2019) and Q. Wu, Xie, and Zheng (2022), who consider different vehicle resources with different characteristics as separate services, the planning is mostly based on the assumption of unlimited transport availability.

Materials: The availability of raw materials is only addressed in the publication of LaiLi, S. Lin, and D. Tang (2020). Apart from that, required materials are neglected.

Objective: With regard to the objective function, most models are based on multi-criteria approaches, which are mainly intended to find the best possible order fulfilment from a customer perspective - either for an individual task or for all tasks simultaneously. Only a few approaches also consider the supplier side.

3.4 Research Gap and Classification of the SLSP

In the previous sections of this chapter, we have reviewed the relevant literature for the service selection problem (SSP) considered in this thesis. We first looked at approaches coming from classical production planning:

Lot-sizing models are used to assign production quantities to planning periods with the objective of meeting expected demand quantities. Those models typically aim to minimise total costs. *Scheduling* models are used to assign jobs to machines and to sequence them within a lot-sizing planning period aiming to optimise order-related time-based criteria. Integrated approaches such as small bucket lot-sizing models or lot-streaming based scheduling models enable simultaneous lot-sizing and scheduling.

Furthermore, we addressed the SSP discussed in the service-oriented CM research. Two problem classes are distinguished in the literature: *SCOS* models are used for the assignment of service candidates to subtasks. *SSOS* models additionally include a scheduling dimension. To gain a more comprehensive insight into this problem class, we have analysed and presented several research papers addressing the SSOS problem. In this respect, it is worth noting that the models considered are closely related to classical scheduling approaches. To the best of our knowledge, quantity-based, i.e. lot-sizing-based, models, however, have not been investigated in the context of CM so far. Existing CM models are based on the processing of complete tasks, a quantity-based splitting and distributing of a task is not investigated.

To close this research gap, we consider a third problem class for service selection problems in CM, the **Service-oriented Lot-Sizing Problem (SLSP)**. In contrast to existing scheduling approaches, no detailed sequencing with to-the-minute time planning is carried out, as quantities are allocated to appropriate resources order-related and period-specific, based on available capacities. As such, a big bucket model is addressed. Due to the fact that an order is already due at the start of planning and the order-related optimisation character, the SLSP also differs from classical lot-sizing problems, which are based on the fulfilment of demand quantities distributed over future periods trying to optimise costs from a production perspective.

We also point out that the aspects of required materials (also referred to as secondary resources) and transport steps are covered more comprehensively in this thesis than in previous works on cloud manufacturing. In particular, the consideration of different transport forms with limited vehicle capacities as well as different types of required materials that may have to be brought to the processing location first are to be mentioned. With these extensions, it is possible to reflect the requirements arising from a real-world production network in more detail.

As a follow-up to fig. 2.22, figure 3.3 summarises the positioning of this work's approach with regard to the SSP in the context of cloud manufacturing.

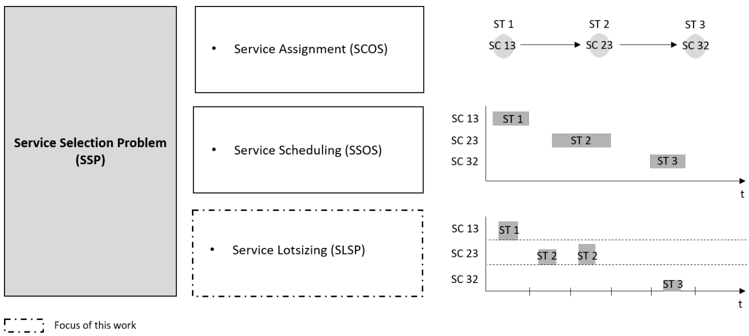

Figure 3.3: Positioning of the approach of this thesis

4 Designing a Private CM Platform

Change is the law of life. And those who look only to the past or the present are certain to miss the future.
-J.F. Kennedy

This chapter explains the underlying modelling approach and functional principles of the designed CM platform. In sec. 4.1, we will first introduce the platform's data model, which represents the regarded system - an internal production network. Afterwards, we will look at how the platform can be used in different cases of production-related disruptions (4.2). In the last subchapter (sec. 4.3), the functional principle of the designed CM platform will be presented following the service composition process introduced in chapter 2.3.

4.1 Data Model

The designed data model represents the system under consideration and serves as input for the SLSP. The modelling is reflected in the centrally operated relational database of the CM platform, which will be discussed in more detail in the technical description of the system in chapter 4.3.

In the next subsection, we will first look at the basic quantities of the data model. Thereafter, static and dynamic, i.e. time-dependent, properties will be introduced in more detail, considering production- and transport-related aspects.

4.1.1 Basic Quantities

As described in previous sections, we consider an internal production network with several locations j, $j \in \mathcal{J} = \{1, .., J_{max}\}$. A total of P_{max} product types being part of a single product group are produced at those sites. Each product type p, $p \in \mathcal{P} = \{1, .., P_{max}\}$ passes through the same multi-stage sequential flexible flow line production process consisting of I_{max} production steps. During this process, a raw material of type p is converted into a finished product of type p in a ratio of 1:1 within several steps. Those production steps can be both manufacturing and assembly activities that are processed in ascending order without having the option of being skipped. For a production step i, $i \in \mathcal{I} = \{1, .., I_{max}\}$, none, one or more production resources r, $r \in \mathcal{R} = \{1, .., R_{max}\}$ are available at a location j. In this respect, a production resource is referred to be either a machine or an assembly station. Taken together, there are R_{max} production resources in the network. In the case of an assembly step, different types of components c, $c \in \mathcal{C} = \{1, .., C_{max}\}$ are added to the product. Finished products are finally packed into a product-specific finished goods container of type f, $f \in \mathcal{F} = \{1, .., F_{max}\}$. Furthermore, different forms of transportation v, $v \in \mathcal{V} = \{1, .., V_{max}\}$ offered by a freight forwarder are considered. As described in chapter 2.1.3, we address, on the one hand, groupage services, which we assign in a fixed manner to the index $v = 1$. Alternatively, direct non-stop transports are possible, whereby the remaining indices $v \in \{2, .., V_{max}\}$ can be used to reflect different vehicle classes to conduct such a transport. Finally, we assume discrete planning periods t, $t \in \mathcal{T} = \{0, .., T_{max}\}$. These periods may represent a shift or a day. In order to be able to describe different kinds of periods, e.g. early shift, late shift, night shift, Saturday, Sunday and public holiday, we define the quantity s, $s \in \mathcal{S} = \{1, .., S_{max}\}$, which represents a period type, decoded as an integer ID. The parameter S_{max} represents the total number of different types of periods considered.

The quantities described are summarised in table 4.1.

Description	Index	Set
Plant	j	$j \in \mathcal{J} = \{1, .., J_{max}\}$
Product type	p	$p \in \mathcal{P} = \{1, .., P_{max}\}$
Production step	i	$i \in \mathcal{I} = \{1, .., I_{max}\}$
Production resource	r	$r \in \mathcal{R} = \{1, .., R_{max}\}$
Component type	c	$c \in \mathcal{C} = \{1, .., C_{max}\}$
Form of transportation	v	$v \in \mathcal{V} = \{1, .., V_{max}\}$
Finished goods container type	f	$f \in \mathcal{F} = \{1, .., F_{max}\}$
Period	t	$t \in \mathcal{T} = \{0, .., T_{max}\}$
Period type	s	$s \in \mathcal{S} = \{1, .., S_{max}\}$

Table 4.1: Basic quantities of the data model

4.1.2 Static Properties

In the upcoming section, the static, i.e. time-independent, properties of the system will be presented. We will look at both the modelling of production-related and transport-related aspects. In terms of notation, it should be noted that we represent the properties as mathematical relations indicating the range of values that can be assigned to the basic quantities.

Production-related Aspects

As for the production-related aspects, we distinguish between properties that relate to the production resources, the bill of materials and the material handling (cf. table 4.2).

Production Resources: Only approved production resources can be used for processing a specific product type. This is expressed by the approval matrix $\mathbf{A}\colon (\mathcal{R} \times \mathcal{P}) \to \{0,1\}$, where the range of values indicates whether a production resource r is approved for a product type p (1) or not (0). The production cost rate (in $\frac{€}{\text{min}}$) when processing a part of type p on a resource r in a period of type s is specified in $\mathbf{CP}\colon (\mathcal{R} \times \mathcal{P} \times \mathcal{S}) \to \mathbb{R}_{\geq 0}$. This formulation makes it possible to vary the cost rate depending on the shift type, e.g. to reflect the effect of making Sunday shifts more expensive. Furthermore, we record the processing time (in minutes) per part of type p on a resource r via $\mathbf{PT}\colon (\mathcal{R} \times \mathcal{P}) \to \mathbb{R}_{\geq 0}$, the sequence-independent set-up time (in minutes) for product type p on a resource r via $\mathbf{ST}\colon (\mathcal{R} \times \mathcal{P}) \to \mathbb{R}_{\geq 0}$ and the machine batch size, i.e. the number of parts of type p that are processable in parallel on a resource r via $\mathbf{PP}\colon (\mathcal{R} \times \mathcal{P}) \to \mathbb{N}_0$. In addition to that, a production resource r is linked to a production step i and is located at a specific plant j, which is captured in $\mathbf{PS}\colon \mathcal{R} \to \mathcal{I}$ and $\mathbf{L}\colon \mathcal{R} \to \mathcal{J}$. Lastly, we use the expression $\mathbf{ML}\colon \mathcal{R} \to \mathbb{N}_0$ to represent the minimum lot size per period that must at least be met when using a production resource r.

Bill of Materials: In an assembly step, components are added to the product. The number of components of type c that are incorporated in production step i when processing a part of product type p is specified in $\mathbf{B}\colon (\mathcal{I} \times \mathcal{P} \times \mathcal{C}) \to \mathbb{N}_0$.

Handling of Materials: Raw materials, semi-finished products and mounting components are handled in specific containers. In this regard, we assume that returnable containers, such as small load carriers, are used, which are available in sufficient quantities at the plants of the network. A possible return transport of empty containers to ensure a balanced container record between the locations of the network is not considered in the context of this thesis, as this is often organised by a separate container management system.

For a product type p, we assume a container holding capacity independent of the production step, which is reflected in $\mathbf{QP}\colon \mathcal{P} \to \mathbb{N}_0$. The assigned value represents the number of raw materials or semi-finished parts of type p that is handled jointly in one production container. The weight (in kg) of a full container with parts of type p is specified in $\mathbf{WP}\colon (\mathcal{P} \times \mathcal{I} \cup \{0\}) \rightarrow \mathbb{R}_{\geq 0}$ and depends on the preceding production stage i. Raw materials and finished goods are therefore indicated by the assignment $i = 0$ and $i = I_{max}$. For a component c, we use the notations $\mathbf{QC}\colon \mathcal{C} \rightarrow \mathbb{N}_0$ and $\mathbf{WC}\colon \mathcal{C} \rightarrow \mathbb{R}_{\geq 0}$ to represent the container holding capacity and the weight (in kg) of a full container.

In the last production step ($i = I_{max}$), the finished goods are packed into product-specific finished goods containers, which are considered as separate material resources f in this thesis. To indicate the holding capacity of the finished goods containers of a product type p, we use the notation $\mathbf{QPF}\colon \mathcal{P} \rightarrow \mathbb{N}_0$. A product type p is assigned to a finished goods container of type f by means of the relation $\mathbf{PF}\colon \mathcal{P} \rightarrow \mathcal{F}$. The weight (in kg) of an empty finished goods container f is captured via $\mathbf{WF}\colon \mathcal{F} \rightarrow \mathbb{R}_{\geq 0}$.

Expression	Domain	Value Range	Unit	Description
		Production Resources		
$\mathbf{A}(r,p)$	$\mathcal{R} \times \mathcal{P}$	$\{0,1\}$	-	Approval matrix of products p on resources r
$\mathbf{CP}(r,p,s)$	$\mathcal{R} \times \mathcal{P} \times \mathcal{S}$	$\mathbb{R}_{\geq 0}$	$\frac{€}{\text{min}}$	Production cost rate for processing a part of type p on resource r in a period of type s
$\mathbf{PT}(r,p)$	$\mathcal{R} \times \mathcal{P}$	$\mathbb{R}_{\geq 0}$	min	Processing time per part of type p on a resource r
$\mathbf{PP}(r,p)$	$\mathcal{R} \times \mathcal{P}$	$\mathbb{N}_0$	-	Machine batch size when processing parts of type p on resource r
$\mathbf{ST}(r,p)$	$\mathcal{R} \times \mathcal{P}$	$\mathbb{R}_{\geq 0}$	min	Sequence-independent set-up time of product type p on a resource r
$\mathbf{PS}(r)$	$\mathcal{R}$	$\mathcal{I}$	-	Production step of a resource r
$\mathbf{L}(r)$	$\mathcal{R}$	$\mathcal{J}$	-	Location of a resource r
$\mathbf{ML}(r)$	$\mathcal{R}$	$\mathbb{N}_0$	-	Minimum lot size of a resource r

Bill of Materials				
$\mathbf{B}(i, p, c)$	$\mathcal{I} \times \mathcal{P} \times \mathcal{C}$	$\mathbb{N}_0$	-	Number of components c to be incorporated per part of type p in a production step i
Handling of Materials				
$\mathbf{QP}(p)$	$\mathcal{P}$	$\mathbb{N}_0$	-	Holding capacity of a production container with raw materials or semi-finished products of type p
$\mathbf{WP}(p, i)$	$\mathcal{P} \times \mathcal{I} \cup \{0\}$	$\mathbb{R}_{\geq 0}$	kg	Weight of a full container with parts of type p after having passed a production step i
$\mathbf{QC}(c)$	$\mathcal{C}$	$\mathbb{N}_0$	-	Holding capacity of a container with components of type c
$\mathbf{WC}(c)$	$\mathcal{C}$	$\mathbb{R}_{\geq 0}$	kg	Weight of a full container with components of type c
$\mathbf{QPF}(p)$	$\mathcal{P}$	$\mathbb{N}_0$	-	Holding capacity of a container with finished goods of type p
$\mathbf{PF}(p)$	$\mathcal{P}$	$\mathcal{F}$	-	Finished goods container of product type p
$\mathbf{WF}(f)$	$\mathcal{F}$	$\mathbb{R}_{\geq 0}$	kg	Weight of an empty finished goods container of type f

Table 4.2: Static production-related properties

Transport-related Aspects

With regard to the transport-related characteristics to be reflected in the CM platform, we distinguish between vehicle restrictions, tariff system and routing properties considering both groupage services and direct non-stop transports (cf. table 4.3).

Vehicle Restrictions: As stated, we address the vehicle capacity only when planning direct non-stop transports, which is why we define the following two properties only for these transport forms. As such, the vehicle type of transport form v offers a certain number of pallet spaces and a maximum load capacity (in kg), which is reflected in $\mathbf{PSV}\colon \mathcal{V} \setminus \{1\} \to \mathbb{N}_0$ and $\mathbf{LC}\colon \mathcal{V} \setminus \{1\} \to \mathbb{N}_0$. Beyond that, and depending on the size and weight of the containers to be carried, the maximum possible number of those containers per pallet, the allowed stacking factor, the height and weight of the pallet carrier itself and the height and maximum load capacity of the vehicle, there is a maximum number of containers that can be accommodated per pallet space at most when making use of a certain transport form v. To capture this number, we use the notation $\mathbf{MCP}\colon (\mathcal{P} \times \mathcal{V}) \to \mathbb{N}_0$ for the transport of raw materials or semi-finished parts of a product type p, the notation $\mathbf{MCC}\colon (\mathcal{C} \times \mathcal{V}) \to \mathbb{N}_0$ for the transport of components of type c, the notation $\mathbf{MCPF}\colon (\mathcal{P} \times \mathcal{V}) \to \mathbb{N}_0$ for the transport of finished products of type p and the notation $\mathbf{MCF}\colon (\mathcal{F} \times \mathcal{V}) \to \mathbb{N}_0$ for the transport of empty finished goods containers of type f. In the case of groupage services ($v = 1$), it is advisable to calculate these figures on the basis of the vehicle class typically employed by the carrier.

Tariff System: Building on chapter 2.1.3, we calculate the transport costs of direct non-stop transports according to the tour-based approach. As a calculation base, we use the vehicle cost rate per freight kilometre $\mathbf{CT}\colon \mathcal{V} \setminus \{1\} \to \mathbb{R}_{\geq 0}$, which depends on the transport form v and the corresponding vehicle class that is being utilised. In addition, we use the expression $\mathbf{MCT}\colon \mathcal{V} \setminus \{1\} \to \mathbb{R}_{\geq 0}$ to capture the minimum cost rates, which must at least be paid per vehicle involved regardless of the distance driven.

In the case of a groupage service, we calculate the transport costs on an order basis. Usually, tariff tables are used for this purpose, in which the transport costs are defined piecewise and often degressively, as shown in fig. 2.15. Dimensions considered are the transport volume, e.g. reflected by weight classes or the number of pallets, and the distance, e.g. reflected by distance classes or transport regions (cf. A. Meyer 2015). An exemplary tariff table is shown in figure 4.1.

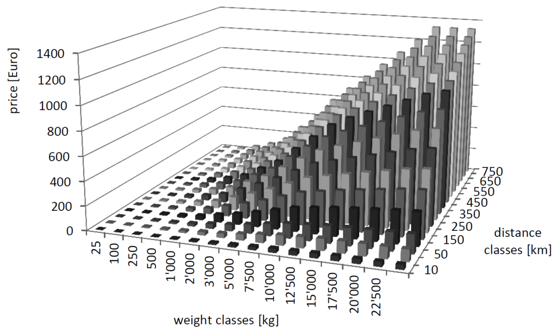

Figure 4.1: Exemplary tariff table (A. Meyer 2015)

Within this thesis, we make a simplifying assumption and allow piecewise degressively increasing transport costs only for the distance dimension. For the volume dimension, we limit ourselves to continuous linear cost functions in order to reduce the modelling complexity. Therefore we introduce the relations $\mathbf{CW}\colon (\mathcal{J} \times \mathcal{J}) \rightarrow \mathbb{R}_{\geq 0}$ and alternatively $\mathbf{CS}\colon (\mathcal{J} \times \mathcal{J}) \rightarrow \mathbb{R}_{\geq 0}$, which capture the (constant) increase rates in transport costs per kg and alternatively per pallet space depending on the distance class of a transport between two locations j and l. In addition to that, we use the expression $\mathbf{BC}\colon (\mathcal{J} \times \mathcal{J}) \rightarrow \mathbb{R}_{\geq 0}$ to represent the basic costs of a transport between j and l, which must be paid regardless of the volume. Fig. 4.2 exemplifies this approach.

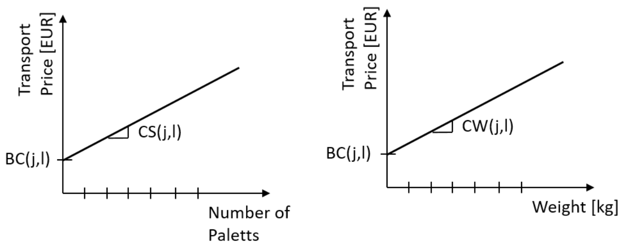

Figure 4.2: Tariff system of a groupage service between locations j and l

Routing: For both groupage services and direct non-stop transports, the direct distances between the locations of the network are needed to determine the resulting transport costs. Those distances are recorded for all locations $j, l \in \mathcal{J}$ in a distance matrix $\mathbf{D} \colon (\mathcal{J} \times \mathcal{J}) \rightarrow \mathbb{R}_{\geq 0}$ per kilometre. In order to be able to factor in possible travel time fluctuations and driver breaks, we do not calculate the travel time to the minute by dividing the distance by the average speed [1] but rather utilise a period-based time estimation. For this purpose, we define the relation $\mathbf{TT} \colon (\mathcal{J} \times \mathcal{J} \times \mathcal{V}) \rightarrow \mathbb{N}_0$, which captures the number of periods required for a transport between locations j and l when using transport form v (without taking into account any blocked periods, see below). The value 1 specifies, for example, that if a transport started in period t at location j, the delivery would be in $t+1$ at location l, assuming we do not have any blocked periods in between. To ensure a worst-case specification, the latest possible point in time within a period is assumed to be the starting time of the transport. Using this notation, we are able to reflect the different transport times of the different transport forms. In addition to that, we use the expression $\mathbf{PB} \colon (\mathcal{S} \times \mathcal{V}) \rightarrow \{0, 1\}$ to indicate whether a transport form v is allowed to be operated in a period of the type s (1) or not (0). This allows certain periods, such as Sundays, to be blocked for specific transport forms, and the travel time $\mathbf{TT}(j, l, v)$ is extended accordingly (cf. chapter 4.3).

Expression	Domain	Value Range	Unit	Description
		Vehicle Restrictions		
$\mathbf{PSV}(v)$	$\mathcal{V} \setminus \{1\}$	$\mathbb{N}_0$	-	Number of pallet spaces of a vehicle within transport form v
$\mathbf{LC}(v)$	$\mathcal{V} \setminus \{1\}$	$\mathbb{R}_{\geq 0}$	kg	Maximum load capacity of a vehicle within transport form v

[1] In the case of groupage services, we do not even know the actual distance travelled accurately

$\mathbf{MCP}(p,v)$	$\mathcal{P} \times \mathcal{V}$	$\mathbb{N}_0$	-	Maximum possible number of containers with raw materials or semi-finished parts of a product type p per pallet space in a vehicle within transport form v
$\mathbf{MCC}(c,v)$	$\mathcal{C} \times \mathcal{V}$	$\mathbb{N}_0$	-	Maximum possible number of containers with components of type c per pallet space in a vehicle within transport form v
$\mathbf{MCPF}(p,v)$	$\mathcal{P} \times \mathcal{V}$	$\mathbb{N}_0$	-	Maximum possible number of containers with finished goods of product type p per pallet space in a vehicle within transport form v
$\mathbf{MCF}(f,v)$	$\mathcal{F} \times \mathcal{V}$	$\mathbb{N}_0$	-	Maximum possible number of empty finished goods containers of type f per pallet space in a vehicle within transport form v
		Tariff System		
$\mathbf{CT}(v)$	$\mathcal{V} \setminus \{1\}$	$\mathbb{R}_{\geq 0}$	$\frac{€}{\text{km}}$	Vehicle cost rate per freight kilometre when using direct transport form v
$\mathbf{MCT}(v)$	$\mathcal{V} \setminus \{1\}$	$\mathbb{R}_{\geq 0}$	€	Minimum costs per vehicle when using direct transport form v
$\mathbf{CW}(j,l)$	$\mathcal{J} \times \mathcal{J}$	$\mathbb{R}_{\geq 0}$	$\frac{€}{\text{kg}}$	Increase rate in transport costs per freight kilogram when using a groupage service between locations j and l
$\mathbf{CS}(j,l)$	$\mathcal{J} \times \mathcal{J}$	$\mathbb{R}_{\geq 0}$	$\frac{€}{\text{Pallet}}$	Increase rate in transport costs per pallet space when using a groupage service between locations j and l
$\mathbf{BC}(j,l)$	$\mathcal{J} \times \mathcal{J}$	$\mathbb{R}_{\geq 0}$	€	Basic costs of a groupage service between locations j and l
		Routing		
$\mathbf{D}(j,l)$	$\mathcal{J} \times \mathcal{J}$	$\mathbb{R}_{\geq 0}$	km	Distance between plant j and plant l
$\mathbf{TT}(j,l,v)$	$\mathcal{J} \times \mathcal{J} \times \mathcal{V}$	$\mathbb{N}_0$	-	Number of periods required for a transport between locations j and l when utilising transport form v

$\mathbf{PB}(s, v)$	$\mathcal{S} \times \mathcal{V}$	$\{0, 1\}$	-	Indicates whether transport form v is allowed to be operated in a period of type s (1) or not (0)

Table 4.3: Static transport-related properties

4.1.3 Dynamic Properties

After having described the static properties of the system, we will now address the time-dependent dynamic properties, which must be updated in a regular manner. We will look at the planning horizon as well as on capacity- and inventory-related aspects (cf. table 4.4).

Planning Horizon: When starting a planning run in the CM platform, the current period is set to $t = 0$. The planning horizon itself starts in the next period, i.e. in the period $t = 1$. Every period t of the planning horizon is uniquely assigned to a period type s. To represent this relationship, we use the expression $\mathbf{PH}\colon \mathcal{T} \to \mathcal{S}$.

Capacity: The approach of this work is based on the idea of exploiting the available capacities of the production resources. To represent the available capacity (in minutes) of a resource r in a period t, we use the expression $\mathbf{AC}\colon (\mathcal{R} \times \mathcal{T}) \to \mathbb{R}_{\geq 0}$. The available capacity of a resource r can either be determined manually by a planner or be calculated by subtracting the planned processing times of the production program in period t from the maximum available working time, adjusted for losses in the overall equipment effectiveness (OEE) (cf. formula 6.1). Also, previously unused shifts, such as Sunday shifts, may be included as further usable slots. In addition to that, we introduce the relation $\mathbf{SH}\colon (\mathcal{R} \times \mathcal{T} \times \mathcal{P}) \to \{0, 1\}$ to indicate whether a product p is already produced on resource r in a period t (1) or not (0). In this way, it is possible to exploit already planned set-up times when using the CM platform.

Inventory: The number of full containers with parts of type p that have passed through production step i, i.e. raw materials ($i = 0$), semi-finished products ($i > 0 \wedge i < I_{max}$) or finished goods ($i = I_{max}$), and which are available from period t on at location j in order to be used by the CM platform, is recorded in $\mathbf{IP}\colon (\mathcal{P} \times \mathcal{I} \cup \{0\} \times \mathcal{J} \times \mathcal{T}) \to \mathbb{N}_0$. Materials already available at the start of planning are captured via the parameter setting $t = 0$. The same logic applies to the number of full containers with components of type c ($\mathbf{IC}\colon (\mathcal{C} \times \mathcal{J} \times \mathcal{T}) \to \mathbb{N}_0$) and the number of empty finished goods containers of type f ($\mathbf{IF}\colon (\mathcal{F} \times \mathcal{J} \times \mathcal{T}) \to \mathbb{N}_0$) being available at location j from period t on in order to be used by the CM platform.

The quantity and the point in time from which on materials are made available to the CM platform can be determined manually by the planner or be calculated by comparing existing stocks, notified deliveries and planned production quantities. One strategy could be, for example, to declare anything as usable for the CM platform that is excess stock (including the notified deliveries) compared to what is planned to be needed within the expected replenishment lead time of the supplier of the respective raw material, component or finished goods container.

Fig. 4.3 shows an example of how the stock level develops over time depending on the notified deliveries and the planned consumption. If a minimum stock level of two containers is assumed, it can be seen that from period $t = 2$ onwards, one container can be made available at the considered plant to be used by the CM platform. The quantity offered on the platform, which is being handled as a (theoretical) consumption element in the table, corresponds to the maximum possible number of containers that can be withdrawn from the stock at the earliest possible time, with the minimum stock level still being maintained throughout the entire replenishment lead time.

Algorithm 1 uses the example of raw materials (**IP**) to demonstrate how the providable stock quantities can be determined algorithmically.

In order to increase the number of materials made available to the platform, it is furthermore possible to record the maximum possible delivery

Algorithm 1: Determining the providable inventory

```
Input: Consumption_t, Deliveries_t, InitalStock,
       ReplenishmentLeadTime, MinimumStockLevel
IP_t ← 0
for t ← 1 to ReplenishmentLeadTime do
   Continue ← true
   while Continue == true do
      IP_t ← IP_t + 1
      for t_1 ← 1 to ReplenishmentLeadTime do
         if t_1 == 1 then
            Stock_{t_1} ← InitStock +
               Deliveries_{t_1} − Consumption_{t_1} − IP_{t_1}
         else
            Stock_{t_1} ← Stock_{t_1−1} +
               Deliveries_{t_1} − Consumption_{t_1} − IP_{t_1}
         end if
         if Stock_{t_1} < MinimumStockLevel then
            IP_t ← IP_t − 1
            Continue ← false
            break
         end if
      end for
   end while
   if IP_t > 0 then
      break
   end if
end for
Output: IP_t
```

		Replenishment lead time of the supplier			
	t=0	t=1	t=2	t=3	t=4
Planned consumption		5	2	4	
Notified deliveries		2	4	3	
Stock at the end of the period	5	2	4	3	
IP/IC/IF			1		20
Stock at the end of the period under consideration of IP/IC/IF	5	2	3	2	

Figure 4.3: Determining the quantity and the point in time from which on materials can be made available to the CM platform assuming a minimum stock level of 2 containers

quantity to be defined in advance with the supplier in the corresponding inventory variables of the plants (**IP**, **IC** or **IF**) in the first time slot after the replenishment lead time has ended. If the platform calls off from this (theoretically available) stock when solving the SLSP, the quantity can be ordered in real terms from the supplier at time $t = 0$, so that it is physically available in the plant at the calculated call-off time. In the above example, we have assumed a replenishment lead time of 3 periods and a maximum quantity of 20 containers providable after this period of time.

An alternative approach, which is in general also possible with the models developed in this work, is to include the 2nd-tier suppliers as participating sites of the production network, which offer their material resources (raw materials, components, finished goods containers) directly on the platform. The lead times and provisionable quantities of the suppliers can be recorded in **IP**, **IC** and **IF** without having the platform to consider their production resources and production processes. The planning of the transports from the suppliers to the plants is done by the platform in this case.

In the further course of this work, however, we will stick to the first option mentioned, as this helps to keep the number of participants small and thus reduces the complexity of the optimisation problem. Apart from that, more options are given to the suppliers to conduct their own plannings and consolidations.

For the semi-finished parts, analogous to the above-mentioned material groups, a comparison can be made between the planned consumption of the downstream stage, the planned production quantity and the minimum stock level to be guaranteed in order to see from when which quantities can be made available to the platform (**IP**). In contrary to the above, however, it is advisable in this case to consider the entire planning horizon when looking at whether the minimum stock level is met.

Expression	Domain	Value Range	Unit	Description
		Planning Horizon		
$\mathbf{PH}(t)$	$\mathcal{T}$	$\mathcal{S}$	-	Period type of planning period t
		Capacity		
$\mathbf{AC}(r,t)$	$\mathcal{R} \times \mathcal{T}$	$\mathbb{R}_{\geq 0}$	min	Available capacity of a resource r in a period t
$\mathbf{SH}(r,t,p)$	$\mathcal{R} \times \mathcal{T} \times \mathcal{P}$	$\{0,1\}$	-	Indicates whether a product p is already produced on resource r in a period t (1) or not (0)
		Inventory		
$\mathbf{IP}(p,i,j,t)$	$\mathcal{P} \times \mathcal{I} \cup \{0\} \times \mathcal{J} \times \mathcal{T}$	$\mathbb{N}_0$	-	Number of full containers with parts of type p, that have passed through production step i, i.e. raw materials ($i = 0$), semi-finished products ($i > 0 \wedge i < I_{max}$) or finished goods ($i = I_{max}$), and which are available from period t on at location j in order to be used by the CM platform
$\mathbf{IC}(c,j,t)$	$\mathcal{C} \times \mathcal{J} \times \mathcal{T}$	$\mathbb{N}_0$	-	Number of full containers with components of type c being available form period t on at location j in order to be used by the CM platform

$\mathbf{IF}(f, j, t)$	$\mathcal{F} \times \mathcal{J} \times \mathcal{T}$	$\mathbb{N}_0$	-	Number of empty finished goods containers of type f being available form period t on at location j in order to be used by the CM platform

Table 4.4: Dynamic properties of the system

4.2 Use of the CM Platform

Having described the underlying data model, we will now look at the use of the CM platform.

The motivation for using the CM platform arises from a production-related disruption. As described in chapter 2.2.2, such a disruption can be induced internally or externally, affecting the production process, the resource provisioning or the production program. In the context of this thesis, we will abstract those dimensions of causes by looking at the resulting effects in a production system based on a distinction between *shortfall quantities* and *excess quantities*. In the following two sections, we will discuss both types of disturbance effects and describe how they can be translated into an order on the CM platform.

4.2.1 Shortfall Quantities

The first disturbance effect we are looking at is characterised by the fact that *temporarily only a reduced amount of resources is available, while the order quantity remains unchanged*. Those resources can refer to both production resources, i.e. machines and assembly lines, and material resources, i.e. (raw) materials, components and finished goods containers. Examples of disruptions that lead to a temporary limited availability of production resources are partial or complete breakdowns of machines. Examples of disruptions that result in a temporary lack of available material resources are delayed deliveries from suppliers. In both cases, it is likely to happen that the production steps cannot be carried out as originally planned due to a lack of materials or because machines or assembly stations are not or only partially available. A **shortfall quantity** occurs.

Figure 4.4 illustrates the effects of such a disruption. The production step marked with the flash is temporarily interrupted due to unavailable resources, resulting in a shortfall quantity. The subsequent station, which follows without being buffered, has to stop its production shortly afterwards due to a lack of incoming parts. If the following larger buffer to the next planning area is not able to absorb the length of the downtime, the production steps in this area will be interrupted after a certain time as well. The disruption continues to propagate (cf. chapter 2.2.1).

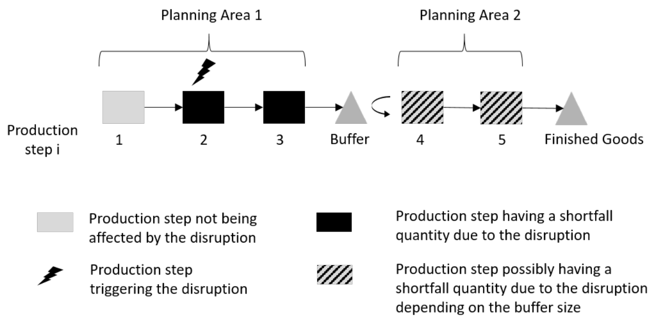

Figure 4.4: Impact of a disruption leading to a shortfall quantity on the production process

Depending on the estimated duration of a disruption, it is task of the planner to identify the affected production steps so that the resulting shortfall quantities can be ordered via the CM platform.

The calculation of the resulting shortfall quantities is exemplified in figure 4.5, based on the above example of a site $j = 1$ comprising two planning areas in which a single product $p = 1$ is produced with an offset of one day. The planning areas include 3 and 2 production steps, respectively, each with one resource for the sake of simplicity.

We assume a processing time of 1 hour per container to be processed, regardless of the production step. Production step $i = 2$ in planning area 1 is interrupted in period $t = 0$ due to a disruption, which leads to a shortfall quantity of 5 containers in the steps $i = 2$ and $i = 3$ in period $t = 0$. Planning area 2 is decoupled from planning area 1 by a buffer of 2 containers before production step $i = 4$. However, these containers go into use in the second period since no parts have been delivered from planning area 1. But as 5 containers were originally planned, there is still a shortage of 3 containers in the steps $i = 4$ and $i = 5$ in period $t = 1$. The remaining production quantities can be produced as originally planned.

				Production Plan			
	Step i	Resource r	Buffer before step i (IQ(p,i))	t=0	t=1	t=2	t=3
Planning Area 1	1	1		5	4	6	5
	2	2		~~5~~ → 0	4	6	5
	3	3		~~5~~ → 0	4	6	5
Planning Area 2	4	4	~~2~~ → 0		~~5~~ → 2	4	6
	5	5			~~5~~ → 2	4	6

Disruption

Figure 4.5: Exemplary calculation of shortfall quantities resulting from a disruption in production step $i = 2$ in period $t = 0$

Looking at the entire planning horizon, the disruption results in 2 missing containers with parts taken from the buffer before step $i = 4$ and 3 missing containers with finished goods. The planner of the affected site could therefore anticipatively order both resulting shortfall quantities at period $t = 0$ via the CM platform by specifying in $\mathbf{Q}\colon (\mathcal{P} \times \mathcal{I}) \rightarrow \mathbb{N}_0$ how many containers with parts of type p that have passed through production step i he wants to receive. In this regard, it should be noted that different product variants with different product levels can be requested simultaneously. In our example, a planner would thus order the quantities $\mathbf{Q}(1,3) = 2$ and $\mathbf{Q}(1,5) = 3$.

In algorithm 2, the calculation of the order quantity $\mathbf{Q}(p,i)$ to be placed on the CM platform in the above-introduced situation is formally described. A planner therefore needs to know which production step i_t is triggering the disruption, how many containers with parts of type p

are being produced less than originally planned during the duration of the disruption in the affected production step ($\mathbf{SQ}(p)$) and how many full containers with parts of type p are being buffered before a production step i ($\mathbf{IQ}(p,i)$). In the above example, those quantities are $i_t = 2, \mathbf{SQ}(1) = 5$ and $\mathbf{IQ}(1,4) = 2$.

Algorithm 2: Calculating $\mathbf{Q}(p,i)$

```
Input: SQ(p), i_t, IQ(p,i)
  for p ← 1 to P_max do
    for i ← (i_t + 1) to I_max do
      Q(p, i − 1) ← min{SQ(p), IQ(p,i)}
      SQ(p) ← (SQ(p) − Q(p, i − 1))
      if SQ(p) == 0 then
        stop
      end if
      if i == I_max then
        Q(p,i) ← SQ(p)
      end if
    end for
  end for
Output: Q(p,i)
```

In addition to the order quantity $\mathbf{Q}(p,i)$, the CM platform receives information about the affected production step (i_0), from which on a rescheduling is to be made, and the plant ordering (j_0). Hence, in our example $i_0 = i_t = 2$ and $j_0 = 1$. Optionally, a planner can specify the time window in which an order should be delivered. $\mathbf{TE}(p,i)$ describes the earliest period in which an order $\mathbf{Q}(p,i)$ is allowed to be delivered, $\mathbf{TL}(p,i)$ the latest period. This is especially interesting if finished goods are affected by a shortage, yet the customer's time window should still be kept. As the last input parameter, we include the planner's weighting of the decision criteria costs ($\alpha \in (0,1)$) and time ($1-\alpha$), which is used to find an appropriate solution for the multi-criteria optimisation problem we are considering.

A summary of the *order information* transmitted as input data to the CM platform is given in table 4.5.

Expression	Domain	Value Range	Unit	Description
$\mathbf{Q}(p,i)$	$\mathcal{P} \times \mathcal{I}$	$\mathbb{N}_0$	-	Number of full containers with parts of type p that have passed through production step i ordered on the CM platform
i_0	-	$\mathcal{I}$	-	Production step, from which on a rescheduling is to be made
j_0	-	$\mathcal{J}$	-	Ordering plant
$\mathbf{TE}(p,i)$	$\mathcal{P} \times \mathcal{I}$	$\mathcal{T}$	-	Earliest period in which an order with parts of type p that have passed through production step i is allowed to be delivered
$\mathbf{TL}(p,i)$	$\mathcal{P} \times \mathcal{I}$	$\mathcal{T}$	-	Latest period in which an order with parts of type p that have passed through production step i is allowed to be delivered
α	-	$(0,1)$	-	Weighting of the decision criterion *costs*. The weighting of the criterion *time* results from $(1-\alpha)$

Table 4.5: Order information submitted as input to the CM platform

Furthermore, we need to update the *dynamic quantities* of the production network. Using the above example, a planner could, for instance, capture the *available capacities* resulting from the lower production quantities in production steps $i = 4$ and $i = 5$ in period $t = 1$ in $\mathbf{AC}(4,1) \leftarrow (\mathbf{AC}(4,1) + 180)$ and $\mathbf{AC}(5,1) \leftarrow (\mathbf{AC}(5,1) + 180)$ in order to make them accessible for planning in addition to the available capacities in the network already gathered. In addition, any stated available capacity, as well as the produced product types at a broken down production resource, are to be set to 0 for the affected periods. Also, the data on *available materials* should be kept up to date. In the above example, the 5 freed-up containers with parts not being processed after production step $i = 1$ due to the downtime of production step $i = 2$ can be added to $\mathbf{IP}(1, 1, 1, 0) \leftarrow (\mathbf{IP}(1, 1, 1, 0) + 5)$ as materials available for the planning of the CM platform from period $t = 0$ onwards. Besides, it must be ensured that materials declared in advance as available to the CM platform at the ordering plant j_0 are not considered twice in the order quantity. We therefore need to set all entries of $\mathbf{IP}(p, i, j_0, t)$ to 0 for which $i \geq i_0$ applies.

Practical Usage

In the above example, we have assumed a cross-planning area perspective. This perspective seems to make sense especially when facing a **closely coupled** material flow. In the following, we will show how the approach can be transferred to practical planning situations with the different planning areas being more strongly **decoupled** from each other. This is the case, for example, in the production network under consideration, where the planning areas usually do not exactly follow the call-off pattern of the respective downstream planning area (customer) - mainly due to the pursued levelling approach.

If, due to the larger buffers required for decoupling, a longer period of time elapses before the downstream area is affected by a material shortage, it may be possible to reschedule the affected orders of the area under consideration within this period of time so that ordering of products from subsequent stages can be avoided. In order to determine the point in time at which a shortage occurs, an inflow-outflow chart can be used, which shows the inventory development on the basis of out-flowing (internal) customer call-offs and in-flowing production quantities (cf. fig. 4.6). The identified shortfall quantity can be ordered on the CM platform using the introduced parameters (cf. table 4.5) with the latest delivery date being set to the period before the shortfall quantity would appear. If the CM platform finds a solution to this problem, the succeeding downstream planning areas can be neglected since they can still be served on time. In the illustrated example, a planner would accordingly order the quantity $\mathbf{Q}(1, 3) = 5$ with the latest possible delivery date being set to $\mathbf{TL}(1,3) = 3$. If the downstream area is not affected by a disruption (no negative buffer level occurs), the planner could still use the CM platform to replenish the stock, i.e. order the quantity $\mathbf{Q}(1,3) = 5$ without defining a latest possible delivery date. If, on the other hand, no solution could be found within the defined time frame, the subsequent planning area must be taken into account as well. A planner would accordingly order the quantity $\mathbf{Q}(1,3) = 3$ to fill up the buffer of planning area 1 and the quantity $\mathbf{Q}(1,5) = 2$ to cover the shortage of planning area 2, with $\mathbf{TL}(1,5)$ being determined analogously to the above example with an inflow-out-flow chart.

			Production Plan				
	Step i	Resource r	t=0	t=1	t=2	t=3	t=4
Planning Area 1	1	1	5 → 0	3	3	2	0
	2	2	5 → 0	3	3	2	0
	3	3	5 → 0	3	3	2	0
Planning Area 2	4	4	1	2	2	4	4
	5	5	1	2	2	4	4

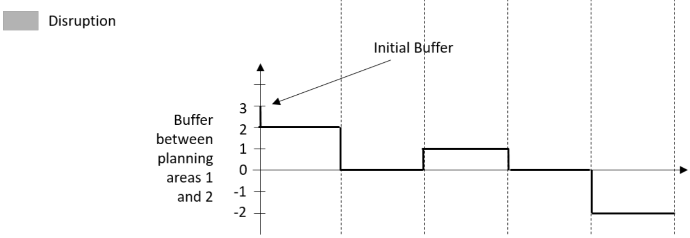

Figure 4.6: Exemplary calculation of the shortfall quantities resulting from a disruption in production step $i = 1$ in period $t = 0$ using an inflow-outflow-chart

To conclude this chapter, we would like to note that the described usage of the CM platform relies on a push-based production planning with defined production plans, as carried out in our used example. Affected production orders that would otherwise have been moved to the backlog in order to be added again to the plan manually if capacity is available, as it is practice in the production network under consideration (cf. algorithm 3 in chapter 6.1), can now be rescheduled to other locations and resources within the frozen (levelling) horizon [2].

The aforementioned does, as a short excursus, however, not exclude the possibility to use the concept in a pull-based system. The production pattern of a heijunka-levelled pacemaker process is based on the expected customer demand (cf. Veit 2010). If a possibly included capacity buffer is not sufficient to promptly reduce a shortfall quantity, which is reflected by the fact that the backlog (as part of the overflow) reaches its control limits as it is filled with deferred production orders, CM-based rescheduling seems to be suitable as well. Accordingly, a planner could use the CM platform to reschedule any backlogged orders at the pacemaker process to other resources and locations within the frozen levelling period, ideally without having to consider the preprocessing steps of the planning area due to a consumption controlled replenishment.

4.2.2 Excess Quantities

The second disturbance effect we are considering is characterised by the fact that *additional order quantities are being inserted while the resources remain unchanged.* Examples of disruptions that lead to this kind of disturbance effect are short-term volume increases in existing customer orders and new rush orders from customers. In both cases, the production has to cope with an **excess quantity** not being planned originally.

As shown in figure 4.7, this type of disruption possibly affects the entire production process, depending on the buffer sizes. As such, additional finished goods are requested, which can either be provided from finished goods buffers in the network or be produced from available semi-finished products or raw materials in the network ($\mathbf{IP}(p, i, j, t)$). In the worst case, the entire production process must be carried out in order to

[2] A restriction to the frozen zone is of course not mandatory. However, since the later planning periods still can change, it seems to make sense to limit the planning to the frozen short-term horizon as far as possible.

manufacture the additional quantity. It is the task of the CM platform to find a solution to this problem.

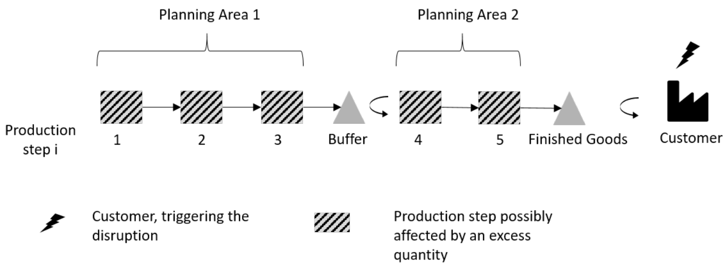

Figure 4.7: Impact of a disruption leading to an excess quantity on the production process

The order information to be submitted to the CM platform in the case of an excess quantity includes the parameters already introduced in table 4.5. The additional quantity to be planned via the CM platform is recorded in $\mathbf{Q}(p,i)$, whereby $i = I_{max}$ applies since finished products are being considered. Those finished products may be used to replenish the finished goods buffer from which the additional demand was served or to satisfy the customer demand directly. In both cases, the complete excess quantity is ordered on the CM platform. Building on the example from the previous chapter, if, for instance, a customer of plant $j_0 = 1$ increases its demand for parts of type $p = 1$ by 3 containers, this could be expressed by setting $\mathbf{Q}(1,5) = 3$. With regard to the parameter i_0, the CM platform needs to take notice of the whole production process, i.e. $i_0 = 1$ is to be set, since all production steps must be carried out in the worst case. Additionally, it is possible to include the delivery time window of the customer using the parameters $\mathbf{TE}(p,i)$ and $\mathbf{TL}(p,i)$ as well as the planner's weighting of the decision criteria costs and time (α), analogous to the previous chapter.

Since the remaining production continues as originally planned, in contrast to the preceding section, no additional capacities and materials are being freed up, which could be made available to the CM platform for planning purposes.

As a concluding side note, we would like to point out once again that the use of the CM platform can also be helpful when operating a pull system. This is especially true when an incoming excess quantity exceeds the demand fluctuations taken into account in the levelling process resulting in a full overflow at the pacemaker step. A planner could, in that case, use the CM platform to reschedule the resulting quantity above the control limit.

4.2.3 Combination of Shortfall Quantities and Excess Quantities

Excess quantities and shortfall quantities can also occur in combination. This is the case, for example, when production orders are to be reissued due to quality-related scrap detected during quality control. As shown in figure 4.8, one possible consequence is a shortfall quantity at the downstream stages due to a lack of replenishment. On the other hand, the upstream processes are threatened by an unplanned excess quantity as those production steps possibly are to be repeated depending on the available stocks in the network.

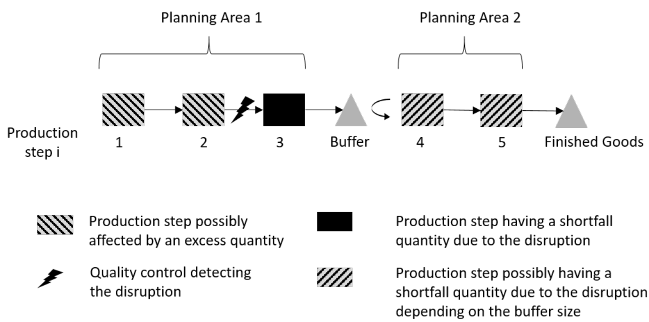

Figure 4.8: Impact of a disruption leading to excess and shortfall quantities on the production process

Using the CM platform in this case, the resulting shortfall quantities are to be ordered ($\mathbf{Q}(p,i)$), which can be determined according to the logic described in chapter 4.2.1. Since, depending on the stocks available for the platform, the production process has to be run through again from the first step onwards in the worst case, $i_0 = 1$ is to be set. Furthermore, the ID of the ordering plant (j_0), a possible delivery time window ($\mathbf{TE}(p,i)$ and $\mathbf{TL}(p,i)$), as well as the planner's weighting of the decision criteria costs and time (α) are submitted as input data to the platform (cf. table 4.5).

If the downstream processes cannot be operated as originally planned due to a lack of replenishment, the freed-up capacities and materials can be added to the dynamic input variables as described in chapter 4.2.1. Likewise, we need to adjust the inventory data ($\mathbf{IP}$) in order to avoid that materials are considered twice with respect to the order quantity (cf. chaper 4.2.1).

Figure 4.9 summarises the properties of the different disturbance effects described in the last chapters, as well as how they can be translated into an order on the CM platform.

4.3 Functional Principle of the CM Platform

In the last chapter, we have looked at how the CM platform can be used in a disruption event. In the upcoming sections, we will address the platform's functional principle. We will first give an overview on the basic concept of the CM platform (chapter 4.3.1), introducing the architecture and describing the order processing. Afterwards, we will focus on the core of the order processing procedure, the service composition process, into which the SLSP is integrated (chapter 4.3.2).

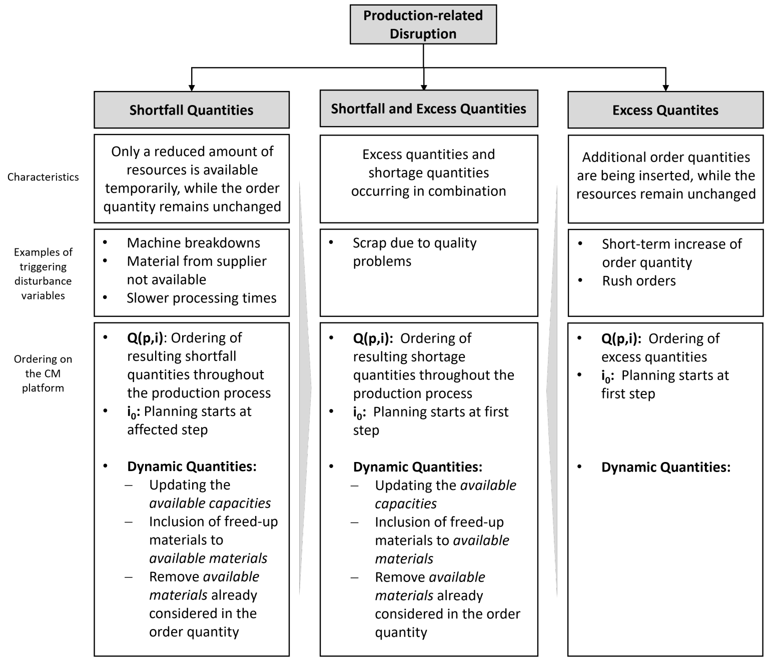

Figure 4.9: Summary of the disturbance effects occurring in a production and how they can be translated into an order on the CM platform

4.3.1 Basic Concepts

In this section, an overview of basic concepts of the CM platform developed in this thesis will be given, covering both the general architecture as well as the order processing. Nonetheless, we would like to note that the focus lies on describing the underlying logic rather than on delineating a concrete technical implementation.

Architecture

Building on chapter 2.3.3, this section outlines the architecture of the developed CM platform. Fig. 4.10 illustrates the basic structure in the form of a multi-layer architecture scheme.

The physical world of the production network - i.e. the production resources and material resources - together with different forms of transportation are described abstractly in a **virtualisation layer**. To virtualise the **physical layer**, we use the data model presented in chapter 4.1. The quantities listed in table 4.1 represent the basic entities of the network embodying the underlying locations, machines, production steps, products, transport forms and materials.

In the **middleware layer**, various functionalities are offered to the users of the platform, i.e. the operator, the different plants of the network and the freight forwarder. New entities and their static production- and transport-related properties and relations can be added to the network with the *network configuration* functionality. Since the CM platform is considered to be private, this functionality, which can be used, for example, to add a new plant and create a new account for it, is restricted to the operator, respectively administrator of the platform, e.g. the lead factory of the network. The individual plants can use the *production configuration* functionality to add in a multi-tenant way their production resources and maintain the corresponding data listed in the same-named section in table 4.2. As stated in chapter 2.1.1, those locations do not necessarily have to be company-owned sites but can also be external sites that are involved in the internal production network, as long as the described requirements regarding data sovereignty and approvals are met. The *dynamic data update* function furthermore allows the plants to control what is offered on the CM platform in terms of capacity and inventory by dynamically adapting the datasets described in the same-named sections in table 4.4. With regard to the transport side, the platform provides a separate portal for the freight forwarder enabling him to add and change the transport forms offered and maintain the corresponding data listed in table 4.3 by using the *transport configuration* functionality.

In addition to the introduced middleware functionalities for adapting and updating the data basis of the production network, there are further functions for *managing the user and order data* recorded in separate databases, e.g. to manage the user login or to view existing orders. The actual value proposition of the platform, however, lies in the *service composition* process that is executed during order processing upon called-up by a plant and which we will introduce in more detail in chapter 4.3.2.

In order to control and display the various functionalities described, the users are on the highest architectural level able to interact with the system via a **graphical user interface**.

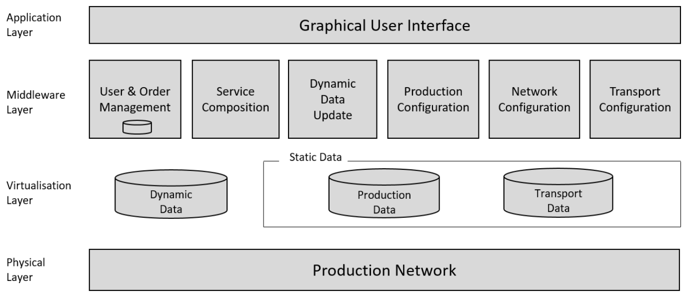

Figure 4.10: Conceptual architecture of the CM platform developed

A prototypical implementation of the described conceptual architecture as a web application has been realised within this work together with Laensitalo (2020). As shown in fig. 4.11, the system is based on a microservice design pattern, with an API gateway controlling the data exchange between the components as well as the management of the databases, i.e. the user & order management, the dynamic data update, the production configuration, the network configuration and the transport configuration. The main logic of the platform, the service composition, is implemented as a separate microservice that is addressed via HTTP requests using a REST API. The microservice retrieves the static and dynamic data required for the calculation directly from the database.

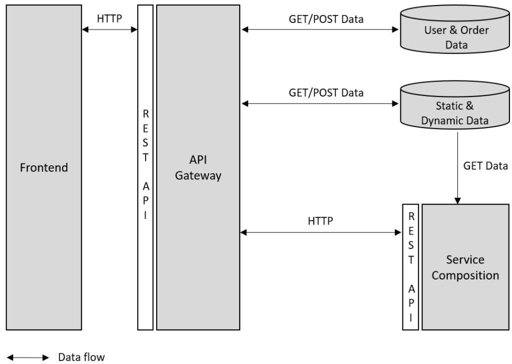

Figure 4.11: IT architecture of the CM platform developed (based on Laensitalo 2020)

Order Processing

The order processing procedure is triggered once a site affected by a disruption updates the dynamic data as described in chapter 4.2 and enters the input data specified in table 4.5 into the system via the user interface. The order data is handed over to the service composition microservice. The microservice fetches the required static and dynamic data from the database and tries to find a solution for an ad hoc value stream according to the service composition process explained below. Due to the multi-criteria optimisation character, there is usually not only a single Pareto optimal solution point. Therefore, the microservice determines several solutions (cf. 5.3.3). In particular, a cost-optimised, a time-optimised and a solution meeting the customer's target weighting are being calculated. If solutions could be found, these are subsequently reported back to the frontend and displayed with the resulting costs and times to the orderer for confirmation.

Depending on the solution chosen by the customer, the freight forwarder and the locations concerned receive information about the steps they are involved in. The selected production sites are informed about which product type is to be produced in which quantities and in which period of time. Additionally, they obtain information about which quantities of which product type or material are being picked up or delivered at a certain period. Likewise, it is displayed which quantities of which materials need to be ordered from the suppliers with a certain delivery date, based on the predefined delivery forecasts (cf. chapter 4.1.3). The freight forwarder receives information about which quantities of which product type or material are to be transported in a specific period with a selected transport form between two selected locations. Moreover, the system needs to subtract the materials and capacities used by the CM platform from **IP**, **IC**, **IF** and **AC** and keep the produced product types captured in **SH** updated.

In case no solution can be found due to a lack of available materials or capacities, the orderer - if helpful in cooperation with the lead factory - is requested to coordinate with the other locations of the network on how additional materials and capacities can be made available for the CM platform in order to increase the solution space within a recalculation. Any additional material deliveries ordered from the suppliers can be added to **IP**, **IC** or **IF**, and any additional capacity made available for CM planning can be added to **AC**. Additional capacities can be made available, for example, by offering further extra shifts. However, if the production is highly utilised, it can also be helpful to free up additional capacities by deferring other products. Using an inflow-outflow chart, a planner could evaluate, for example, if it is possible to reduce the production of a high-runner product, as it is recommended in the production guidelines of the Robert Bosch GmbH when facing a capacity bottleneck.

If deviations occur during the subsequent execution process, a recalculation may become necessary as well. For this purpose, the status of an order is recorded in order to stop the current process, release the planned materials and capacities and trigger a recalculation in case of process derogations.

The order processing procedure described is summarised in a Unified Modeling Language (UML) activity diagram displayed in fig. 4.12. Appendix A furthermore provides a selection of screenshots showing how the frontend visualisations were realised in the prototype implementation developed as part of this work.

It is to be noted, however, that the described concept does not consider any interfaces to other systems, such as production and transport planning software. The same applies to the developed prototype, which was implemented as a stand-alone platform. All static and dynamic data therefore needs to be maintained via frontend input. Though, real added value in practical use is only achieved with proper system connections. In case interfaces to other planning systems exist, the static and dynamic production data could be kept up to date automatically, allowing to directly derive the needed information from available production plans and inventory data. Likewise, the created production and purchase requests could be immediately transferred back to the planning software of the plants. With regard to the transport, we would like to recall that the freight forwarder has its own platform access in the described concept. In a practical implementation, however, it is also conceivable that the transport is managed by a separate transport management system of the company, which provides the necessary static transport planning data and finally commissions the freight forwarder.

4.3.2 Service Composition Process

The service composition process of the designed CM platform is based on the process flow described in chapter 2.3.4 and follows a 4-step procedure illustrated in figure 4.13. The first three steps aim to prepare the presented data (table 4.1, 4.2, 4.3, 4.4 and 4.5) in such a way it can be used as input for the SLSP while keeping the problem instance as small as possible. In the fourth process step, the service selection,

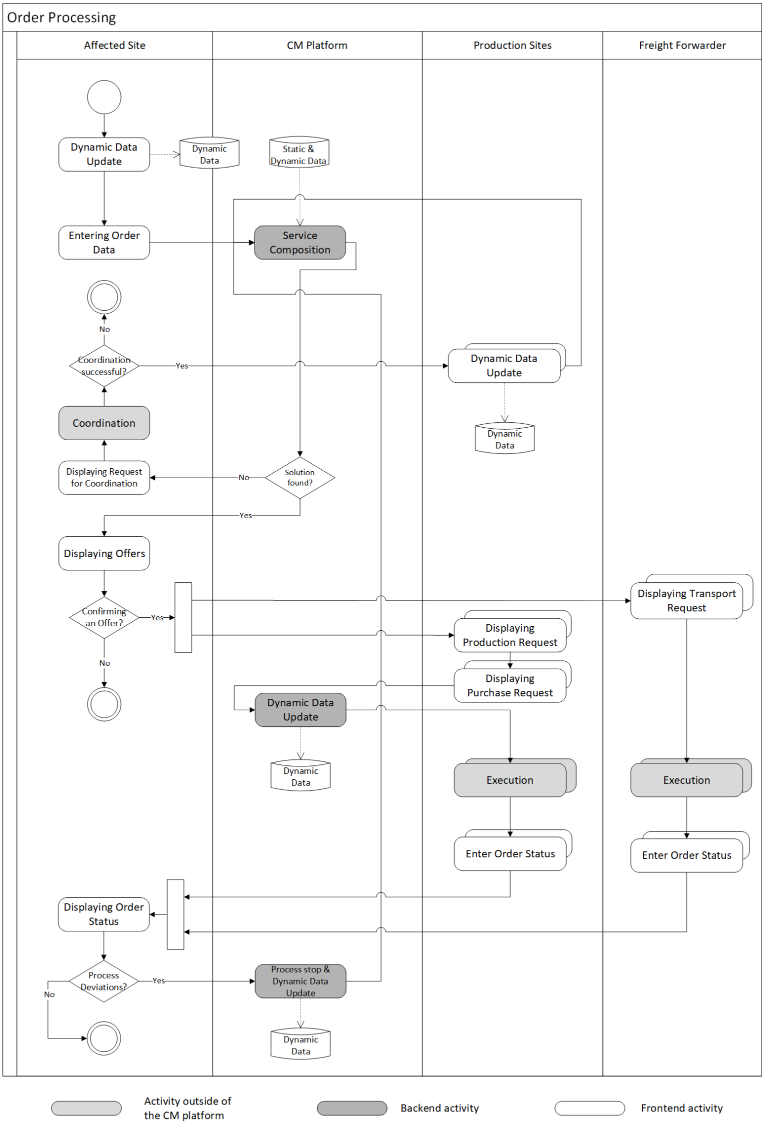

Figure 4.12: Order processing procedure of the CM platform developed

the SLSP is solved in order to generate an ad hoc value chain. In the following sections, we will look at the individual steps of the service composition process in detail.

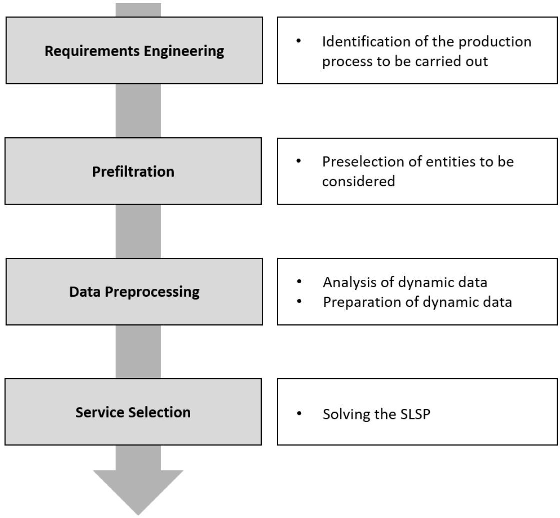

Figure 4.13: Service composition process of the CM platform developed

Requirements Engineering

It is the task of the requirements engineering step to derive the production process to be planned from the order information provided by the customer. Since we are looking at a production network with known products, the required production steps and their sequence do not have to be derived from a CAD file or a technical drawing first but are already predefined. Each product type passes through the steps contained in $\mathcal{I}$ in the same ascending order starting with step $i = 1$ and ending with step $i = I_{max}$. However, since it is advisable in terms of computing time performance to keep the problem instance as small as possible, it is helpful not to consider all production steps in the optimisation problem. We therefore restrict the input space of the SLSP to the steps between i_0 and i_{max}, which is defined accordingly to formula 4.1.

$$i_{max} := \arg\max_i \{\mathbf{Q}(p,i) \mid p \in \mathcal{P} \land i \in \mathcal{I} \land \mathbf{Q}(p,i) > 0\} \tag{4.1}$$

Only those production steps are relevant for the optimisation problem. All further steps proceed as originally planned and do not need to be taken into account in the SLSP. The set of production steps to be considered in the optimisation problem is thus expressed by $\tilde{\mathcal{I}} \subseteq \mathcal{I}$, as defined in formula 4.2:

$$\tilde{\mathcal{I}} := \{i \in \mathcal{I} \mid i \geq i_0 \land i \leq i_{max}\} \tag{4.2}$$

In order to be able to use the filtered set as an input in the SLSP, we perform an index transformation based on the positions of the elements with the aim of defining a substitute index set that starts to count from the value 1 (cf. eq. 4.3). In this respect, $Pos_{\tilde{\mathcal{I}}_T} : \tilde{\mathcal{I}} \rightarrow \mathbb{N}$ represents the position of an element $i \in \tilde{\mathcal{I}}$ in $\tilde{\mathcal{I}_T}$, with $\tilde{\mathcal{I}_T}$ being a tuple containing the elements of $\tilde{\mathcal{I}}$ ascendingly sorted.

$$\hat{\imath} \in \hat{\mathcal{I}} := \{Pos_{\tilde{\mathcal{I}}_T}(i) \mid i \in \tilde{\mathcal{I}}\} \tag{4.3}$$

For example, if the steps $i = 4$, $i = 5$ and $i = 6$ are to be considered, i.e. $\tilde{\mathcal{I}_T} = (4, 5, 6)$ applies, $\hat{\mathcal{I}} = \{1, 2, 3\}$ is received with $\hat{\imath} = 1$ representing step $i = 4$.

Prefiltration

Based on the identified production steps and the order information submitted, the relevant entities are filtered out of the basic quantities presented in table 4.1, again with the goal of keeping the problem instance as small as possible.

Firstly, only those product types that are ordered by the customer need to be considered in the optimisation problem. This is captured by the quantity $\tilde{\mathcal{P}} \subseteq \mathcal{P}$ defined in formula 4.4:

$$\tilde{\mathcal{P}} := \{p \in \mathcal{P} \mid \exists i \in \mathcal{I} : \mathbf{Q}(p, i) > 0\} \tag{4.4}$$

Analogous to the production steps, a new index set is defined with the help of the positions of the elements $p \in \tilde{\mathcal{P}}$ in $\tilde{\mathcal{P}_T}$ with $\tilde{\mathcal{P}_T}$ being an tuple containing the elements of $\tilde{\mathcal{P}}$ ascendingly sorted: $Pos_{\tilde{\mathcal{P}}_T} : \tilde{\mathcal{P}} \to \mathbb{N}$.

$$\hat{p} \in \hat{\mathcal{P}} := \{Pos_{\tilde{\mathcal{P}_T}}(p) \mid p \in \tilde{\mathcal{P}}\} \tag{4.5}$$

To filter out the suitable production resources $\tilde{\mathcal{R}} \subseteq \mathcal{R}$ that need to be considered when solving the SLSP, we make use of formula 4.6:

$$\begin{aligned} \tilde{\mathcal{R}} := \{r \in \mathcal{R} \mid \exists p \in \mathcal{P}, \exists i \in \mathcal{I} : \mathbf{A}(r, p) > 0 \wedge \mathbf{Q}(p, i) > 0 \\ \wedge \mathbf{PS}(r) \leq i \wedge \mathbf{PS}(r) \geq i_0\} \end{aligned} \tag{4.6}$$

The new index set again results from using the positioning of an element $r \in \tilde{\mathcal{R}}$ within $\tilde{\mathcal{R}_T}$ containing the elements of $\tilde{\mathcal{R}}$ ascendingly sorted: $Pos_{\tilde{\mathcal{R}}_T} : \tilde{\mathcal{R}} \to \mathbb{N}$.

$$\hat{r} \in \hat{\mathcal{R}} := \{Pos_{\tilde{\mathcal{R}_T}}(r) \mid r \in \tilde{\mathcal{R}}\} \tag{4.7}$$

Taking the selected production resources, we can, in a next step, preselect the sites $\tilde{\mathcal{J}} \subseteq \mathcal{J}$ to be included by applying formula 4.8. In that respect, we restrict ourselves to the sites providing the filtered out production resources plus the ordering plant, assuming that those plants also hold the materials required to manufacture the ordered products. This assumption should be relaxed if the required materials are available at other sites as well.

$$\tilde{\mathcal{J}} := \{j \in \mathcal{J} \mid \exists r \in \tilde{\mathcal{R}} : \mathbf{L}(r) = j\} \cup \{j_0\} \tag{4.8}$$

In order to determine the new index set of the locations to be considered, we use again the positions of the locations $j \in \tilde{\mathcal{J}} \setminus j_0$ within the ascendingly ordered tuple $\tilde{\mathcal{J}}_{T\setminus j_0}$, which however does not contain the customer location j_0: $Pos_{\tilde{\mathcal{J}}_{T\setminus j_0}} : \tilde{\mathcal{J}} \setminus j_0 \to \mathbb{N}$. The customer location j_0 is added as an additional location at the index position $\hat{j} = 0$ in order to mark it separately in the new index set:

$$\hat{j} \in \hat{\mathcal{J}} := \{Pos_{\tilde{\mathcal{J}}_{T\setminus j_0}}(j) \mid j \in \tilde{\mathcal{J}} \setminus j_0\} \cup \{0\} \tag{4.9}$$

Finally, we can use the products to be manufactured and the steps to be performed to filter out the required mounting components $\tilde{\mathcal{C}} \subseteq \mathcal{C}$ and finished goods containers $\tilde{\mathcal{F}} \subseteq \mathcal{F}$ by applying the formulas 4.10 and 4.11.

$$\begin{aligned}\tilde{\mathcal{C}} := \{c \in \mathcal{C} \mid \exists i_1, i_2 \in \mathcal{I}, \exists p \in \mathcal{P} : \mathbf{B}(i_1, p, c) > 0 \wedge \\ \mathbf{Q}(p, i_2) > 0 \wedge i_1 \leq i_2 \wedge i_1 \geq i_0\}\end{aligned} \tag{4.10}$$

$$\tilde{\mathcal{F}} := \{f \in \mathcal{F} \mid \exists p \in \mathcal{P} : \mathbf{PF}(p) = f \wedge \mathbf{Q}(p, I_{max}) > 0\} \tag{4.11}$$

The new index sets are again obtained by using the positions within the ascendingly ordered tuples $\tilde{\mathcal{C}_T}$ and $\tilde{\mathcal{F}_T}$, expressed by $Pos_{\tilde{\mathcal{C}_T}} : \tilde{\mathcal{C}} \to \mathbb{N}$ and $Pos_{\tilde{\mathcal{F}_T}} : \tilde{\mathcal{F}} \to \mathbb{N}$:

$$\hat{c} \in \hat{\mathcal{C}} := \{Pos_{\tilde{\mathcal{C}_T}}(c) \mid c \in \tilde{\mathcal{C}}\} \tag{4.12}$$

$$\hat{f} \in \hat{\mathcal{F}} := \{Pos_{\tilde{\mathcal{F}_T}}(f) \mid f \in \tilde{\mathcal{F}}\} \tag{4.13}$$

With regard to the quantities $\mathcal{V}$, $\mathcal{S}$ and $\mathcal{T}$, no pre-filtering is conducted.

Data Preprocessing

During data preprocessing, the dynamic data (table 4.4) is prepared for being used as input in the optimisation problem. In doing so, it must first be ensured that the dynamic data is updated with the current period at the time of ordering being set to $t = 0$. The subsequent preprocessing procedure includes a *data analysis* step, which examines whether the material resources provided are sufficient to solve the problem, and a *data preparation* step, which converts the dynamic data into the format required for optimisation. In the following sections, we will look at these two steps in more detail.

Analysis of Dynamic Data: Within the dynamic data analysis, it is evaluated if enough materials, i.e. components ($\mathbf{IC}$), raw materials and semi-finished products ($\mathbf{IP}$) as well as finished goods containers ($\mathbf{IF}$) are available to execute an order. For this purpose, the required amount of raw materials and semi-finished products is determined based on the quantities ordered. To ascertain the required amount of components, the number of parts to be produced in a production step is multiplied by the number of components needed per part ($\mathbf{B}(i,p,c)$). The required amount of finished goods containers is derived from the ordered amount of finished products. These quantities are compared with the amount of materials being available for the CM platform throughout the planning horizon. In the case of missing materials, the service composition process is terminated, and a notification is sent back to the customer. In the case of insufficient capacity, an error message will be generated in the service selection step of the service composition process when trying to solve the SLSP.

Preparation of Dynamic Data: As part of the data preparation step, the dynamic transport times are being determined. Using the (uninterrupted) transport times stored in $\mathbf{TT}(j,l,v)$ and the blocked periods specified in $\mathbf{PB}(s,v)$, the actual transport time (in periods) from a location j to a location l when utilising transport form v and starting in period t is being calculated and recorded in $\mathbf{T}\colon (\mathcal{J} \times \mathcal{J} \times \mathcal{V} \times \mathcal{T}) \to \mathbb{N}_0$. Additionally, we capture the actual transport time (in periods) from the perspective of the receiver in $\mathbf{TR}\colon (\mathcal{J} \times \mathcal{J} \times \mathcal{V} \times \mathcal{T}) \to \mathbb{N}_0$, which indicates that a transport with transport form v that arrived at location l in period t had a transport time of $\mathbf{TR}(j, l, v, t)$ periods when starting at location j. Figure 4.14 exemplifies this approach.

			Arrival at plant l=2									
		t	1	2	3	4	5	6	7	8	9	10
	t	s	Mo	Tu	We	Th	Fr	Sa	So	Mo	Tu	We
Depature at plant j=1	1	Mo		x								
	2	Tu			x							
	3	We				x						
	4	Th					x					
	5	Fr						x				
	6	Sa								x		
	7	So										
	8	Mo									x	
	9	Tu										x
	10	We										

Figure 4.14: Exemplary calculation of the actual transport time between two locations

The (uninterrupted) transport time between the locations $j = 1$ and $l = 2$ when using transport form $v = 1$ amounts to one period, i.e. $\mathbf{TT}(1, 2, 1) = 1$. If the transport starts in period $t = 1$, in our example a Monday, at location $j = 1$ (rows), then the transport arrives in period $t = 2$ at location $l = 2$ (columns). The actual transport time corresponds to the uninterrupted transport time in this case, i.e. $\mathbf{TT}(1, 2, 1) = \mathbf{T}(1, 2, 1, 1) = 1$ applies. Furthermore, we assume that it is not possible to operate transport form $v = 1$ on Sundays, which is recorded in $\mathbf{PB}(s, v)$. A transport can therefore neither start, arrive, nor be performed on a Sunday. A transport that starts in period $t = 6$, a Saturday, will therefore arrive on Monday ($t = 8$). As easily seen in this example, the actual transport time increases by one unit for each blocked period in between. The actual transport time hence adds up to 2 periods. From the perspective of the sending location $j = 1$, $\mathbf{T}(1, 2, 1, 6) = 2$ applies accordingly. From the standpoint of the receiving location $l = 2$, $\mathbf{TR}(1, 2, 1, 8) = 2$ results. At this point, we note that $\mathbf{TR}(j, l, v, t)$ can only be calculated if the relationship between the starting period and the arriving period is injective, which is given in the described approach.

Service Selection

In the last step of the service composition process, the service selection, the SLSP is solved, which we will discuss in detail in the next chapter. For this purpose, the required input data is passed to a solver. The calculated solution, if found, is in turn presented to the customer.

5 Modelling of the SLSP

Every solution of a problem is
a new problem.
-J.W. von Goethe

This chapter introduces the service-oriented lot-sizing problem (SLSP), which is being utilised in the designed CM platform to address the problem of service selection (SSP). The SLSP is to be solved within the service composition process in order to determine a production and transport plan. Formulated as a big bucket model, it aims to allocate production quantities to approved resources as well as to plan possible transport steps between the involved locations in terms of time and quantity so that an order can be fulfilled to the best possible extent. Therefore, a multi-objective optimisation problem, which takes into account the criteria time and costs from the perspective of the customer, is approached. In the following sections, we will first introduce the index sets (sec. 5.1) and input data (sec. 5.2) used for modelling. Afterwards, we will describe the mixed-integer linear programming (MILP) based base model version of the SLSP (sec. 5.3). Based on this, we will present further extension possibilities in chapter 5.4. In the last subchapter, an LP reformulation of the base model, which bypasses the integer restrictions and can therefore be solved in polynomial time, will be discussed.

5.1 Indices

We use the prefiltered sets introduced in chapter 4 as index sets in the modelling of the SLSP. To ensure a uniform notation delimited from the basic quantities of the CM platform (table 4.1), we have marked those sets and the corresponding variables with a hat ($\wedge$) labelling indicating them as SLSP sizes. Following this notation, we additionally introduce the identifiers $\hat{t} \in \hat{\mathcal{T}} := \mathcal{T}$ and $\hat{v} \in \hat{\mathcal{V}} := \mathcal{V}$ for the non-prefiltered quantities $\mathcal{V}$ and $\mathcal{T}$. The prefiltered sets are linked to the basic quantities presented in table 4.1 via the position functions, as defined in the previous chapter. Taking the example of the production steps, a production step $i \in \tilde{\mathcal{I}}_T$ refers to $\hat{\imath}$ via $Pos_{\tilde{\mathcal{I}}_T}(i)$. In turn, $\hat{\imath}$ links to i through the inverse function $Pos^{-1}_{\tilde{\mathcal{I}}_T}(\hat{\imath})$.

Table 5.1 summarises the index sets considered in the modelling of the SLSP.

Description	Index	Set
Plant	$\hat{\jmath}$	$\hat{\jmath} \in \hat{\mathcal{J}} = \{0, .., \hat{J}_{max}\}$
Product type	$\hat{p}$	$\hat{p} \in \hat{\mathcal{P}} = \{1, .., \hat{P}_{max}\}$
Production step	$\hat{\imath}$	$\hat{\imath} \in \hat{\mathcal{I}} = \{1, .., \hat{I}_{max}\}$
Production resource	$\hat{r}$	$\hat{r} \in \hat{\mathcal{R}} = \{1, .., \hat{R}_{max}\}$
Component type	$\hat{c}$	$\hat{c} \in \hat{\mathcal{C}} = \{1, .., \hat{C}_{max}\}$
Finished goods container type	$\hat{f}$	$\hat{f} \in \hat{\mathcal{F}} = \{1, .., \hat{F}_{max}\}$
Transport form	$\hat{v}$	$\hat{v} \in \hat{\mathcal{V}} = \{1, .., \hat{V}_{max}\}$
Period	$\hat{t}$	$\hat{t} \in \hat{\mathcal{T}} = \{0, .., \hat{T}_{max}\}$

Table 5.1: Index sets considered in the SLSP

5.2 Input Data

Having introduced the index sets, we will now look at the required input data. Table 5.2 provides a compilation of all input data used in the modelling of the different variants of the SLSP, divided into the sections order information, static production-related properties, static transport-related properties, dynamic production-related properties and dynamic transport-related properties.

As shown in the table, the input data of the SLSP is derived from the input data of the CM platform outlined in tables 4.2, 4.3, 4.4 and 4.5, as well as from the parameters deduced from those sizes within the service composition process, using the position functions as a transformation base. In order to distinguish the input data of the SLSP from the input data of the CM platform, we follow the notation of the previous section and use again the hat ($\wedge$) labelling to mark the SLSP-related data.

The *order information* section contains the order-related input data of the SLSP, derived from the input quantities presented in table 4.5.

The *static production-related input* and *static transport-related input* sections contain the static input data of the SLSP extracted in a transformed state from tables 4.2 and 4.3.

The capacity and inventory data taken from table 4.4, as well as the production costs taken from table 4.2, represent the *dynamic production-related input* of the SLSP. The production costs (**CP**) are thereby made dynamic by being converted onto the regarded planning periods using the period types of those periods recorded in **PH**.

The last section provides the *dynamic transport-related input* containing the dynamic transport times determined during data preprocessing and the transport approvals taken from table 4.3. Analogously to the production costs, the transport approvals (**PB**) are made dynamic by being translated onto the planning periods with the help of **PH**.

For the sake of clarity, we will in the following make use of a shortened index notation when addressing the input data. Taking the example of the order quantity, we will thus refer to the short form $\hat{\mathbf{Q}}_{\hat{p}\hat{\imath}}$, replacing the written-out $\hat{\mathbf{Q}}(\hat{p}, \hat{\imath})$.

Expression	Domain	Value Range
Order Information		
$\hat{\mathbf{Q}}(\hat{p},\hat{\imath}) = \mathbf{Q}(Pos^{-1}_{\tilde{\mathcal{P}}_T}(\hat{p}), Pos^{-1}_{\tilde{\mathcal{I}}_T}(\hat{\imath}))$	$\hat{\mathcal{P}} \times \hat{\mathcal{I}}$	$\mathbb{N}_0$
$\hat{\mathbf{TE}}(\hat{p},\hat{\imath}) = \mathbf{TE}(Pos^{-1}_{\tilde{\mathcal{P}}_T}(\hat{p}), Pos^{-1}_{\tilde{\mathcal{I}}_T}(\hat{\imath}))$	$\hat{\mathcal{P}} \times \hat{\mathcal{I}}$	$\hat{\mathcal{T}}$
$\hat{\mathbf{TL}}(\hat{p},\hat{\imath}) = \mathbf{TL}(Pos^{-1}_{\tilde{\mathcal{P}}_T}(\hat{p}), Pos^{-1}_{\tilde{\mathcal{I}}_T}(\hat{\imath}))$	$\hat{\mathcal{P}} \times \hat{\mathcal{I}}$	$\hat{\mathcal{T}}$
α	-	$(0,1)$
Static Production-related Input		
Production Resources		
$\hat{\mathbf{A}}(\hat{r},\hat{p}) = \mathbf{A}(Pos^{-1}_{\tilde{\mathcal{R}}_T}(\hat{r}), Pos^{-1}_{\tilde{\mathcal{P}}_T}(\hat{p}))$	$\hat{\mathcal{R}} \times \hat{\mathcal{P}}$	$\{0,1\}$
$\hat{\mathbf{PT}}(\hat{r},\hat{p}) = \mathbf{PT}(Pos^{-1}_{\tilde{\mathcal{R}}_T}(\hat{r}), Pos^{-1}_{\tilde{\mathcal{P}}_T}(\hat{p}))$	$\hat{\mathcal{R}} \times \hat{\mathcal{P}}$	$\mathbb{R}_{\geq 0}$
$\hat{\mathbf{PP}}(\hat{r},\hat{p}) = \mathbf{PP}(Pos^{-1}_{\tilde{\mathcal{R}}_T}(\hat{r}), Pos^{-1}_{\tilde{\mathcal{P}}_T}(\hat{p}))$	$\hat{\mathcal{R}} \times \hat{\mathcal{P}}$	$\mathbb{N}_0$
$\hat{\mathbf{ST}}(\hat{r},\hat{p}) = \mathbf{ST}(Pos^{-1}_{\tilde{\mathcal{R}}_T}(\hat{r}), Pos^{-1}_{\tilde{\mathcal{P}}_T}(\hat{p}))$	$\hat{\mathcal{R}} \times \hat{\mathcal{P}}$	$\mathbb{R}_{\geq 0}$
$\hat{\mathbf{PS}}(\hat{r}) = Pos_{\tilde{\mathcal{I}}_T}(\mathbf{PS}(Pos^{-1}_{\tilde{\mathcal{R}}_T}(\hat{r})))$	$\hat{\mathcal{R}}$	$\hat{\mathcal{I}}$
$\hat{\mathbf{L}}(\hat{r}) = \begin{cases} Pos_{\tilde{\mathcal{J}}_T \setminus j_0}(\mathbf{L}(Pos^{-1}_{\tilde{\mathcal{R}}_T}(\hat{r}))) & \text{if } \mathbf{L}(Pos^{-1}_{\tilde{\mathcal{R}}_T}(\hat{r})) \neq j_0 \\ 0 & \text{if } \mathbf{L}(Pos^{-1}_{\tilde{\mathcal{R}}_T}(\hat{r})) = j_0 \end{cases}$	$\hat{\mathcal{R}}$	$\hat{\mathcal{J}}$
$\hat{\mathbf{ML}}(\hat{r}) = \mathbf{ML}(Pos^{-1}_{\tilde{\mathcal{R}}_T}(\hat{r}))$	$\hat{\mathcal{R}}$	$\mathbb{N}_0$
Bill of Materials		
$\hat{\mathbf{B}}(\hat{\imath},\hat{p},\hat{c}) = \mathbf{B}(Pos^{-1}_{\tilde{\mathcal{I}}_T}(\hat{\imath}), Pos^{-1}_{\tilde{\mathcal{P}}_T}(\hat{p}), Pos^{-1}_{\tilde{\mathcal{C}}_T}(\hat{c}))$	$\hat{\mathcal{I}} \times \hat{\mathcal{P}} \times \hat{\mathcal{C}}$	$\mathbb{N}_0$
Handling of Materials		
$\hat{\mathbf{QP}}(\hat{p}) = \mathbf{QP}(Pos^{-1}_{\tilde{\mathcal{P}}_T}(\hat{p}))$	$\hat{\mathcal{P}}$	$\mathbb{N}_0$
$\hat{\mathbf{WP}}(\hat{p},\hat{\imath}) = \begin{cases} \mathbf{WP}(Pos^{-1}_{\tilde{\mathcal{P}}_T}(\hat{p}) \\ , Pos^{-1}_{\tilde{\mathcal{I}}_T}(\hat{\imath})) & \text{if } \hat{\imath} > 0 \\ \mathbf{WP}(Pos^{-1}_{\tilde{\mathcal{P}}_T}(\hat{p}) \\ , Pos^{-1}_{\tilde{\mathcal{I}}_T}(\hat{\imath}+1)-1) & \text{if } \hat{\imath} = 0 \end{cases}$	$\hat{\mathcal{P}} \times \hat{\mathcal{I}} \cup \{0\}$	$\mathbb{R}_{\geq 0}$
$\hat{\mathbf{QC}}(\hat{c}) = \mathbf{QC}(Pos^{-1}_{\tilde{\mathcal{C}}_T}(\hat{c}))$	$\hat{\mathcal{C}}$	$\mathbb{N}_0$
$\hat{\mathbf{WC}}(\hat{c}) = \mathbf{WC}(Pos^{-1}_{\tilde{\mathcal{C}}_T}(\hat{c}))$	$\hat{\mathcal{C}}$	$\mathbb{R}_{\geq 0}$
$\hat{\mathbf{QPF}}(\hat{p}) = \mathbf{QPF}(Pos^{-1}_{\tilde{\mathcal{P}}_T}(\hat{p}))$	$\hat{\mathcal{P}}$	$\mathbb{N}_0$
$\hat{\mathbf{PF}}(\hat{p}) = Pos_{\tilde{\mathcal{F}}_T}(\mathbf{PF}(Pos^{-1}_{\tilde{\mathcal{P}}_T}(\hat{p})))$	$\hat{\mathcal{P}}$	$\hat{\mathcal{F}}$
$\hat{\mathbf{WF}}(\hat{f}) = \mathbf{WF}(Pos^{-1}_{\tilde{\mathcal{F}}_T}(\hat{f}))$	$\hat{\mathcal{F}}$	$\mathbb{R}_{\geq 0}$
Static Transport-related Input		
Vehicle Restrictions		
$\hat{\mathbf{PSV}}(\hat{v}) = \mathbf{PSV}(\hat{v})$	$\hat{\mathcal{V}} \setminus \{1\}$	$\mathbb{N}_0$
$\hat{\mathbf{LC}}(\hat{v}) = \mathbf{LC}(\hat{v})$	$\hat{\mathcal{V}} \setminus \{1\}$	$\mathbb{R}_{\geq 0}$
$\hat{\mathbf{MCP}}(\hat{p},\hat{v}) = \mathbf{MCP}(Pos^{-1}_{\tilde{\mathcal{P}}_T}(\hat{p}), \hat{v})$	$\hat{\mathcal{P}} \times \hat{\mathcal{V}}$	$\mathbb{N}_0$

$\hat{\mathbf{MCC}}(\hat{c},\hat{v}) = \mathbf{MCC}(Pos^{-1}_{\tilde{\mathcal{C}}_T}(\hat{c}),\hat{v})$	$\hat{\mathcal{C}} \times \hat{\mathcal{V}}$	$\mathbb{N}_0$
$\hat{\mathbf{MCPF}}(\hat{p},\hat{v}) = \mathbf{MCPF}(Pos^{-1}_{\tilde{\mathcal{P}}_T}(\hat{p}),\hat{v})$	$\hat{\mathcal{P}} \times \hat{\mathcal{V}}$	$\mathbb{N}_0$
$\hat{\mathbf{MCF}}(\hat{f},\hat{v}) = \mathbf{MCF}(Pos^{-1}_{\tilde{\mathcal{F}}_T}(\hat{f}),\hat{v})$	$\hat{\mathcal{F}} \times \hat{\mathcal{V}}$	$\mathbb{N}_0$
Tariff System		
$\hat{\mathbf{CT}}(\hat{v}) = \mathbf{CT}(\hat{v})$	$\hat{\mathcal{V}} \setminus \{1\}$	$\mathbb{R}_{\geq 0}$
$\hat{\mathbf{MCT}}(\hat{v}) = \mathbf{MCT}(\hat{v})$	$\hat{\mathcal{V}} \setminus \{1\}$	$\mathbb{R}_{\geq 0}$
$\hat{\mathbf{CW}}(\hat{\jmath},\hat{l}) = \begin{cases} \mathbf{CW}(Pos^{-1}_{\tilde{\mathcal{J}}_{T\setminus j_0}}(\hat{\jmath}), Pos^{-1}_{\tilde{\mathcal{J}}_{T\setminus j_0}}(\hat{l})) & \text{if } \hat{\jmath},\hat{l} \neq 0 \\ \mathbf{CW}(j_0, Pos^{-1}_{\tilde{\mathcal{J}}_{T\setminus j_0}}(\hat{l})) & \text{if } \hat{\jmath} = 0 \\ \mathbf{CW}(Pos^{-1}_{\tilde{\mathcal{J}}_{T\setminus j_0}}(\hat{\jmath}), j_0) & \text{if } \hat{l} = 0 \end{cases}$	$\hat{\mathcal{J}} \times \hat{\mathcal{J}}$	$\mathbb{R}_{\geq 0}$
$\hat{\mathbf{CS}}(\hat{\jmath},\hat{l}) = \begin{cases} \mathbf{CS}(Pos^{-1}_{\tilde{\mathcal{J}}_{T\setminus j_0}}(\hat{\jmath}), Pos^{-1}_{\tilde{\mathcal{J}}_{T\setminus j_0}}(\hat{l})) & \text{if } \hat{\jmath},\hat{l} \neq 0 \\ \mathbf{CS}(j_0, Pos^{-1}_{\tilde{\mathcal{J}}_{T\setminus j_0}}(\hat{l})) & \text{if } \hat{\jmath} = 0 \\ \mathbf{CS}(Pos^{-1}_{\tilde{\mathcal{J}}_{T\setminus j_0}}(\hat{\jmath}), j_0) & \text{if } \hat{l} = 0 \end{cases}$	$\hat{\mathcal{J}} \times \hat{\mathcal{J}}$	$\mathbb{R}_{\geq 0}$
$\hat{\mathbf{BC}}(\hat{\jmath},\hat{l}) = \begin{cases} \mathbf{BC}(Pos^{-1}_{\tilde{\mathcal{J}}_{T\setminus j_0}}(\hat{\jmath}), Pos^{-1}_{\tilde{\mathcal{J}}_{T\setminus j_0}}(\hat{l})) & \text{if } \hat{\jmath},\hat{l} \neq 0 \\ \mathbf{BC}(j_0, Pos^{-1}_{\tilde{\mathcal{J}}_{T\setminus j_0}}(\hat{l})) & \text{if } \hat{\jmath} = 0 \\ \mathbf{BC}(Pos^{-1}_{\tilde{\mathcal{J}}_{T\setminus j_0}}(\hat{\jmath}), j_0) & \text{if } \hat{l} = 0 \end{cases}$	$\hat{\mathcal{J}} \times \hat{\mathcal{J}}$	$\mathbb{R}_{\geq 0}$
Routing		
$\hat{\mathbf{D}}(\hat{\jmath},\hat{l}) = \begin{cases} \mathbf{D}(Pos^{-1}_{\tilde{\mathcal{J}}_{T\setminus j_0}}(\hat{\jmath}), Pos^{-1}_{\tilde{\mathcal{J}}_{T\setminus j_0}}(\hat{l})) & \text{if } \hat{\jmath},\hat{l} \neq 0 \\ \mathbf{D}(j_0, Pos^{-1}_{\tilde{\mathcal{J}}_{T\setminus j_0}}(\hat{l})) & \text{if } \hat{\jmath} = 0 \\ \mathbf{D}(Pos^{-1}_{\tilde{\mathcal{J}}_{T\setminus j_0}}(\hat{\jmath}), j_0) & \text{if } \hat{l} = 0 \end{cases}$	$\hat{\mathcal{J}} \times \hat{\mathcal{J}}$	$\mathbb{R}_{\geq 0}$
Dynamic Production-related Input		
Costs		
$\hat{\mathbf{CP}}(\hat{r},\hat{p},\hat{t}) = \mathbf{CP}(Pos^{-1}_{\tilde{\mathcal{R}}_T}(\hat{r}), Pos^{-1}_{\tilde{\mathcal{P}}_T}(\hat{p}), \mathbf{PH}(\hat{t}))$	$\hat{\mathcal{R}} \times \hat{\mathcal{P}} \times \hat{\mathcal{T}}$	$\mathbb{R}_{\geq 0}$
Capacity		
$\hat{\mathbf{AC}}(\hat{r},\hat{t}) = \mathbf{AC}(Pos^{-1}_{\tilde{\mathcal{R}}_T}(\hat{r}),\hat{t})$	$\hat{\mathcal{R}} \times \hat{\mathcal{T}}$	$\mathbb{R}_{\geq 0}$
$\hat{\mathbf{SH}}(\hat{r},\hat{t},\hat{p}) = \mathbf{SH}(Pos^{-1}_{\tilde{\mathcal{R}}_T}(\hat{r}),\hat{t}, Pos^{-1}_{\tilde{\mathcal{P}}_T}(\hat{p}))$	$\hat{\mathcal{R}} \times \hat{\mathcal{T}} \times \hat{\mathcal{P}}$	$\{0,1\}$
Inventory		

$\hat{\mathbf{IP}}(\hat{p},\hat{\imath},\hat{\jmath},\hat{t}) = \begin{cases} \mathbf{IP}(Pos^{-1}_{\tilde{\mathcal{P}}_T}(\hat{p}), Pos^{-1}_{\tilde{\mathcal{I}}_T}(\hat{\imath}), Pos^{-1}_{\tilde{\mathcal{J}}_{T\setminus j_0}}(\hat{\jmath}), \hat{t}) & \text{if } \hat{\jmath} \neq 0 \wedge \hat{\imath} > 0 \\ \mathbf{IP}(Pos^{-1}_{\tilde{\mathcal{P}}_T}(\hat{p}), Pos^{-1}_{\tilde{\mathcal{I}}_T}(\hat{\imath}), j_0, \hat{t}) & \text{if } \hat{\jmath} = 0 \wedge \hat{\imath} > 0 \\ \mathbf{IP}(Pos^{-1}_{\tilde{\mathcal{P}}_T}(\hat{p}), Pos^{-1}_{\tilde{\mathcal{I}}_T}(\hat{\imath}+1)-1, Pos^{-1}_{\tilde{\mathcal{J}}_{T\setminus j_0}}(\hat{\jmath}), \hat{t}) & \text{if } \hat{\jmath} \neq 0 \wedge \hat{\imath} = 0 \\ \mathbf{IP}(Pos^{-1}_{\tilde{\mathcal{P}}_T}(\hat{p}), Pos^{-1}_{\tilde{\mathcal{I}}_T}(\hat{\imath}+1)-1, j_0, \hat{t}) & \text{if } \hat{\jmath} = 0 \wedge \hat{\imath} = 0 \end{cases}$	$\hat{\mathcal{P}} \times \hat{\mathcal{I}} \cup \{0\} \times \hat{\mathcal{J}} \times \hat{\mathcal{T}}$	$\mathbb{N}_0$
$\hat{\mathbf{IC}}(\hat{c},\hat{\jmath},\hat{t}) = \begin{cases} \mathbf{IC}(Pos^{-1}_{\tilde{\mathcal{C}}_T}(\hat{c}), Pos^{-1}_{\tilde{\mathcal{J}}_{T\setminus j_0}}(\hat{\jmath}), \hat{t}) & \text{if } \hat{\jmath} \neq 0 \\ \mathbf{IC}(Pos^{-1}_{\tilde{\mathcal{C}}_T}(\hat{c}), j_0, \hat{t}) & \text{if } \hat{\jmath} = 0 \end{cases}$	$\hat{\mathcal{C}} \times \hat{\mathcal{J}} \times \hat{\mathcal{T}}$	$\mathbb{N}_0$
$\hat{\mathbf{IF}}(\hat{f},\hat{\jmath},\hat{t}) = \begin{cases} \mathbf{IF}(Pos^{-1}_{\tilde{\mathcal{F}}_T}(\hat{f}), Pos^{-1}_{\tilde{\mathcal{J}}_{T\setminus j_0}}(\hat{\jmath}), \hat{t}) & \text{if } \hat{\jmath} \neq 0 \\ \mathbf{IF}(Pos^{-1}_{\tilde{\mathcal{F}}_T}(\hat{f}), j_0, \hat{t}) & \text{if } \hat{\jmath} = 0 \end{cases}$	$\hat{\mathcal{F}} \times \hat{\mathcal{J}} \times \hat{\mathcal{T}}$	$\mathbb{N}_0$
Dynamic Transport-related Input		
Transport Time		
$\hat{\mathbf{T}}(\hat{\jmath},\hat{l},\hat{v},\hat{t}) = \begin{cases} \mathbf{T}(Pos^{-1}_{\tilde{\mathcal{J}}_{T\setminus j_0}}(\hat{\jmath}), Pos^{-1}_{\tilde{\mathcal{J}}_{T\setminus j_0}}(\hat{l}), \hat{v}, \hat{t}) & \text{if } \hat{\jmath}, \hat{l} \neq 0 \\ \mathbf{T}(j_0, Pos^{-1}_{\tilde{\mathcal{J}}_{T\setminus j_0}}(\hat{l}), \hat{v}, \hat{t}) & \text{if } \hat{\jmath} = 0 \\ \mathbf{T}(Pos^{-1}_{\tilde{\mathcal{J}}_{T\setminus j_0}}(\hat{\jmath}), j_0, \hat{v}, \hat{t}) & \text{if } \hat{l} = 0 \end{cases}$	$\hat{\mathcal{J}} \times \hat{\mathcal{J}} \times \hat{\mathcal{V}} \times \hat{\mathcal{T}}$	$\mathbb{N}_0$
$\hat{\mathbf{TR}}(\hat{\jmath},\hat{l},\hat{v},\hat{t}) = \begin{cases} \mathbf{TR}(Pos^{-1}_{\tilde{\mathcal{J}}_{T\setminus j_0}}(\hat{\jmath}), Pos^{-1}_{\tilde{\mathcal{J}}_{T\setminus j_0}}(\hat{l}), \hat{v}, \hat{t}) & \text{if } \hat{\jmath}, \hat{l} \neq 0 \\ \mathbf{TR}(j_0, Pos^{-1}_{\tilde{\mathcal{J}}_{T\setminus j_0}}(\hat{l}), \hat{v}, \hat{t}) & \text{if } \hat{\jmath} = 0 \\ \mathbf{TR}(Pos^{-1}_{\tilde{\mathcal{J}}_{T\setminus j_0}}(\hat{\jmath}), j_0, \hat{v}, \hat{t}) & \text{if } \hat{l} = 0 \end{cases}$	$\hat{\mathcal{J}} \times \hat{\mathcal{J}} \times \hat{\mathcal{V}} \times \hat{\mathcal{T}}$	$\mathbb{N}_0$
Transport Availability		
$\hat{\mathbf{PB}}(\hat{t},\hat{v}) = \mathbf{PB}(\mathbf{PH}(\hat{t}),\hat{v})$	$\hat{\mathcal{T}} \times \hat{\mathcal{V}}$	$\{0,1\}$

Table 5.2: Input data of the SLSP

5.3 Base Model (SLSP-B)

The SLSP is used to determine a production and transport plan in order to fulfil a customer order on the CM platform. Formulated as a multi-objective optimisation problem, it aims to optimise the criteria time and costs from the perspective of the customer. In its base model version (SLSP-B), the SLSP is modelled as a mixed-integer linear program (MILP). As such, it is based on the following general problem formulation (cf. Conforti, Cornuejols, and Zambelli 2014):

$$\max_{x}\{c^T x : Ax \leq b, x \geq 0, x_G \in \mathbb{N}_0^G, c \in \mathbb{R}^n, b \in \mathbb{R}^m, A \in \mathbb{R}^{m \times n}\} \quad (5.1)$$

Accordingly, a subset $G \subseteq \{1, ..., n\}$ of the decision variables is required to assume integer values, and the objective function, as well as the constraints, are modelled as linear functions. Mixed-integer problems are being examined in the context of integer optimisation [1]. Integer problems are, however, in general NP hard (cf. Nickel, Stein, and Waldmann 2011). This means that there is no algorithm yet that solves the most difficult instances in polynomial effort (cf. Domschke et al. 2015). For this reason, we will present an alternative relaxed problem formulation in chapter 5.5.

In the upcoming sections, we will look at limiting assumptions, decision variables, constraints and the objective function of the SLSP-B.

[1] In the special case that all variables are integers, one speaks of (pure) integer linear programming (ILP) (cf. Conforti, Cornuejols, and Zambelli 2014).

5.3.1 Assumptions

With regard to the problem formulation of the SLSP-B, we make some limiting assumptions, which we will, however, include as model extensions in chapter 5.4. The following four restrictions do apply:

- In the SLSP-B, we assume that **components** are available in sufficient quantities at all locations. This assumption can be made for products for which no or only standard components, such as bolts or nuts, are needed. Components are therefore not modelled as separate material resources and, as such, not further considered in the model.
- Similarly, we make the assumption that the required **finished goods containers** are available in sufficient quantities at all locations and do not depict them as separate material resources. This assumption is valid for products that are delivered to the customer in standard containers such as large load carriers or disposable containers, for which it is reasonable to assume unlimited availability at the sites.
- Additionally, we will not consider any **minimum transport costs** ($\hat{\mathbf{MCT}}$) in the case of direct non-stop transports. This assumption can be made for production networks in which the locations involved are located sufficiently far apart from each other so that the distance-dependent transport costs exceed the minimum transport costs. Formally expressed when $\min_{\hat{\jmath},\hat{l} \in \hat{\mathcal{J}} | \hat{\jmath} \neq \hat{l}} \{\hat{\mathbf{D}}_{\hat{\jmath},\hat{l}} \cdot \hat{\mathbf{CT}}_{\hat{v}}\} > \hat{\mathbf{MCT}}_{\hat{v}}, \forall \hat{v} \in \hat{\mathcal{V}} \setminus \{1\}$ applies. Also, we will disregard the **basic costs** ($\hat{\mathbf{BC}}$) of groupage services, i.e. only allow tariff systems without a fixed-cost component.
- Finally, we neglect the aspect of **time windows** ($\hat{\mathbf{TE}}$ and $\hat{\mathbf{TL}}$). A customer is thus able to control the delivery date by choosing the parameter α, but not by explicitly specifying a time window.

5.3.2 Decision Variables

In terms of the decision variables of the SLSP-B, we distinguish between result variables to be calculated and auxiliary variables required for the calculation.

Result Variables

The two decision variables $q_{\hat{r},\hat{p},\hat{t}}$ and $NP_{\hat{\imath},\hat{p},\hat{\jmath},\hat{l},\hat{t},\hat{v}}$ indicate which quantities of a certain product type are to be processed on a specific resource in a particular period respectively, how many pallets slots are required for the transportation of products of a certain type and value-added stage in a particular period between two specific network locations using a certain transport form. For transport forms representing direct non-stop transports, we additionally determine the number of vehicles that are to be employed to conduct a direct transport between two specific network locations in a particular period ($NV_{\hat{\jmath},\hat{l},\hat{t},\hat{v}}$).

$q_{\hat{r},\hat{p},\hat{t}} \in \mathbb{N}_0$ = Number of full containers of product $\hat{p} \in \hat{\mathcal{P}}$ to be processed on resource $\hat{r} \in \hat{\mathcal{R}}$ in period $\hat{t} \in \hat{\mathcal{T}} \setminus \{0\}$

$NP_{\hat{\imath},\hat{p},\hat{\jmath},\hat{l},\hat{t},\hat{v}} \in \mathbb{N}_0$ = Number of pallets slots required for transporting parts of type $\hat{p} \in \hat{\mathcal{P}}$ that have passed step $\hat{\imath} \in \hat{\mathcal{I}} \cup \{0\}$ from location $\hat{\jmath} \in \hat{\mathcal{J}}$ to location $\hat{l} \in \hat{\mathcal{J}}$ in period $\hat{t} \in \hat{\mathcal{T}} \setminus \{0\}$ using transport form $\hat{v} \in \hat{\mathcal{V}}$. Starting materials are captured via $\hat{\imath} = 0$. For output materials, we use $\hat{\imath} = \hat{I}_{max}$

$NV_{\hat{\jmath},\hat{l},\hat{t},\hat{v}} \in \mathbb{N}_0$ = Number of vehicles to be used to conduct a direct non-stop transport from location $\hat{\jmath} \in \hat{\mathcal{J}}$ to location $\hat{l} \in \hat{\mathcal{J}}$ in period $\hat{t} \in \hat{\mathcal{T}} \setminus \{0\}$ with transport form $\hat{v} \in \hat{\mathcal{V}} \setminus \{1\}$

These variables represent the result of the calculation and define the computed production and transport plan. Due to the discrete character of the lot sizes, which are required to be integer multiples of the container filling quantity in the considered production network, we define $q_{\hat{r},\hat{p},\hat{t}}$ as an integer variable allowing only full containers to be processed. To ensure that only whole pallet slots are considered in transport planning, we define $NP_{\hat{\imath},\hat{p},\hat{\jmath},\hat{l},\hat{t},\hat{v}}$ as an integer variable as well. Likewise, we accept only integer numbers of vehicles to be used in a direct non-stop transport between two network locations and therefore also limit the variable $NV_{\hat{\jmath},\hat{l},\hat{t},\hat{v}}$ to integer values.

Auxiliary Variables

Furthermore, we introduce a binary set-up variable $x_{\hat{r},\hat{p},\hat{t}}$, which indicates whether production takes place in a certain period ($q_{\hat{r},\hat{p},\hat{t}} > 0$) or not ($q_{\hat{r},\hat{p},\hat{t}} = 0$) and which is needed to model set-up operations and minimum lot-sizes. Besides, we define the variable $Q_{\hat{\imath},\hat{p},\hat{\jmath},\hat{t}}$ to capture the inventory quantities of a specific product type at a certain value-added stage. For transport planning purposes, we additionally introduce the variable $b_{\hat{\imath},\hat{p},\hat{\jmath},\hat{l},\hat{t},\hat{v}}$ to record the number of containers to be transported:

$x_{\hat{r},\hat{p},\hat{t}} \in \{0,1\}$ = Binary variable to $q_{\hat{r},\hat{p},\hat{t}}$ that assumes value 1 if $q_{\hat{r},\hat{p},\hat{t}} > 0$ and 0, otherwise

$Q_{\hat{\imath},\hat{p},\hat{\jmath},\hat{t}} \in \mathbb{R}_{\geq 0}$ = Stock of containers with parts $\hat{p} \in \hat{\mathcal{P}}$ that have passed stage $\hat{\imath} \in \hat{\mathcal{I}} \cup \{0\}$ at location $\hat{\jmath} \in \hat{\mathcal{J}}$ at the end of period $\hat{t} \in \hat{\mathcal{T}}$. Starting materials are captured via $\hat{\imath} = 0$. For output materials, we use $\hat{\imath} = \hat{I}_{max}$

$b_{\hat{\imath},\hat{p},\hat{\jmath},\hat{l},\hat{t},\hat{v}} \in \mathbb{R}_{\geq 0}$ = Number of containers with parts of type $\hat{p} \in \hat{\mathcal{P}}$ having passed step $\hat{\imath} \in \hat{\mathcal{I}} \cup \{0\}$ to be shipped from location $\hat{\jmath} \in \hat{\mathcal{J}}$ to location $\hat{l} \in \hat{\mathcal{J}}$ in period $\hat{t} \in \hat{\mathcal{T}} \setminus \{0\}$ using transport form $\hat{v} \in \hat{\mathcal{V}}$. Starting materials are captured via $\hat{\imath} = 0$. For output materials, we use $\hat{\imath} = \hat{I}_{max}$

5.3.3 Objective Function

In order to be able to explain the objective function of the SLSP-B, we will first introduce some basic concepts of multi-objective optimisation. Building on this, we will present and discuss the chosen modelling approach in detail.

Multi-objective Optimisation

In multi-objective optimisation, several objective functions are considered simultaneously. In its general form, a multi-objective optimisation problem is specified as follows (cf. Scholz 2018):

$$\min_{x \in X} g(x) = \Big(g_1(x), ..., g_K(x)\Big) \tag{5.2}$$

$X \subset \mathbb{R}^n$ represents the feasible set and $g\colon \mathbb{R}^n \to \mathbb{R}^K$ with $g_k\colon \mathbb{R}^n \to \mathbb{R}$ for $k = 1, ..., K$ specifies the objective vector. Due to the vectorial character, such an optimisation problem is also called a **vector optimisation** problem (cf. Nickel, Stein, and Waldmann 2011). For competing objective functions, however, there is no perfect solution, a so-called utopia point, which optimally solves all objective functions simultaneously (cf. Nickel, Stein, and Waldmann 2011). Instead, a number of compromise solutions can be found. Such a compromise solution $x^{par} \in X$ is called **Pareto optimal** and the associated objective function value $g(x^{par})$ is considered to be **efficient** if there is no other point $x \in X$ that is at least equally good in all objective functions and strictly better than x^{par} in at least one objective function (cf. Nickel, Stein, and Waldmann 2011). The set of all Pareto optimal points is named **Pareto set** or non-dominated set (cf. Scholz 2018, M. J. Geiger 2005). Furthermore, a point $x^* \in X$ is referred to be **weakly Pareto optimal**, if there is no $x \in X$ with $g_k(x) < g_k(x^*)$ $\forall k = 1, ..., K$ (cf. Scholz 2018, M. J. Geiger 2005).

There are several approaches to solve multi-objective optimisation problems, which we will present in the following. The explanations are based on Miettinen (1999), Nickel, Stein, and Waldmann (2011) and Domschke et al. (2015), to whom we refer for further details.

Lexicographic optimisation optimises the objective functions successively using the sequence specified by the decision-maker, with the downstream objective function being optimised over the remaining degrees of freedom. In this way, a Pareto optimal solution is generated. However, less important objective functions often have no influence at all due to an already fixed solution. (cf. Miettinen 1999)

With the **ϵ-constraint method**, the main objective function is optimised, and the remaining objective functions are transformed into constraints in order to meet defined target levels. A solution found is guaranteed to be weakly Pareto optimal, and in case it is the only solution or if the found solution solves the ϵ-constraint-problem optimally for all objective functions with all constraints meeting the target levels, additionally Pareto optimal. Thus, the proof of Pareto optimality is rather complex, and the definition of the target levels can be difficult as well. Theoretically, however, any Pareto optimal solution can be found with this method. (cf. Miettinen 1999)

The **weighting method** is a widely used approach that optimises the weighted sum of the objective functions. The individual objective functions receive a weight λ_k and are summed up to form a single objective function $\tilde{g}(x) = \sum_{k=1}^{K} \lambda_k \cdot g_k(x)$ with $\sum_{k=1}^{K} \lambda_k = 1$. A solution found with that method is weakly Pareto optimal if all weights are ≥ 0 and guaranteed to be Pareto optimal if it is the only solution or if all weights are > 0. For problems with sets of feasible solutions that are convex in the objective space, the entire Pareto set can be found by varying the weights. For non-convex problems, this might not be possible. (cf. Miettinen 1999)

The **method of weighted metrics** minimises the distance of the objective function values of a solution found $g_k(x)$ to the optimal objective function values g_k^* according to formula 5.3.

$$\min_{x \in X} \qquad \tilde{g}(x) = \begin{cases} \left(\sum\limits_{k=1}^{K} \lambda_k \cdot |g_k^* - g_k(x)|^q \right)^{\frac{1}{q}} & ,\text{if } 1 \leq q < \infty \\ \max\limits_{k=1,..,K} \{\lambda_k \cdot |g_k^* - g_k(x)|\} & ,\text{if } q = \infty \end{cases} \tag{5.3}$$

To measure the distance, different L_q metrics can be used. For $q = 1$, the Manhattan distance is utilised, and the optimisation problem corresponds to the problem of the weighted sum if we resolve the absolute value and neglect the constant factor. In the case of $q = \infty$, the Chebyshev distance is employed, with the maximum distance being minimised. A solution found with $1 \leq q < \infty$ is Pareto optimal if the solution is unique or if all weights λ_k are > 0. However, only in the case of a convex problem, it is guaranteed that the whole Pareto set can be found. A solution found with the Chebyshev distance is weakly Pareto optimal for positive weights and additionally guaranteed to be Pareto optimal if it is the only solution. Beyond that, an extended Chebyshev variant using an additional augmentation term exists that guarantees a Pareto optimal solution in all cases. Notwithstanding this, all Pareto solutions can be found with the Chebyshev distance even without convexity. Finally, it has to be considered that for all $q > 1$, a non-linear objective function is created. Nevertheless, it is possible to linearise the Chebyshev distance by minimising an auxiliary variable, which is required to be larger than all objective functions what needs to be defined in additional constraints. (cf. Miettinen 1999, Nickel, Stein, and Waldmann 2011)

A generalisation of the weighted metric approach is the **goal programming method**, in which the distance to target levels set by the decision-maker is minimised rather than to the optimal values. In this case, though, it is not possible to omit the absolute value property. The objective function therefore becomes non-linear for all L_q metrics. (cf. Domschke et al. 2015)

Modelling Approach

The multi-objective modelling approach of the SLSP-B, which in literature is classified as a multi-objective MILP (MOMILP), considers both time and costs criteria, which are typically contradictory target dimensions. We are aiming to minimise the values of both dimensions from the customer's point of view. Formulas 5.4 and 5.5 show the calculation logic of the cost and time functions applied.

$$
\begin{aligned}
g_1 := & \sum_{\hat{r}=1}^{\hat{R}_{max}} \sum_{\hat{p}=1}^{\hat{P}_{max}} \sum_{\hat{t}=1}^{\hat{T}_{max}} \hat{\mathbf{CP}}_{\hat{r}\hat{p}\hat{t}} \cdot q_{\hat{r},\hat{p},\hat{t}} \cdot \hat{\mathbf{QP}}_{\hat{p}} \cdot \hat{\mathbf{PT}}_{\hat{r}\hat{p}} + \\
& \sum_{\hat{r}=1}^{\hat{R}_{max}} \sum_{\hat{p}=1}^{\hat{P}_{max}} \sum_{\hat{t}=1}^{\hat{T}_{max}} \hat{\mathbf{CP}}_{\hat{r}\hat{p}\hat{t}} \cdot x_{\hat{r},\hat{p},\hat{t}} \cdot (1 - \hat{\mathbf{SH}}_{\hat{r}\hat{p}\hat{t}}) \cdot \hat{\mathbf{ST}}_{\hat{r}\hat{p}} + \\
& \sum_{\hat{j}=0}^{\hat{J}_{max}} \sum_{\hat{l}=0}^{\hat{J}_{max}} \sum_{\hat{t}=1}^{\hat{T}_{max}} \sum_{\hat{v}=2}^{\hat{V}_{max}} \hat{\mathbf{CT}}_{\hat{v}} \cdot NV_{\hat{j},\hat{l},\hat{t},\hat{v}} \cdot \hat{\mathbf{D}}_{\hat{j}\hat{l}} + \\
& \sum_{\hat{j}=0}^{\hat{J}_{max}} \sum_{\hat{l}=0}^{\hat{J}_{max}} \sum_{\hat{t}=1}^{\hat{T}_{max}} \sum_{\hat{\imath}=0}^{\hat{I}_{max}} \sum_{\hat{p}=1}^{\hat{P}_{max}} \hat{\mathbf{CS}}_{\hat{j}\hat{l}} \cdot NP_{\hat{\imath},\hat{p},\hat{j},\hat{l},\hat{t},1}
\end{aligned} \tag{5.4}
$$

The **total costs**, specified in g_1, consist of production costs, set-up costs and transport costs. The *production costs* are obtained from the arithmetic product of the production quantity with the processing time and the period-dependent cost rate. The *set-up costs* are calculated by multiplying the set-up time with the period-dependent cost rate. These costs, however, are not included if it is known that a product is already being produced on a resource in a specific period, i.e. $\hat{\mathbf{SH}}_{\hat{r}\hat{p}\hat{t}} = 1$ applies. To calculate the *transportation costs*, we refer to the tour-based calculation method in the case of direct non-stop transports and to the order-based calculation method in the case of groupage services (cf. chapter 2.1.3). The resulting transport costs of a direct non-stop transport are thus computed by multiplying the distance driven with the vehicle cost rate and the number of vehicles utilised. The transport costs of a groupage service are calculated by multiplying the transport cost rate per pallet slot by the number of pallet slots required.

With regard to the material costs for the materials brought in by the plants, we assume that these are identical throughout the network and can therefore be neglected. We also do not consider inventory holding costs due to the given quantity of parts in the network assuming similar inventory holding cost rates at the different locations.

The second target criterion, time, aims to achieve the fastest possible completion of an order. For that purpose, we add up the delivery times to the customer. To take into account that a delivery can be spread over several sub-deliveries, we weight the delivery time with the quantity handed over. The resulting added-up and **weighted delivery time** is specified in g_2. In this respect, it should be noted that deliveries can come from other locations and from the customer's own production. In the case of deliveries from other locations, a further distinction is made as to whether finished goods are considered or not due to the different container filling quantities.

$$g_2 := \sum_{\hat{\imath}=1}^{\hat{I}_{max}} \sum_{\substack{\hat{p}=1 \\ \hat{\mathbf{Q}}_{\hat{p}\hat{\imath}}>0}}^{\hat{P}_{max}} \cdot \Big[\sum_{\hat{\jmath}=1}^{\hat{J}_{max}} \sum_{\hat{t}=1}^{\hat{T}_{max}} \sum_{\hat{v}=1}^{\hat{V}_{max}} b_{\hat{\imath},\hat{p},\hat{\jmath},0,\hat{t},\hat{v}} \cdot (\hat{t} + \hat{\mathbf{T}}_{\hat{\jmath}0\hat{v}\hat{t}}) \cdot$$
$$(\mathbb{1}_{Pos^{-1}_{\tilde{\mathcal{I}}_T}(\hat{\imath})=I_{max}} \cdot \hat{\mathbf{QPF}}_{\hat{p}} + \mathbb{1}_{Pos^{-1}_{\tilde{\mathcal{I}}_T}(\hat{\imath})\neq I_{max}} \cdot \hat{\mathbf{QP}}_{\hat{p}}) +$$
$$\sum_{\substack{\hat{r}=1 \\ \hat{\mathbf{L}}_{\hat{r}}=0 \\ \wedge \hat{\mathbf{PS}}_{\hat{r}}=\hat{\imath}}}^{\hat{R}_{max}} \sum_{\hat{t}=1}^{\hat{T}_{max}} q_{\hat{r},\hat{p},\hat{t}} \cdot \hat{\mathbf{QP}}_{\hat{p}} \cdot \hat{t} \Big] \quad (5.5)$$

In order to be able to consider the two presented objective functions simultaneously in a multi-objective way, we make use of the **weighting method**.

The reason for choosing this method is the guaranteed Pareto optimality of a found solution in the case of weights > 0. Furthermore, there are no non-linear terms and additional constraints, which keeps the modelling simple and lean and does not increase the computational complexity compared to the single-objective problems (cf. Ehrgott 2006). Nevertheless, due to the non-convexity of the feasible set and thus of the feasible solution space in the case of integer problems, it is not possible to guarantee that the entire Pareto set can be found (cf. Antunes, Alves, and Clímaco 2016, Alves and Clímaco 2009). In the considered use case, however, this is not of relevance since only a limited number of solution alternatives, 3 to be specific, and not the entire Pareto set are being determined within the service composition process. We are thus looking at an **a priori** approach with the preferences of the decision-maker being known before the calculation starts (cf. Miettinen 1999).[2]

As described in chapter 4.3.1, a cost-effective, a fast and a solution according to the customer's target weighting are to be calculated. In order to reflect the different scalings of the objective functions in the customer's target weighting, we use the degree of target achievement to normalise the objective functions to the value 1 (cf. Nickel, Stein, and Waldmann 2011). To do so, we relate the objective function value to its optimal value and minimise the relative deviation from the optimal value.

The following formulas formally express the approach:

[2] If, on the other hand, the entire Pareto set is being determined and only compared with the preferences of the decision-maker after the calculation, one speaks of an **a posteriori** approach (cf. Miettinen 1999).

$$\min_{x \in X} \quad \tilde{g}(x) = \sum_{k=1}^{2} \lambda_k \cdot \frac{g_k(x)}{g_k^*} \tag{5.6}$$

$$\text{s.t.} \quad \sum_{k=1}^{2} \lambda_k = 1 \tag{5.7}$$

$$\lambda_k > 0 \qquad \forall k = 1, 2 \tag{5.8}$$

The algorithm for solving the multi-objective SLSP within the service composition process follows the procedure specified below:

1. Solving the mono-criterion problems 5.9 and 5.10 in order to determine the optimal values for normalisation:

$$g_1^* := \min_{x \in X} g_1(x) \tag{5.9}$$

$$g_2^* := \min_{x \in X} g_2(x) \tag{5.10}$$

2. Calculation of a cost-effective solution by solving the problem specified in formulas 5.6 - 5.8 whereby $\lambda_1 + \epsilon = 1$, $\lambda_2 > 0$ and $\lambda_1 + \lambda_2 = 1$ applies with ϵ being a small number.
3. Calculation of a fast solution by solving the problem specified in formulas 5.6 - 5.8 whereby $\lambda_2 + \epsilon = 1$, $\lambda_1 > 0$ and $\lambda_1 + \lambda_2 = 1$ applies with ϵ being a small number.
4. Calculation of a solution according to the customer's target weighting by solving the problem specified in formulas 5.6 - 5.8 whereby $\lambda_1 = \alpha$ and $\lambda_2 = (1 - \alpha)$ applies.

In this respect, we would like to point out that steps 2 and 3 are performed to generate a efficient cost-effective and a efficient fast solution with weights >0 as the Pareto optimality cannot be guaranteed with the optimal mono-criterion values calculated in step 1.

5.3.4 Constraints

After having addressed the objective function, we will now look at the constraints that limit the set of feasible solutions. In the following sections, we will introduce the restrictions applying to the SLSP-B, divided among inventory-related, order-related, production-related and transport-related constraints.

Inventory-Related

First of all and analogously to classical lot-sizing models (cf. chapter 3.2.1), we record the inventory development of full containers filled with products of different value-added stages at the different network locations (cf. formula 5.11). Inventory increases when materials are made available to the platform ($\mathbf{I\hat{P}}_{\hat{p}\hat{\imath}\hat{\jmath}\hat{t}}$), deliveries from other locations that were sent away before $\mathbf{T\hat{R}}_{\hat{\imath}\hat{\jmath}\hat{o}\hat{t}}$ periods arrive at the location under consideration, or when materials from the previous value-added stage are coming out from production. That said, we would like to point out that the quantity of finished products coming out from production per period is not required to be an integer multiple of the filling quantity of the end product container ($\mathbf{Q\hat{P}F}_{\hat{p}}$). Only partially filled finished goods containers are therefore possible. Outflows result from containers that are sent to other locations and from containers that flow into the succeeding production stage.

$$Q_{\hat{\imath},\hat{p},\hat{\jmath},\hat{t}} = Q_{\hat{\imath},\hat{p},\hat{\jmath},(\hat{t}-1)} + \hat{\mathbf{IP}}_{\hat{p}\hat{\imath}\hat{\jmath}\hat{t}} + \sum_{\substack{\hat{l}=0\\ \hat{l}\neq\hat{\jmath}}}^{\hat{J}_{max}} \sum_{\substack{\hat{v}=1\\ \hat{t}-\hat{\mathbf{TR}}_{\hat{l}\hat{\jmath}\hat{v}\hat{t}}\geq 1}}^{\hat{V}_{max}} b_{\hat{\imath},\hat{p},\hat{l},\hat{\jmath},(\hat{t}-\hat{\mathbf{TR}}_{\hat{l}\hat{\jmath}\hat{v}\hat{t}}),\hat{v}} -$$

$$\sum_{\substack{\hat{l}=0\\ \hat{l}\neq\hat{\jmath}}}^{\hat{J}_{max}} \sum_{\hat{v}=1}^{\hat{V}_{max}} b_{\hat{\imath},\hat{p},\hat{\jmath},\hat{l},\hat{t},\hat{v}} + \sum_{\substack{\hat{r}=1\\ \hat{\mathbf{L}}_{\hat{r}}=\hat{\jmath}\\ \wedge\hat{\mathbf{PS}}_{\hat{r}}=\hat{\imath}}}^{\hat{R}_{max}} q_{\hat{r},\hat{p},\hat{t}} \cdot \mathbb{1}_{Pos^{-1}_{\hat{\mathcal{I}}_T}(\hat{\imath})\neq I_{max}} +$$

$$\sum_{\substack{\hat{r}=1\\ \hat{\mathbf{L}}_{\hat{r}}=\hat{\jmath}\\ \wedge\hat{\mathbf{PS}}_{\hat{r}}=\hat{\imath}}}^{\hat{R}_{max}} \frac{q_{\hat{r},\hat{p},\hat{t}} \cdot \hat{\mathbf{QP}}_{\hat{p}}}{\hat{\mathbf{QPF}}_{\hat{p}}} \cdot \mathbb{1}_{Pos^{-1}_{\hat{\mathcal{I}}_T}(\hat{\imath})= I_{max}} - \sum_{\substack{\hat{r}=1\\ \hat{\mathbf{L}}_{\hat{r}}=\hat{\jmath}\\ \wedge\hat{\mathbf{PS}}_{\hat{r}}=\hat{\imath}+1}}^{\hat{R}_{max}} q_{\hat{r},\hat{p},\hat{t}},$$

$$\forall \hat{\imath} \in \hat{\mathcal{I}} \cup \{0\}, \hat{p} \in \hat{\mathcal{P}}, \hat{\jmath} \in \hat{\mathcal{J}}, \hat{t} \in \hat{\mathcal{T}} \setminus \{0\} \quad (5.11)$$

Furthermore, we set the initial inventory ($t = 0$) to the number of containers that are available for the CM platform at the start of planning (cf. formula 5.12).

$$Q_{\hat{\imath},\hat{p},\hat{\jmath},0} = \hat{\mathbf{IP}}_{\hat{p}\hat{\imath}\hat{\jmath}0}, \qquad \forall \hat{\imath} \in \hat{\mathcal{I}} \cup \{0\}, \hat{p} \in \hat{\mathcal{P}}, \hat{\jmath} \in \hat{\mathcal{J}} \quad (5.12)$$

Finally, we stipulate that only as many containers can flow into production or else be transported to other locations as there are available. This is defined in formula 5.13. Hereto we note, that materials, which are added to the stock in period t, become available for further usage in period $t + 1$.

$$\sum_{\substack{\hat{l}=0\\ \hat{\jmath}\neq\hat{l}}}^{\hat{J}_{max}} \sum_{\hat{v}=1}^{\hat{V}_{max}} b_{\hat{\imath},\hat{p},\hat{\jmath},\hat{l},\hat{t},\hat{v}} + \sum_{\substack{\hat{r}=1\\ \hat{\mathbf{L}}_{\hat{r}}=\hat{\jmath}\\ \wedge\hat{\mathbf{PS}}_{\hat{r}}=\hat{\imath}+1}}^{\hat{R}_{max}} q_{\hat{r},\hat{p},\hat{t}} \leq Q_{\hat{\imath},\hat{p},\hat{\jmath},(\hat{t}-1)},$$

$$\forall \hat{\imath} \in \hat{\mathcal{I}} \cup \{0\}, \hat{p} \in \hat{\mathcal{P}}, \hat{\jmath} \in \hat{\mathcal{J}}, \hat{t} \in \hat{\mathcal{T}} \setminus \{0\} \quad (5.13)$$

Order-Related

With regard to the order data submitted to the CM platform, it must be ensured that the ordered quantity is going to be delivered to the customer. This is achieved with constraint 5.14.

$$\sum_{\hat{t}=1}^{\hat{T}_{max}} \Bigg[\sum_{\hat{j}=1}^{\hat{J}_{max}} \sum_{\hat{v}=1}^{\hat{V}_{max}} b_{\hat{\imath},\hat{p},\hat{j},0,\hat{t},\hat{v}} - \sum_{\hat{l}=1}^{\hat{J}_{max}} \sum_{\hat{v}=1}^{\hat{V}_{max}} b_{\hat{\imath},\hat{p},0,\hat{l},\hat{t},\hat{v}} + \sum_{\substack{\hat{r}=1 \\ \hat{\mathbf{L}}_{\hat{r}}=0 \\ \wedge \hat{\mathbf{PS}}_{\hat{r}}=\hat{\imath}}}^{\hat{R}_{max}} q_{\hat{r},\hat{p},\hat{t}} \cdot \mathbb{1}_{Pos^{-1}_{\hat{\mathcal{I}}_T}(\hat{\imath}) \neq I_{max}} + \sum_{\substack{\hat{r}=1 \\ \hat{\mathbf{L}}_{\hat{r}}=0 \\ \wedge \hat{\mathbf{PS}}_{\hat{r}}=\hat{\imath}}}^{\hat{R}_{max}} \frac{q_{\hat{r},\hat{p},\hat{t}} \cdot \hat{\mathbf{QP}}_{\hat{p}}}{\hat{\mathbf{QPF}}_{\hat{p}}} \cdot \mathbb{1}_{Pos^{-1}_{\hat{\mathcal{I}}_T}(\hat{\imath}) = I_{max}} - \sum_{\substack{\hat{r}=1 \\ \hat{\mathbf{L}}_{\hat{r}}=0 \\ \wedge \hat{\mathbf{PS}}_{\hat{r}}=\hat{\imath}+1}}^{\hat{R}_{max}} q_{\hat{r},\hat{p},\hat{t}} \Bigg] = \hat{\mathbf{Q}}_{\hat{p}\hat{\imath}}, \qquad \forall \hat{\imath} \in \hat{\mathcal{I}}, \hat{p} \in \hat{\mathcal{P}} \mid \hat{\mathbf{Q}}_{\hat{p}\hat{\imath}} > 0 \quad (5.14)$$

Production-Related

Looking at the production-related properties, we first need to ensure that there is enough capacity available to fulfil a production request on a certain resource in a specific period (cf. formula 5.15). Therefore, we compare the available capacity with the required capacity, which is calculated by multiplying the number of parts to be processed by the processing time and dividing it by the number of parts that can be processed in parallel. In case it is unknown whether a product type is already being produced on a specific resource in a particular period, we additionally add the set-up time in order to reflect the changeover process.

$$\sum_{\hat{p}=1}^{\hat{P}_{max}} \Big[\frac{q_{\hat{r},\hat{p},\hat{t}} \cdot \hat{\mathbf{QP}}_{\hat{p}} \cdot \hat{\mathbf{PT}}_{\hat{r}\hat{p}}}{\hat{\mathbf{PP}}_{\hat{r}\hat{p}}} + x_{\hat{r},\hat{p},\hat{t}} \cdot \hat{\mathbf{ST}}_{\hat{r}\hat{p}} \cdot (1 - \hat{\mathbf{SH}}_{\hat{r}\hat{p}\hat{t}})\Big] \leq \hat{\mathbf{AC}}_{\hat{r}\hat{t}}, \quad \forall \hat{r} \in \hat{\mathcal{R}}, \hat{t} \in \hat{\mathcal{T}} \setminus \{0\} \quad (5.15)$$

Constraint 5.16 ensures that production is only carried out when the corresponding machine has been set up. The right side of the inequality represents the maximum possible production quantity, which is used as a tight Big-M in terms of numerical efficiency (cf. Kallrath 2013).

$$q_{\hat{r},\hat{p},\hat{t}} \cdot \hat{\mathbf{QP}}_{\hat{p}} \leq \Big[\sum_{\hat{\imath}=1}^{\hat{I}_{max}} (\hat{\mathbf{QP}}_{\hat{p}} \cdot \hat{\mathbf{Q}}_{\hat{p}\hat{\imath}} \cdot \mathbb{1}_{Pos^{-1}_{\hat{\mathcal{I}}_T}(\hat{\imath}) \neq I_{max}} + \mathbf{Q\hat{P}F}_{\hat{p}} \cdot \hat{\mathbf{Q}}_{\hat{p}\hat{\imath}} \cdot \mathbb{1}_{Pos^{-1}_{\hat{\mathcal{I}}_T}(\hat{\imath}) = I_{max}})\Big] \cdot x_{\hat{r},\hat{p},\hat{t}}, \quad \forall \hat{r} \in \hat{\mathcal{R}}, \hat{p} \in \hat{\mathcal{P}}, \hat{t} \in \hat{\mathcal{T}} \setminus \{0\} \quad (5.16)$$

At last, we use constraint 5.17 to specify that production can only take place if a production resource is approved to conduct a certain production step, and at the same time to ensure that the specified minimum lot-size quantity is exceeded.

$$x_{\hat{r},\hat{p},\hat{t}} \cdot \hat{\mathbf{ML}}_{\hat{r}} \leq q_{\hat{r},\hat{p},\hat{t}} \cdot \hat{\mathbf{QP}}_{\hat{p}} \cdot \hat{\mathbf{A}}_{\hat{r}\hat{p}}, \qquad \forall \hat{r} \in \hat{\mathcal{R}}, \hat{p} \in \hat{\mathcal{P}}, \hat{t} \in \hat{\mathcal{T}} \setminus \{0\} \quad (5.17)$$

Transport-Related

To plan the transports, we first record the number of required pallet slots per shipment via constraint 5.18 by dividing the number of containers to be transported by the maximum possible number of containers per pallet space. We assume single item stacks and accept non-full pallet slots as $NP_{\hat{\imath},\hat{p},\hat{\jmath},\hat{l},\hat{t},\hat{v}}$ is rounded up to the next integer value.

$$\frac{b_{\hat{\imath},\hat{p},\hat{\jmath},\hat{l},\hat{t},\hat{v}}}{\mathbf{M\hat{C}P}_{\hat{p}\hat{v}}} \cdot \mathbb{1}_{\hat{\imath}=0} + \frac{b_{\hat{\imath},\hat{p},\hat{\jmath},\hat{l},\hat{t},\hat{v}}}{\mathbf{M\hat{C}P}_{\hat{p}\hat{v}}} \cdot \mathbb{1}_{\hat{\imath}\neq 0 \wedge Pos^{-1}_{\tilde{\mathcal{I}}_T}(\hat{\imath})\neq I_{max}} + \frac{b_{\hat{\imath},\hat{p},\hat{\jmath},\hat{l},\hat{t},\hat{v}}}{\mathbf{M\hat{C}PF}_{\hat{p}\hat{v}}} \cdot \mathbb{1}_{\hat{\imath}\neq 0 \wedge Pos^{-1}_{\tilde{\mathcal{I}}_T}(\hat{\imath})= I_{max}} \leq NP_{\hat{\imath},\hat{p},\hat{\jmath},\hat{l},\hat{t},\hat{v}},$$
$$\forall \hat{\imath} \in \hat{\mathcal{I}} \cup \{0\}, \hat{p} \in \hat{\mathcal{P}}, \hat{\jmath} \in \hat{\mathcal{J}}, \hat{l} \in \hat{\mathcal{J}}, \hat{t} \in \hat{\mathcal{T}} \setminus \{0\}, \hat{v} \in \hat{\mathcal{V}} \quad (5.18)$$

Furthermore, we use the constraints 5.19 and 5.20 to guarantee that the vehicle restrictions are met in the case of direct non-stop transports. On the one hand, it must be ensured that the total number of pallet slots required for all shipments to be transported with a certain vehicle type does not exceed the provided vehicle capacity (cf. formula 5.19). On the other hand, the permissible upper weight limit of a vehicle is not allowed to be exceeded (cf. formula 5.20). As a result, these two constraints make sure that enough vehicles are utilised when directly transporting materials.

$$\sum_{\hat{\imath}=0}^{\hat{I}_{max}} \sum_{\hat{p}=1}^{\hat{P}_{max}} NP_{\hat{\imath},\hat{p},\hat{\jmath},\hat{l},\hat{t},\hat{v}} \leq \mathbf{P\hat{S}V}_{\hat{v}} \cdot NV_{\hat{\jmath},\hat{l},\hat{t},\hat{v}},$$
$$\forall \hat{\jmath} \in \hat{\mathcal{J}}, \hat{l} \in \hat{\mathcal{J}}, \hat{t} \in \hat{\mathcal{T}} \setminus \{0\}, \hat{v} \in \hat{\mathcal{V}} \setminus \{1\} \quad (5.19)$$

$$\sum_{\hat{\imath}=0}^{\hat{I}_{max}} \sum_{\hat{p}=1}^{\hat{P}_{max}} b_{\hat{\imath},\hat{p},\hat{\jmath},\hat{l},\hat{t},\hat{v}} \cdot \mathbf{\hat{W}P}_{\hat{p}\hat{\imath}} \leq \mathbf{L\hat{C}}_{\hat{v}} \cdot NV_{\hat{\jmath},\hat{l},\hat{t},\hat{v}},$$
$$\forall \hat{\jmath} \in \hat{\mathcal{J}}, \hat{l} \in \hat{\mathcal{J}}, \hat{t} \in \hat{\mathcal{T}} \setminus \{0\}, \hat{v} \in \hat{\mathcal{V}} \setminus \{1\} \quad (5.20)$$

As a last restriction, we set up constraint 5.21 to ensure that no transport starts in a period in which no transport is allowed to take place. Additionally, this constraint guarantees that no transports are planned between two identical locations.

$$b_{\hat{\imath},\hat{p},\hat{\jmath},\hat{l},\hat{t},\hat{v}} = 0, \qquad \hat{\imath} \in \hat{\mathcal{I}} \cup \{0\}, \hat{p} \in \hat{\mathcal{P}}, \hat{\jmath} \in \hat{\mathcal{J}}, \hat{l} \in \hat{\mathcal{J}}, \hat{t} \in \hat{\mathcal{T}} \setminus \{0\}, \hat{v} \in \hat{\mathcal{V}} \mid \hat{\jmath} = \hat{l} \vee \hat{\mathbf{PB}}_{\hat{t}\hat{v}} = 0 \quad (5.21)$$

5.4 Model Extensions

After having introduced the base model version of the SLSP, we will now present several possibilities to extend the model. In chapter 5.4.1, we will complement the logic to calculate the transport costs by including fixed-costs elements. In chapter 5.4.2, it is shown how to include secondary resources such as components and finished goods containers. Chapter 5.4.3 examines how to integrate a time window-based delivery.

5.4.1 Transport Costs (TC)

In the base model version of the SLSP, we have assumed that the plants are located far enough apart from each other so that the minimum transport costs that must at least be paid when utilising a vehicle in the case of a direct non-stop transport are definitely exceeded. In addition, we have neglected possible basic costs that are added to the volume-dependent variable cost component when using groupage services. If these assumptions cannot be made, we need to consider those aspects when calculating the resulting transport costs as well. In the following sections, we will explain how the above-mentioned extensions affect the decision variables, the objective function and the constraints. In doing so, we will only address the necessary modifications, all other aspects remain unchanged.

Decision Variables

To calculate the transport costs of a direct non-stop transport under consideration of minimum transport costs, we introduce an additional cost variable $TCD_{\hat{\jmath},\hat{l},\hat{t},\hat{v}}$, that captures the resulting cost values:

$TCD_{\hat{\jmath},\hat{l},\hat{t},\hat{v}} \in \mathbb{R}_{\geq 0}$ = Resulting transport costs of a direct transport from location $\hat{\jmath} \in \hat{\mathcal{J}}$ to location $\hat{l} \in \hat{\mathcal{J}}$ in period $\hat{t} \in \hat{\mathcal{T}} \setminus \{0\}$ using transport form $\hat{v} \in \hat{\mathcal{V}} \setminus \{1\}$

For the purpose of integrating the basic costs of a groupage service, we furthermore add the binary auxiliary variable $y_{\hat{\jmath},\hat{l},\hat{t}}$.

$y_{\hat{\jmath},\hat{l},\hat{t}} \in \{0, 1\}$ = Binary variable that assumes value 1 if materials are transported from location $\hat{\jmath} \in \hat{\mathcal{J}}$ to location $\hat{l} \in \hat{\mathcal{J}}$ in period $\hat{t} \in \hat{\mathcal{T}} \setminus \{0\}$ using a groupage service, and value 0, otherwise

Objective Function

To integrate the newly defined variables in the calculation of the transport costs, we need to modify the objective function g_1. As shown in formula 5.22, the total transport costs related to direct non-stop transports are now being calculated by adding up the variable $TCD_{\hat{\jmath},\hat{l},\hat{t},\hat{v}}$. With regard to the transport costs related to groupage services, we use the newly defined binary variable $y_{\hat{\jmath},\hat{l},\hat{t}}$ to add up both the basic costs and the volume-dependent variable portion.

$$g_1 := \sum_{\hat{r}=1}^{\hat{R}_{max}} \sum_{\hat{p}=1}^{\hat{P}_{max}} \sum_{\hat{t}=1}^{\hat{T}_{max}} \hat{\mathbf{CP}}_{\hat{r}\hat{p}\hat{t}} \cdot q_{\hat{r},\hat{p},\hat{t}} \cdot \hat{\mathbf{QP}}_{\hat{p}} \cdot \hat{\mathbf{PT}}_{\hat{r}\hat{p}} +$$
$$\sum_{\hat{r}=1}^{\hat{R}_{max}} \sum_{\hat{p}=1}^{\hat{P}_{max}} \sum_{\hat{t}=1}^{\hat{T}_{max}} \hat{\mathbf{CP}}_{\hat{r}\hat{p}\hat{t}} \cdot x_{\hat{r},\hat{p},\hat{t}} \cdot (1 - \hat{\mathbf{SH}}_{\hat{r}\hat{p}\hat{t}}) \cdot \hat{\mathbf{ST}}_{\hat{r}\hat{p}} +$$
$$\sum_{\hat{j}=0}^{\hat{J}_{max}} \sum_{\hat{l}=0}^{\hat{J}_{max}} \sum_{\hat{t}=1}^{\hat{T}_{max}} \sum_{\hat{v}=2}^{\hat{V}_{max}} TCD_{\hat{j},\hat{l},\hat{t},\hat{v}} +$$
$$\sum_{\hat{j}=0}^{\hat{J}_{max}} \sum_{\hat{l}=0}^{\hat{J}_{max}} \sum_{\hat{t}=1}^{\hat{T}_{max}} \Big[\sum_{\hat{\imath}=0}^{\hat{I}_{max}} \sum_{\hat{p}=1}^{\hat{P}_{max}} (NP_{\hat{\imath},\hat{p},\hat{j},\hat{l},\hat{t},1} \cdot \hat{\mathbf{CS}}_{\hat{j}\hat{l}}) + y_{\hat{j},\hat{l},\hat{t}} \cdot \hat{\mathbf{BC}}_{\hat{j}\hat{l}} \Big] \quad (5.22)$$

Constraints

To determine the values of $TCD_{\hat{j},\hat{l},\hat{t}\hat{v}}$, we introduce two additional constraints (5.23 and 5.24). These constraints ensure that the maximum of the distance-dependent transport costs and the minimum transport costs is paid for each vehicle used.

$$TCD_{\hat{j},\hat{l},\hat{t}\hat{v}} \geq \hat{\mathbf{CT}}_{\hat{v}} \cdot NV_{\hat{j},\hat{l},\hat{t},\hat{v}} \cdot \hat{\mathbf{D}}_{\hat{j}\hat{l}}, \quad \forall \hat{j} \in \hat{\mathcal{J}}, \hat{l} \in \hat{\mathcal{J}}, \hat{t} \in \hat{\mathcal{T}} \setminus \{0\}, \hat{v} \in \hat{\mathcal{V}} \setminus \{1\} \quad (5.23)$$

$$TCD_{\hat{j},\hat{l},\hat{t}\hat{v}} \geq \hat{\mathbf{MCT}}_{\hat{v}} \cdot NV_{\hat{j},\hat{l},\hat{t},\hat{v}}, \quad \forall \hat{j} \in \hat{\mathcal{J}}, \hat{l} \in \hat{\mathcal{J}}, \hat{t} \in \hat{\mathcal{T}} \setminus \{0\}, \hat{v} \in \hat{\mathcal{V}} \setminus \{1\} \quad (5.24)$$

Moreover, we include constraint 5.25 to define the relationship between $y_{\hat{j},\hat{l},\hat{t}}$ and $NP_{\hat{\imath},\hat{p},\hat{j},\hat{l},\hat{t},1}$, with the right side representing a tight border for the maximum possible number of pallets in the sense of a narrow Big-M formulation.

$$NP_{\hat{\imath}_0,\hat{p},\hat{\jmath},\hat{l},\hat{t},1} \leq y_{\hat{\jmath},\hat{l},\hat{t}} \cdot \Big[\sum_{\hat{\imath}=1}^{\hat{I}_{max}} \Big(\frac{\hat{\mathbf{Q}}_{\hat{p}\hat{\imath}}}{\mathbf{M\hat{C}P}_{\hat{p}1}} \cdot \mathbb{1}_{Pos^{-1}_{\hat{\mathcal{I}}_T}(\hat{\imath}) \neq I_{max}} + \frac{\hat{\mathbf{Q}}_{\hat{p}\hat{\imath}}}{\min\{\mathbf{M\hat{C}PF}_{\hat{p}1}, \mathbf{M\hat{C}P}_{\hat{p}1}\}} \cdot \mathbb{1}_{Pos^{-1}_{\hat{\mathcal{I}}_T}(\hat{\imath}) = I_{max}} + 1 \cdot \mathbb{1}_{\hat{\mathbf{Q}}_{\hat{p}\hat{\imath}} > 0}\Big)\Big],$$
$$\forall \hat{\imath}_0 \in \hat{\mathcal{I}} \cup \{0\}, \hat{p} \in \hat{\mathcal{P}}, \hat{\jmath} \in \hat{\mathcal{J}}, \hat{l} \in \hat{\mathcal{J}}, \hat{t} \in \hat{\mathcal{T}} \setminus \{0\} \quad (5.25)$$

5.4.2 Secondary Material Resources (SMR)

Another way to expand the SLSP-B involves including secondary material resources that are being consumed during production. Using the examples of mounting components and empty finished goods containers, we will explain in the following sections how these resources can be added to the model. As in the previous chapter, we will again focus on the necessary modifications, with all other aspects remaining unchanged.

Decision Variables

Analogous to the parts to be processed, we need to include additional stock variables (Q) and transport variables (b and NP) for the two types of resources.

For the components, the following variables are defined:

$Q_{\hat{c},\hat{\jmath},\hat{t}} \in \mathbb{R}_{\geq 0}$ = Inventory stock of containers with components of type $\hat{c} \in \hat{\mathcal{C}}$ at location $\hat{\jmath} \in \hat{\mathcal{J}}$ at the end of period $\hat{t} \in \hat{\mathcal{T}}$

$b_{\hat{c},\hat{\jmath},\hat{l},\hat{t},\hat{v}} \in \mathbb{R}_{\geq 0}$ = Number of containers with components of type $\hat{c} \in \hat{\mathcal{C}}$ to be shipped from location $\hat{\jmath} \in \hat{\mathcal{J}}$ to location $\hat{l} \in \hat{\mathcal{J}}$ in period $\hat{t} \in \hat{\mathcal{T}} \setminus \{0\}$ using transport form $\hat{v} \in \hat{\mathcal{V}}$

$NP_{\hat{c},\hat{\jmath},\hat{l},\hat{t},\hat{v}} \in \mathbb{N}_0$ = Number of pallet slots required for transporting components of type $\hat{c} \in \hat{\mathcal{C}}$ from location $\hat{\jmath} \in \hat{\mathcal{J}}$ to location $\hat{l} \in \hat{\mathcal{J}}$ in period $\hat{t} \in \hat{\mathcal{T}} \setminus \{0\}$ using transport form $\hat{v} \in \hat{\mathcal{V}}$

Likewise, we add the variables described below for the empty finished goods containers. In contrary to the component variables defined above, however, we limit the range of values to integer numbers to ensure that only complete containers are possible.

$Q_{\hat{f},\hat{\jmath},\hat{t}} \in \mathbb{N}_0$ = Inventory stock of empty finished goods containers of type $\hat{f} \in \hat{\mathcal{F}}$ at location $\hat{\jmath} \in \hat{\mathcal{J}}$ at the end of period $\hat{t} \in \hat{\mathcal{T}}$

$b_{\hat{f},\hat{\jmath},\hat{l},\hat{t},\hat{v}} \in \mathbb{N}_0$ = Number of empty finished containers of type $\hat{f} \in \hat{\mathcal{F}}$ to be shipped from location $\hat{\jmath} \in \hat{\mathcal{J}}$ to location $\hat{l} \in \hat{\mathcal{J}}$ in period $\hat{t} \in \hat{\mathcal{T}} \setminus \{0\}$ using transport form $\hat{v} \in \hat{\mathcal{V}}$

$NP_{\hat{f},\hat{\jmath},\hat{l},\hat{t},\hat{v}} \in \mathbb{N}_0$ = Number of pallet slots required for transporting empty finished goods containers of type $\hat{f} \in \hat{\mathcal{F}}$ from location $\hat{\jmath} \in \hat{\mathcal{J}}$ to location $\hat{l} \in \hat{\mathcal{J}}$ in period $\hat{t} \in \hat{\mathcal{T}} \setminus \{0\}$ using transport form $\hat{v} \in \hat{\mathcal{V}}$

Due to the integer characteristic of the empty finished goods containers, we additionally introduce the auxiliary variable $H_{\hat{\jmath},\hat{p},\hat{t}}$ to enforce that only integer quantities of containers are being filled per product type and location in one period:

$H_{\hat{\jmath},\hat{p},\hat{t}} \in \mathbb{N}_0 =$ Number of containers with finished goods of type $\hat{p} \in \hat{\mathcal{P}}$ being filled in period $\hat{t} \in \hat{\mathcal{T}} \setminus \{0\}$ at location $\hat{\jmath} \in \hat{\mathcal{J}}$

Objective Function

In order to include the transport costs arising from transporting the secondary material resources in the total costs, we redefine the cost-based objective function g_1, as described in formula 5.26:

$$
\begin{aligned}
g_1 := & \sum_{\hat{r}=1}^{\hat{R}_{max}} \sum_{\hat{p}=1}^{\hat{P}_{max}} \sum_{\hat{t}=1}^{\hat{T}_{max}} \hat{\mathbf{CP}}_{\hat{r}\hat{p}\hat{t}} \cdot q_{\hat{r},\hat{p},\hat{t}} \cdot \hat{\mathbf{QP}}_{\hat{p}} \cdot \hat{\mathbf{PT}}_{\hat{r}\hat{p}} + \\
& \sum_{\hat{r}=1}^{\hat{R}_{max}} \sum_{\hat{p}=1}^{\hat{P}_{max}} \sum_{\hat{t}=1}^{\hat{T}_{max}} \hat{\mathbf{CP}}_{\hat{r}\hat{p}\hat{t}} \cdot x_{\hat{r},\hat{p},\hat{t}} \cdot (1 - \hat{\mathbf{SH}}_{\hat{r}\hat{p}\hat{t}}) \cdot \hat{\mathbf{ST}}_{\hat{r}\hat{p}} + \\
& \sum_{\hat{\jmath}=0}^{\hat{J}_{max}} \sum_{\hat{l}=0}^{\hat{J}_{max}} \sum_{\hat{t}=1}^{\hat{T}_{max}} \sum_{\hat{v}=2}^{\hat{V}_{max}} \hat{\mathbf{CT}}_{\hat{v}} \cdot NV_{\hat{\jmath},\hat{l},\hat{t},\hat{v}} \cdot \hat{\mathbf{D}}_{\hat{\jmath}\hat{l}} + \\
& \sum_{\hat{\jmath}=0}^{\hat{J}_{max}} \sum_{\hat{l}=0}^{\hat{J}_{max}} \sum_{\hat{t}=1}^{\hat{T}_{max}} \sum_{\hat{\imath}=0}^{\hat{I}_{max}} \sum_{\hat{p}=1}^{\hat{P}_{max}} \hat{\mathbf{CS}}_{\hat{\jmath}\hat{l}} \cdot NP_{\hat{\imath},\hat{p},\hat{\jmath},\hat{l},\hat{t},1} + \\
& \sum_{\hat{\jmath}=0}^{\hat{J}_{max}} \sum_{\hat{l}=0}^{\hat{J}_{max}} \sum_{\hat{t}=1}^{\hat{T}_{max}} \sum_{\hat{c}=1}^{\hat{C}_{max}} \hat{\mathbf{CS}}_{\hat{\jmath}\hat{l}} \cdot NP_{\hat{c},\hat{\jmath},\hat{l},\hat{t},1} + \\
& \sum_{\hat{\jmath}=0}^{\hat{J}_{max}} \sum_{\hat{l}=0}^{\hat{J}_{max}} \sum_{\hat{t}=1}^{\hat{T}_{max}} \sum_{\hat{f}=1}^{\hat{F}_{max}} \hat{\mathbf{CS}}_{\hat{\jmath}\hat{l}} \cdot NP_{\hat{f},\hat{\jmath},\hat{l},\hat{t},1}
\end{aligned} \tag{5.26}
$$

Constraints

To correctly model the secondary material resources on the inventory side, we need to add several **inventory-related** constraints similar to the constraints introduced for the parts to be processed. These constraints are intended to update the stock development, to define the initial stock level and to ensure that only as much material resources as available are taken from the stock.

For the components, constraints 5.27, 5.28 and 5.29 are included. Increases in inventory result from deliveries from other locations or when components are made available to the platform ($\mathbf{I\hat{C}}_{\hat{c}\hat{\jmath}\hat{t}}$). Outflows result from components sent away and from components being consumed during production according to the bill of materials. Please note that opened containers are considered.

$$Q_{\hat{c},\hat{\jmath},\hat{t}} = Q_{\hat{c},\hat{\jmath},(\hat{t}-1)} + \mathbf{I\hat{C}}_{\hat{c}\hat{\jmath}\hat{t}} + \sum_{\substack{\hat{l}=0 \\ \hat{l}\neq\hat{\jmath}}}^{\hat{J}_{max}} \sum_{\substack{\hat{v}=1 \\ \hat{t}-\mathbf{T\hat{R}}_{\hat{l}\hat{\jmath}\hat{v}\hat{t}}\geq 1}}^{\hat{V}_{max}} b_{\hat{c},\hat{l},\hat{\jmath},(\hat{t}-\mathbf{T\hat{R}}_{\hat{l}\hat{\jmath}\hat{v}\hat{t}}),\hat{v}} - \sum_{\substack{\hat{l}=0 \\ \hat{l}\neq\hat{\jmath}}}^{\hat{J}_{max}} \sum_{\hat{v}=1}^{\hat{V}_{max}} b_{\hat{c},\hat{\jmath},\hat{l},\hat{t},\hat{v}} - \sum_{\hat{p}=1}^{\hat{P}_{max}} \sum_{\hat{\imath}=1}^{\hat{I}_{max}} \sum_{\substack{\hat{r}=1 \\ \hat{\mathbf{L}}_{\hat{r}}=\hat{\jmath} \\ \wedge \mathbf{P\hat{S}}_{\hat{r}}=\hat{\imath}}}^{\hat{R}_{max}} \frac{q_{\hat{r},\hat{p},\hat{t}} \cdot \mathbf{Q\hat{P}}_{\hat{p}} \cdot \hat{\mathbf{B}}_{\hat{\imath}\hat{p}\hat{c}}}{\mathbf{Q\hat{C}}_{\hat{c}}},$$
$$\forall \hat{c} \in \hat{\mathcal{C}}, \hat{\jmath} \in \hat{\mathcal{J}}, \hat{t} \in \hat{\mathcal{T}} \setminus \{0\} \quad (5.27)$$

$$Q_{\hat{c},\hat{\jmath},0} = \mathbf{I\hat{C}}_{\hat{c}\hat{\jmath}0}, \qquad \forall \hat{c} \in \hat{\mathcal{C}}, \hat{\jmath} \in \hat{\mathcal{J}} \quad (5.28)$$

$$\sum_{\substack{\hat{l}=0 \\ \hat{\jmath}\neq\hat{l}}}^{\hat{J}_{max}} \sum_{\hat{v}=1}^{\hat{V}_{max}} b_{\hat{c},\hat{\jmath},\hat{l},\hat{t},\hat{v}} + \sum_{\hat{p}=1}^{\hat{P}_{max}} \sum_{\hat{\imath}=1}^{\hat{I}_{max}} \sum_{\substack{\hat{r}=1 \\ \hat{\mathbf{L}}_{\hat{r}}=\hat{\jmath} \\ \wedge \mathbf{P\hat{S}}_{\hat{r}}=\hat{\imath}}}^{\hat{R}_{max}} \frac{q_{\hat{r},\hat{p},\hat{t}} \cdot \mathbf{Q\hat{P}}_{\hat{p}} \cdot \hat{\mathbf{B}}_{\hat{\imath}\hat{p}\hat{c}}}{\mathbf{Q\hat{C}}_{\hat{c}}} \leq Q_{\hat{c},\hat{\jmath},(\hat{t}-1)},$$
$$\forall \hat{c} \in \hat{\mathcal{C}}, \hat{\jmath} \in \hat{\mathcal{J}}, \hat{t} \in \hat{\mathcal{T}} \setminus \{0\} \quad (5.29)$$

Likewise, we define the inventory-related constraints for the empty finished goods containers according to the formulas 5.30, 5.31 and 5.32.

$$Q_{\hat{f},\hat{\jmath},\hat{t}} = Q_{\hat{f},\hat{\jmath},(\hat{t}-1)} + \hat{\mathbf{IF}}_{\hat{f}\hat{\jmath}\hat{t}} + \sum_{\substack{\hat{l}=0 \\ \hat{l}\neq\hat{\jmath}}}^{\hat{J}_{max}} \sum_{\substack{\hat{v}=1 \\ \hat{t}-\hat{\mathbf{TR}}_{\hat{l}\hat{\jmath}\hat{v}\hat{t}}\geq 1}}^{\hat{V}_{max}} b_{\hat{f},\hat{l},\hat{\jmath},(\hat{t}-\hat{\mathbf{TR}}_{\hat{l}\hat{\jmath}\hat{v}\hat{t}}),\hat{v}} - \sum_{\substack{\hat{l}=0 \\ \hat{l}\neq\hat{\jmath}}}^{\hat{J}_{max}} \sum_{\hat{v}=1}^{\hat{V}_{max}} b_{\hat{f},\hat{\jmath},\hat{l},\hat{t},\hat{v}} - \sum_{\substack{\hat{p}=1 \\ \hat{\mathbf{PF}}_{\hat{p}}=\hat{f}}}^{\hat{P}_{max}} \sum_{\substack{\hat{r}=1 \\ \hat{\mathbf{L}}_{\hat{r}}=\hat{\jmath} \\ \wedge Pos^{-1}_{\tilde{\mathcal{I}}_T}(\hat{\mathbf{PS}}_{\hat{r}})=I_{max}}}^{\hat{R}_{max}} \frac{q_{\hat{r},\hat{p},\hat{t}} \cdot \hat{\mathbf{QP}}_{\hat{p}}}{\hat{\mathbf{QPF}}_{\hat{p}}},$$

$$\forall \hat{f} \in \hat{\mathcal{F}}, \hat{\jmath} \in \hat{\mathcal{J}}, \hat{t} \in \hat{\mathcal{T}} \setminus \{0\} \quad (5.30)$$

$$Q_{\hat{f},\hat{\jmath},0} = \hat{\mathbf{IF}}_{\hat{f}\hat{\jmath}0}, \qquad \forall \hat{f} \in \hat{\mathcal{F}}, \hat{\jmath} \in \hat{\mathcal{J}} \quad (5.31)$$

$$\sum_{\substack{\hat{l}=0 \\ \hat{\jmath}\neq\hat{l}}}^{\hat{J}_{max}} \sum_{\hat{v}=1}^{\hat{V}_{max}} b_{\hat{f},\hat{\jmath},\hat{l},\hat{t},\hat{v}} + \sum_{\substack{\hat{p}=1 \\ \hat{\mathbf{PF}}_{\hat{p}}=\hat{f}}}^{\hat{P}_{max}} \sum_{\substack{\hat{r}=1 \\ \hat{\mathbf{L}}_{\hat{r}}=\hat{\jmath} \\ \wedge Pos^{-1}_{\tilde{\mathcal{I}}_T}(\hat{\mathbf{PS}}_{\hat{r}})=I_{max}}}^{\hat{R}_{max}} \frac{q_{\hat{r},\hat{p},\hat{t}} \cdot \hat{\mathbf{QP}}_{\hat{p}}}{\hat{\mathbf{QPF}}_{\hat{p}}} \leq Q_{\hat{f},\hat{\jmath},(\hat{t}-1)},$$

$$\forall \hat{f} \in \hat{\mathcal{F}}, \hat{\jmath} \in \hat{\mathcal{J}}, \hat{t} \in \hat{\mathcal{T}} \setminus \{0\} \quad (5.32)$$

The amount of empty finished goods containers flowing into production is being determined from the quotient of the produced quantity and the holding capacity of the finished goods container. To ensure that only an integer quantity of finished goods containers is being filled per product, location and period, we additionally introduce constraint 5.33. As a result, it is no longer feasible to fill a finished goods container only partially, as it is possible in the base model version.

$$\sum_{\substack{\hat{r}=1\\ \hat{\mathbf{L}}_{\hat{r}}=\hat{\jmath}\\ \wedge Pos^{-1}_{\tilde{\mathcal{I}}_T}(\hat{\mathbf{PS}}_{\hat{r}})=I_{max}}}^{\hat{R}_{max}} \frac{q_{\hat{r},\hat{p},\hat{t}} \cdot \hat{\mathbf{QP}}_{\hat{p}}}{\hat{\mathbf{QPF}}_{\hat{p}}} = H_{\hat{\jmath},\hat{p},\hat{t}},$$

$$\forall \hat{\jmath} \in \hat{\mathcal{J}}, \hat{p} \in \hat{\mathcal{P}}, \hat{t} \in \hat{\mathcal{T}} \setminus \{0\} \quad (5.33)$$

Moreover, we have to adjust the **transport-related** constraints. In analogy to constraint 5.18, we record the number of pallets slots required by setting up the additional constraints 5.34 for the components and 5.35 for the empty finished goods containers.

$$\frac{b_{\hat{c},\hat{\jmath},\hat{l},\hat{t},\hat{v}}}{\hat{\mathbf{MCC}}_{\hat{c}\hat{v}}} \leq NP_{\hat{c},\hat{\jmath},\hat{l},\hat{t},\hat{v}},$$

$$\forall \hat{c} \in \hat{\mathcal{C}}, \hat{\jmath} \in \hat{\mathcal{J}}, \hat{l} \in \hat{\mathcal{J}}, \hat{t} \in \hat{\mathcal{T}} \setminus \{0\}, \hat{v} \in \hat{\mathcal{V}} \quad (5.34)$$

$$\frac{b_{\hat{f},\hat{\jmath},\hat{l},\hat{t},\hat{v}}}{\hat{\mathbf{MCF}}_{\hat{f}\hat{v}}} \leq NP_{\hat{f},\hat{\jmath},\hat{l},\hat{t},\hat{v}},$$

$$\forall \hat{f} \in \hat{\mathcal{F}}, \hat{\jmath} \in \hat{\mathcal{J}}, \hat{l} \in \hat{\mathcal{J}}, \hat{t} \in \hat{\mathcal{T}} \setminus \{0\}, \hat{v} \in \hat{\mathcal{V}} \quad (5.35)$$

In addition, we need to make sure that these shipments are being considered when looking at the vehicle utilisation in the case of a direct non-stop transport. For this purpose, we extend the constraints 5.19 and 5.20, which ensure that the capacity limits and weight limits of the vehicles are met and redefine them in 5.36 and 5.37.

$$\sum_{\hat{\imath}=0}^{\hat{I}_{max}} \sum_{\hat{p}=1}^{\hat{P}_{max}} NP_{\hat{\imath},\hat{p},\hat{\jmath},\hat{l},\hat{t},\hat{v}} + \sum_{\hat{c}=1}^{\hat{C}_{max}} NP_{\hat{c},\hat{\jmath},\hat{l},\hat{t},\hat{v}} + \sum_{\hat{f}=1}^{\hat{F}_{max}} NP_{\hat{f},\hat{\jmath},\hat{l},\hat{t},\hat{v}} \leq \mathbf{P\hat{S}V}_{\hat{v}} \cdot NV_{\hat{\jmath},\hat{l},\hat{t},\hat{v}}, \quad \forall \hat{\jmath} \in \hat{\mathcal{J}}, \hat{l} \in \hat{\mathcal{J}}, \hat{t} \in \hat{\mathcal{T}} \setminus \{0\}, \hat{v} \in \hat{\mathcal{V}} \setminus \{1\} \tag{5.36}$$

$$\sum_{\hat{\imath}=0}^{\hat{I}_{max}} \sum_{\hat{p}=1}^{\hat{P}_{max}} b_{\hat{\imath},\hat{p},\hat{\jmath},\hat{l},\hat{t},\hat{v}} \cdot \mathbf{\hat{W}P}_{\hat{p}\hat{\imath}} + \sum_{\hat{c}=1}^{\hat{C}_{max}} b_{\hat{c},\hat{\jmath},\hat{l},\hat{t},\hat{v}} \cdot \mathbf{\hat{W}C}_{\hat{c}} + \sum_{\hat{f}=1}^{\hat{F}_{max}} b_{\hat{f},\hat{\jmath},\hat{l},\hat{t},\hat{v}} \cdot \mathbf{\hat{W}F}_{\hat{f}} \leq \mathbf{L\hat{C}}_{\hat{v}} \cdot NV_{\hat{\jmath},\hat{l},\hat{t},\hat{v}}, \quad \forall \hat{\jmath} \in \hat{\mathcal{J}}, \hat{l} \in \hat{\mathcal{J}}, \hat{t} \in \hat{\mathcal{T}} \setminus \{0\}, \hat{v} \in \hat{\mathcal{V}} \setminus \{1\} \tag{5.37}$$

As the last point, we add the constraints 5.38 and 5.39 to allow the start of a transport with components and empty finished goods containers only in a period in which it is permitted, as well as to prohibit any transport between the same location.

$$b_{\hat{c},\hat{\jmath},\hat{l},\hat{t},\hat{v}} = 0, \qquad \hat{c} \in \hat{\mathcal{C}}, \hat{\jmath} \in \hat{\mathcal{J}}, \hat{l} \in \hat{\mathcal{J}}, \hat{t} \in \hat{\mathcal{T}} \setminus \{0\}, \hat{v} \in \hat{\mathcal{V}} \mid \hat{\jmath} = \hat{l} \lor \mathbf{P\hat{B}}_{\hat{t}\hat{v}} = 0 \tag{5.38}$$

$$b_{\hat{f},\hat{\jmath},\hat{l},\hat{t},\hat{v}} = 0, \qquad \hat{f} \in \hat{\mathcal{F}}, \hat{\jmath} \in \hat{\mathcal{J}}, \hat{l} \in \hat{\mathcal{J}}, \hat{t} \in \hat{\mathcal{T}} \setminus \{0\}, \hat{v} \in \hat{\mathcal{V}} \mid \hat{\jmath} = \hat{l} \lor \mathbf{P\hat{B}}_{\hat{t}\hat{v}} = 0 \tag{5.39}$$

5.4.3 Time Window-based Delivery (TW)

The third model extension we discuss is the time window-based delivery. This extension allows the customer to define a time frame in which a delivery is supposed to arrive.

Objective Function

Due to the predefined time frame, an optimisation of the delivery time becomes obsolete. For this reason, we omit the objective function g_2 and only optimise cost-oriented according to objective function g_1. The model thus becomes mono-objective with problem 5.9 to be solved. Consequently, with this extension option, only one solution is reported back to the customer as a result of the service composition process.

Constraints

To model the time window-based delivery, we define two additional constraints that ensure that no deliveries arrive at the customer site after the latest possible delivery period (5.40) as well as not before the earliest possible delivery period (5.41).

$$b_{\hat{\imath},\hat{p},\hat{\jmath},0,\hat{t},\hat{v}} = 0, \qquad \forall \hat{\imath} \in \hat{\mathcal{I}}, \hat{p} \in \hat{\mathcal{P}}, \hat{\jmath} \in \hat{\mathcal{J}}, \\ \hat{t} \in \hat{\mathcal{T}} \setminus \{0\}, \hat{v} \in \hat{\mathcal{V}} \mid \hat{\mathbf{Q}}_{\hat{p}\hat{\imath}} > 0 \wedge \hat{t} + \hat{\mathbf{T}}_{\hat{\jmath}0\hat{v}\hat{t}} > \hat{\mathbf{TL}}_{\hat{p}\hat{\imath}} \tag{5.40}$$

$$b_{\hat{\imath},\hat{p},\hat{\jmath},0,\hat{t},\hat{v}} = 0, \qquad \forall \hat{\imath} \in \hat{\mathcal{I}}, \hat{p} \in \hat{\mathcal{P}}, \hat{\jmath} \in \hat{\mathcal{J}}, \\ \hat{t} \in \hat{\mathcal{T}} \setminus \{0\}, \hat{v} \in \hat{\mathcal{V}} \mid \hat{\mathbf{Q}}_{\hat{p}\hat{\imath}} > 0 \wedge \hat{t} + \hat{\mathbf{T}}_{\hat{\jmath}0\hat{v}\hat{t}} < \hat{\mathbf{TE}}_{\hat{p}\hat{\imath}} \tag{5.41}$$

5.5 LP-Reformulation (SLSP-LP)

Having introduced the base model version of the SLSP formulated as a MILP and several extension possibilities, this chapter presents a linear programming (LP)-based reformulation.

According to the following generic formulation, a linear program is characterised by continuous variables and by a linear objective function and linear constraints (cf. Nickel, Stein, and Waldmann 2011):

$$\max_{x}\{c^T x : Ax \leq b, x \in \mathbb{R}^n, c \in \mathbb{R}^n, b \in \mathbb{R}^m, A \in \mathbb{R}^{m \times n}\} \tag{5.42}$$

Our goal is thus to translate the integer variables of the SLSP-B into continuous variables. In doing so, we do not only want to redefine the integer variables to continuous variables, what is called a LP relaxation (cf. Nickel, Stein, and Waldmann 2011), but also adapt the corresponding problem formulation logically.

The main advantage of working with LP problems is the efficient solvability of this problem class. Thus even the most difficult instances of LP problems can be solved in polynomial effort. In contrast to integer problems, LP problems therefore lie in the complexity class P.[3] Exemplary solution algorithms that solve LP problems efficiently are interior point methods. (cf. Domschke et al. 2015)

Below, we will present the limiting assumptions necessary for the LP-reformulation as well as the resulting model formulation.

5.5.1 Assumptions

Compared to the base model version of the SLSP, we make the following restrictions when looking at the LP-reformulation:

- With the LP-Reformulation, we disregard any possible **set-up times**. This assumption is especially plausible when the set-up

[3] assuming P$\neq$NP

times are that small or even non-existent so that they are negligible anyway. Additionally, this assumption can be made if the maximum possible set-up time has already been deducted from the available capacity ($\hat{\mathbf{AC}}$) in the sense of a worst-case consideration.

- Moreover, we neglect **minimum lot sizes**. Production orders of any size are therefore possible at all resources.
- In terms of **transport**, we limit the LP-reformulation to groupage services. Consequently, no direct non-stop transports with dedicated vehicles are planned. This restriction is particularly plausible when a job is less time-critical and more attention is paid to cost optimisation.
- Finally, we relax the assumption of **discrete lot sizes** and allow lot sizes that are not an integer multiple of the container filling quantity.

5.5.2 Decision Variables

As a modelling base, we define the following reduced set of continuous decision variables. For a better distinction from the variables of the base model version, we mark them with an additional "LP". Along with that, it should be noted that we neglect the index v in the definition of variable $b^{LP}_{\hat{\imath},\hat{p},\hat{\jmath},\hat{l},\hat{t}}$ since there is no variation as only groupage services with $v = 1$ are being considered.

$q^{LP}_{\hat{r},\hat{p},\hat{t}} \in \mathbb{R}_{\geq 0}$ = Number of full containers of product $\hat{p} \in \hat{\mathcal{P}}$ to be processed on resource $\hat{r} \in \hat{\mathcal{R}}$ in period $\hat{t} \in \hat{\mathcal{T}} \setminus \{0\}$

$Q^{LP}_{\hat{\imath},\hat{p},\hat{\jmath},\hat{t}} \in \mathbb{R}_{\geq 0}$ = Stock of containers with parts $\hat{p} \in \hat{\mathcal{P}}$ that have passed stage $\hat{\imath} \in \hat{\mathcal{I}} \cup \{0\}$ at location $\hat{\jmath} \in \hat{\mathcal{J}}$ at the end of period $\hat{t} \in \hat{\mathcal{T}}$. Starting materials are captured via $\hat{\imath} = 0$. For output materials, we use $\hat{\imath} = \hat{I}_{max}$

$b^{LP}_{\hat{\imath},\hat{p},\hat{\jmath},\hat{l},\hat{t}} \in \mathbb{R}_{\geq 0}$ = Number of full containers with parts of type $\hat{p} \in \hat{\mathcal{P}}$ that have passed step $\hat{\imath} \in \hat{\mathcal{I}} \cup \{0\}$, and which are to be shipped from location $\hat{\jmath} \in \hat{\mathcal{J}}$ to location $\hat{l} \in \hat{\mathcal{J}}$ in period $\hat{t} \in \hat{\mathcal{T}} \setminus \{0\}$ using a groupage service. Starting materials are captured via $\hat{\imath} = 0$. For output materials, we use $\hat{\imath} = \hat{I}_{max}$

5.5.3 Objective Function

Since the LP reformulation omits set-ups and direct transports, we neglect the associated costs and define a reduced cost-based objective function g_1 according to formula 5.43. With this formula, we add up the resulting production costs as well as the transport costs related to groupage services. Please note that we assume a weight-based transport cost rate in this case, as this allows us to work with a continuous transport volume compared to the pallet slot-based approach we applied in the base model version.

$$g_1 := \sum_{\hat{r}=1}^{\hat{R}_{max}} \sum_{\hat{p}=1}^{\hat{P}_{max}} \sum_{\hat{t}=1}^{\hat{T}_{max}} \mathbf{\hat{CP}}_{\hat{r}\hat{p}\hat{t}} \cdot q^{LP}_{\hat{r},\hat{p},\hat{t}} \cdot \mathbf{\hat{QP}}_{\hat{p}} \cdot \mathbf{\hat{PT}}_{\hat{r}\hat{p}} + \sum_{\hat{\jmath}=0}^{\hat{J}_{max}} \sum_{\hat{l}=0}^{\hat{J}_{max}} \sum_{\hat{t}=1}^{\hat{T}_{max}} \sum_{\hat{\imath}=0}^{\hat{I}_{max}} \sum_{\hat{p}=1}^{\hat{P}_{max}} \mathbf{\hat{CW}}_{\hat{\jmath}\hat{l}} \cdot b^{LP}_{\hat{\imath},\hat{p},\hat{\jmath},\hat{l},\hat{t}} \cdot \mathbf{\hat{WP}}_{\hat{p}\hat{\imath}} \quad (5.43)$$

With regard to the time-based objective function g_2, we adopt the formulation of the base model version (formula 5.5), using the LP variables defined:

$$g_2 := \sum_{\hat{\imath}=1}^{\hat{I}_{max}} \sum_{\substack{\hat{p}=1 \\ \hat{\mathbf{Q}}_{\hat{p}\hat{\imath}}>0}}^{\hat{P}_{max}} \cdot \Big[\sum_{\hat{\jmath}=1}^{\hat{J}_{max}} \sum_{\hat{t}=1}^{\hat{T}_{max}} b^{LP}_{\hat{\imath},\hat{p},\hat{\jmath},0,\hat{t}} \cdot (\hat{t} + \hat{\mathbf{T}}_{\hat{\jmath}0\hat{t}1}) \cdot (\mathbb{1}_{Pos^{-1}_{\tilde{\mathcal{I}}_T}(\hat{\imath})=I_{max}} \cdot \hat{\mathbf{QPF}}_{\hat{p}} + \mathbb{1}_{Pos^{-1}_{\tilde{\mathcal{I}}_T}(\hat{\imath})\neq I_{max}} \cdot \hat{\mathbf{QP}}_{\hat{p}}) + \sum_{\substack{\hat{r}=1 \\ \hat{\mathbf{L}}_{\hat{r}}=0 \\ \wedge \hat{\mathbf{PS}}_{\hat{r}}=\hat{\imath}}}^{\hat{R}_{max}} \sum_{\hat{t}=1}^{\hat{T}_{max}} q^{LP}_{\hat{r},\hat{p},\hat{t}} \cdot \hat{\mathbf{QP}}_{\hat{p}} \cdot \hat{t} \Big] \tag{5.44}$$

In terms of the solution algorithm for solving the multi-objective LP problem (MOLP), we make use of the weighting method-based approach described in section 5.3.3, similarly to the base model version. As a side note, we would like to mention that due to the convexity of LP problems (cf. Boyd and Vandenberghe 2009), the weighting method is theoretically able to find in this case even the entire Pareto set by varying the target weights systematically (cf. Miettinen 1999).

5.5.4 Constraints

With the LP reformulation, also an adjustment of the constraints becomes necessary, which we will discuss in the following sections.

Inventory-Related

The inventory-related constraints are formulated analogously to the SLSP-B, and record the inventory development (5.45), define the initial inventory level (5.46) and ensure that sufficient inventory is available when performing an action (5.47).

$$Q^{LP}_{\hat{\imath},\hat{p},\hat{\jmath},\hat{t}} = Q^{LP}_{\hat{\imath},\hat{p},\hat{\jmath},(\hat{t}-1)} + \mathbf{I\hat{P}}_{\hat{p}\hat{\imath}\hat{\jmath}\hat{t}} + \sum_{\substack{\hat{l}=0\\ \hat{l}\neq\hat{\jmath}\\ \wedge\hat{t}-\mathbf{T\hat{R}}_{\hat{l}\hat{\jmath}1\hat{t}}\geq 1}}^{\hat{J}_{max}} b^{LP}_{\hat{\imath},\hat{p},\hat{l},\hat{\jmath},(\hat{t}-\mathbf{T\hat{R}}_{\hat{l}\hat{\jmath}1\hat{t}})} - \sum_{\substack{\hat{l}=0\\ \hat{l}\neq\hat{\jmath}}}^{\hat{J}_{max}} b^{LP}_{\hat{\imath},\hat{p},\hat{\jmath},\hat{l},\hat{t}} + \sum_{\substack{\hat{r}=1\\ \mathbf{\hat{L}}_{\hat{r}}=\hat{\jmath}\\ \wedge\mathbf{P\hat{S}}_{\hat{r}}=\hat{\imath}}}^{\hat{R}_{max}} q^{LP}_{\hat{r},\hat{p},\hat{t}} \cdot \mathbb{1}_{Pos^{-1}_{\hat{\mathcal{I}}_T}(\hat{\imath})\neq I_{max}} + \sum_{\substack{\hat{r}=1\\ \mathbf{\hat{L}}_{\hat{r}}=\hat{\jmath}\\ \wedge\mathbf{P\hat{S}}_{\hat{r}}=\hat{\imath}}}^{\hat{R}_{max}} \frac{q^{LP}_{\hat{r},\hat{p},\hat{t}} \cdot \mathbf{Q\hat{P}}_{\hat{p}}}{\mathbf{Q\hat{P}F}_{\hat{p}}} \cdot \mathbb{1}_{Pos^{-1}_{\hat{\mathcal{I}}_T}(\hat{\imath})= I_{max}} - \sum_{\substack{\hat{r}=1\\ \mathbf{\hat{L}}_{\hat{r}}=\hat{\jmath}\\ \wedge\mathbf{P\hat{S}}_{\hat{r}}=\hat{\imath}+1}}^{\hat{R}_{max}} q^{LP}_{\hat{r},\hat{p},\hat{t}},$$

$$\forall \hat{\imath} \in \hat{\mathcal{I}} \cup \{0\}, \hat{p} \in \hat{\mathcal{P}}, \hat{\jmath} \in \hat{\mathcal{J}}, \hat{t} \in \hat{\mathcal{T}} \setminus \{0\} \quad (5.45)$$

$$Q^{LP}_{\hat{\imath},\hat{p},\hat{\jmath},0} = \mathbf{I\hat{P}}_{\hat{p}\hat{\imath}\hat{\jmath}0}, \qquad \forall \hat{\imath} \in \hat{\mathcal{I}} \cup \{0\}, \hat{p} \in \hat{\mathcal{P}}, \hat{\jmath} \in \hat{\mathcal{J}} \quad (5.46)$$

$$\sum_{\substack{\hat{l}=0\\ \hat{\jmath}\neq\hat{l}}}^{\hat{J}_{max}} b^{LP}_{\hat{\imath},\hat{p},\hat{\jmath},\hat{l},\hat{t}} + \sum_{\substack{\hat{r}=1\\ \mathbf{\hat{L}}_{\hat{r}}=\hat{\jmath}\\ \wedge\mathbf{P\hat{S}}_{\hat{r}}=\hat{\imath}+1}}^{\hat{R}_{max}} q^{LP}_{\hat{r},\hat{p},\hat{t}} \leq Q^{LP}_{\hat{\imath},\hat{p},\hat{\jmath},(\hat{t}-1)},$$

$$\forall \hat{\imath} \in \hat{\mathcal{I}} \cup \{0\}, \hat{p} \in \hat{\mathcal{P}}, \hat{\jmath} \in \hat{\mathcal{J}}, \hat{t} \in \hat{\mathcal{T}} \setminus \{0\} \quad (5.47)$$

Order-Related

The constraint ensuring that the ordered quantity is being delivered to the customer is also formulated in the same way as in the base model version, using the LP variables defined:

$$\sum_{\hat{t}=1}^{\hat{T}_{max}} \Big[\sum_{\hat{j}=1}^{\hat{J}_{max}} b^{LP}_{\hat{\imath},\hat{p},\hat{j},0,\hat{t}} - \sum_{\hat{l}=1}^{\hat{J}_{max}} b^{LP}_{\hat{\imath},\hat{p},0,\hat{l},\hat{t}} +$$

$$\sum_{\substack{\hat{r}=1 \\ \hat{\mathbf{L}}_{\hat{r}}=0 \\ \wedge \hat{\mathbf{PS}}_{\hat{r}}=\hat{\imath}}}^{\hat{R}_{max}} q^{LP}_{\hat{r},\hat{p},\hat{t}} \cdot \mathbb{1}_{Pos^{-1}_{\tilde{\mathcal{I}}_T}(\hat{\imath}) \neq I_{max}} + \sum_{\substack{\hat{r}=1 \\ \hat{\mathbf{L}}_{\hat{r}}=0 \\ \wedge \hat{\mathbf{PS}}_{\hat{r}}=\hat{\imath}}}^{\hat{R}_{max}} \frac{q^{LP}_{\hat{r},\hat{p},\hat{t}} \cdot \hat{\mathbf{QP}}_{\hat{p}}}{\hat{\mathbf{QPF}}_{\hat{p}}} \cdot \mathbb{1}_{Pos^{-1}_{\tilde{\mathcal{I}}_T}(\hat{\imath}) = I_{max}} -$$

$$\sum_{\substack{\hat{r}=1 \\ \hat{\mathbf{L}}_{\hat{r}}=0 \\ \wedge \hat{\mathbf{PS}}_{\hat{r}}=\hat{\imath}+1}}^{\hat{R}_{max}} q^{LP}_{\hat{r},\hat{p},\hat{t}} \Big] = \hat{\mathbf{Q}}_{\hat{p}\hat{\imath}}, \qquad \forall \hat{\imath} \in \hat{\mathcal{I}}, \hat{p} \in \hat{\mathcal{P}} \mid \hat{\mathbf{Q}}_{\hat{p}\hat{\imath}} > 0 \quad (5.48)$$

Production-Related

With regard to the capacity constraint, which ensures that enough capacity is available when undertaking a production step, we remove the set-up time from being considered in the calculation of the required capacity:

$$\sum_{\hat{p}=1}^{\hat{P}_{max}} \Big[\frac{q^{LP}_{\hat{r},\hat{p},\hat{t}} \cdot \hat{\mathbf{QP}}_{\hat{p}} \cdot \hat{\mathbf{PT}}_{\hat{r}\hat{p}}}{\hat{\mathbf{PP}}_{\hat{r}\hat{p}}} \Big] \leq \hat{\mathbf{AC}}_{\hat{r}\hat{t}}, \qquad \forall \hat{r} \in \hat{\mathcal{R}}, \hat{t} \in \hat{\mathcal{T}} \setminus \{0\} \quad (5.49)$$

In addition, we set up constraint 5.50 to make sure that production is only carried out on approved resources, ignoring minimum lot sizes. The expression on the right side represents the maximum possible production quantity in the sense of a tight Big-M, analogous to the formulation in the base model version.

$$q^{LP}_{\hat{r},\hat{p},\hat{t}} \cdot \hat{\mathbf{QP}}_{\hat{p}} \leq \Big[\sum_{\hat{\imath}=1}^{\hat{I}_{max}} (\hat{\mathbf{QP}}_{\hat{p}} \cdot \hat{\mathbf{Q}}_{\hat{p}\hat{\imath}} \cdot \mathbb{1}_{Pos^{-1}_{\hat{\mathcal{I}}_T}(\hat{\imath}) \neq I_{max}} + \mathbf{Q\hat{P}F}_{\hat{p}} \cdot \hat{\mathbf{Q}}_{\hat{p}\hat{\imath}} \cdot \mathbb{1}_{Pos^{-1}_{\hat{\mathcal{I}}_T}(\hat{\imath}) = I_{max}}) \Big] \cdot \hat{\mathbf{A}}_{\hat{r}\hat{p}}, \quad \forall \hat{r} \in \hat{\mathcal{R}}, \hat{p} \in \hat{\mathcal{P}}, \hat{t} \in \hat{\mathcal{T}} \setminus \{0\} \tag{5.50}$$

Transport-Related

As far as transport-related constraints are concerned, we can omit most of the restrictions formulated in the SLSP-B, since only groupage services are taken into account. The remaining constraint 5.51 ensures that no transport starts in a period in which no transports are allowed to take place and disallows any transport between the same location.

$$b^{LP}_{\hat{\imath},\hat{p},\hat{\jmath},\hat{l},\hat{t}} = 0, \qquad \forall \hat{\imath} \in \hat{\mathcal{I}} \cup \{0\}, \hat{p} \in \hat{\mathcal{P}}, \hat{\jmath} \in \hat{\mathcal{J}}, \hat{l} \in \hat{\mathcal{J}}, \hat{t} \in \hat{\mathcal{T}} \setminus \{0\} \mid \hat{\jmath} = \hat{l} \vee \mathbf{P\hat{B}}_{\hat{t}1} = 0 \tag{5.51}$$

To conclude this chapter, we note that except for the inclusion of the basic transport costs and of the finished goods containers, which require integer variables for modelling, all further presented extension options of the base model version are also possible in the LP reformulation.

5.6 Model Variations

Figure 5.1 summarises the different model variants and the combination possibilities derived from them. As can be seen, it is possible to combine the two basic models with the presented extensions in different ways.

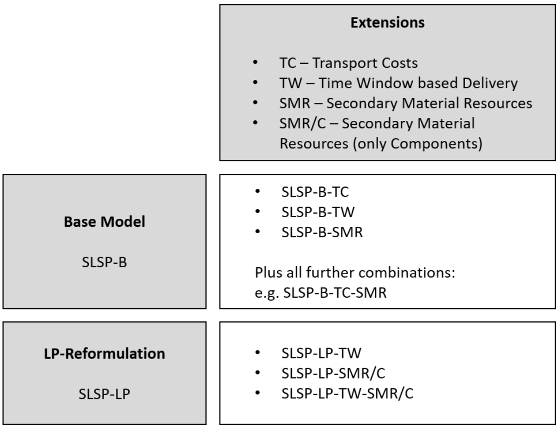

Figure 5.1: Combination possibilities and nomenclature of the different model variants of the SLSP

6 Case Study

Theory is a lovely furrow with
nothing but poppy plants;
practice is a furrow with a few
poppy plants hidden among
lots of weeds.
-S. Scholl

After having introduced the approach of this thesis in an abstract way in the last two chapters, we will evaluate and test the developed models in a case study in this chapter. Our goal is to assess whether it is possible to apply the concepts in a real-world example and to examine which effects and interrelationships result from this. The case study is based on the production network of the Robert Bosch GmbH described in chapter 2. In our analyses, we will distinguish between a single-stage production process (cf. section 6.1) and a multi-stage production process (cf. section 6.2) and look at scenarios with both shortfall quantities and excess quantities.

6.1 Single-Stage Production Process

Using a real-world data set as an example, we will first look at the single-stage application of the developed CM platform. The chapter starts with an introduction to the general problem setting. Afterwards, we will take a closer look at the provided data set and describe how the data was prepared for further usage. The results of the analyses, including calculation outputs and runtime behaviour, will be presented in the last subchapter.

6.1.1 Problem Setting

The investigations in this chapter are based on the example of planning area 1 shown in fig. 2.8. Production step 1 represents the bottleneck stage of this planning area throughout the network and is therefore used as the basis for planning. Based on a representative data set from November 2019, the goal of this case study is to investigate how in the case of a (simulated) disrupted bottleneck resource at the lead factory, the resulting **shortfall quantities** can be rescheduled in the network using the developed CM platform.

6.1.2 Data Base

In the following, we will present the data set provided by the Robert Bosch GmbH. With regard to the transport side, we refer to an additional transport data set provided by the Transport Betz GmbH, a freight forwarder involved in the research project of this work. However, in order to protect the confidential data of both sources, we will not give real names and designations but remain on an abstract level. In doing so, we will discuss both how we have prepared the data sets in order to make them usable for the developed CM platform as well as where we have supplemented them with reasonably realistic assumptions.

Basic Quantities

As mentioned above, we are looking at production step 1 of the presented production process, which represents the bottleneck step within planning area 1. We therefore only consider this step in the CM platform, i.e. $\mathcal{I} = \{1\}$ applies. However, it should be noted that due to missing buffers, the subsequent steps within the regarded planning area must be rescheduled as well in case step 1 is being disrupted. But since those steps are always executed together with step 1 at one location with the corresponding resources not being a bottleneck, we can neglect them in the planning. A rescheduling of step 1 to another location via the CM platform consequently implies that all 3 steps are carried out at that location. Furthermore, we assume that there is a sufficiently large buffer to the subsequent planning areas so that we can neglect them in the planning as well.

In total, there are 3 locations available for conducting the production steps of planning area 1 in the regarded production network, i.e. $\mathcal{J} = \{1, 2, 3\}$ applies. More precisely, the bottleneck step can be carried out in the German lead factory ($j = 1$), in the Czech source factory ($j = 2$), and in a Romanian process plant ($j = 3$), operated by an external company, on a total of 41 resources $\mathcal{R} = \{1, ..., 41\}$ (cf. fig. 2.5).

The provided data set covers the frozen period of one month being planned on a daily basis. The planning horizon $\mathcal{T} = \{1, ..., 28\}$ starts on Monday the 4th of November 2019 ($t = 1$) and ends on Sunday the 1st of December 2019 ($t = 28$). Since there are no public holidays during this period, $\mathcal{S} = \{1, ..., 7\}$ applies, with $s = 1$ representing Monday to $s = 7$ representing Sunday. In total, 17 different product types have been scheduled to be machined at the lead factory within the regarded time frame. As we use the lead factory as the guiding example to simulate a disrupted bottleneck resource, we only consider those product types $\mathcal{P} = \{1, ..., 17\}$ in the planning.

In terms of transport, the freight forwarder provided us with data on different forms of transportation $\mathcal{V} = \{1, ..., 7\}$. Out of these, $v = 1$ represents the groupage service and $v = 2$ to $v = 7$ refer to direct non-stop transports conducted with a Caddy, a transporter, a tarpaulin transporter, a 7.5-ton truck, a 12-ton truck or a 40-ton truck, ordered ascendantly.

The quantities $\mathcal{F}$ and $\mathcal{C}$ are not considered since no components and packaging are required in the production step taken into account.

Static Properties

Production-Related: The data provided has been transformed into the format used in this thesis and assigned to the input variables introduced in chapter 4. The **resource-related** data can be found in appendix B.1. The attached data table contains, among others, the input data on the locations ($\mathbf{L}(r)$) and the production steps ($\mathbf{PS}(r)$) of the regarded resources. With regard to the minimum lot size ($\mathbf{ML}(r)$) of a resource r, we assume $\mathbf{ML}(r) = 0, \forall r \in \mathcal{R}$ as there is no written rule for this in the regarded network. This assumption is also consistent with the general efforts of lean manufacturing systems to produce with smaller lot sizes (cf. Liker 2004). For the cost-related input quantities of those resources, we use a realistic approximation since we are not able to publish the real production cost rates ($\mathbf{CP}(r, p, s)$). In general, the production costs consist of fixed and variable machine costs and labour costs (cf. Hering 2014). Due to the fact that the machining steps are similar at all locations, we neglect the machine cost portion, assuming it has no impact on the decision. Instead, we focus on the labour costs. The average labour cost rate per hour in the manufacturing industry amounts to 40.90€ in Germany, to 13.50€ in the Czech Republic and to 6.60€ in Romania (cf. Statistisches Bundesamt 2020). Per machine, two employees are required. Furthermore, it has to be considered that location $j = 3$ is an external company that demands a margin. We therefore add a margin to the labour costs of location $j = 3$ and consider the production costs of locations $j = 2$ and $j = 3$ to be the same. This results in a product-independent production cost rate of $1.36\frac{€}{\text{min}}$ at location $j = 1$ and of $0.45\frac{€}{\text{min}}$ at location $j = 2$ and at location $j = 3$. Moreover, we assume a surcharge of 70% for Sunday working at all locations, based on the labour agreement of the corresponding labour union in Germany (cf. IG Metall 2025).

The **product-related** data can be found in appendix B.2. The data table enclosed contains the provided information on approvals ($\mathbf{A}(r, p)$), processing times ($\mathbf{PT}(r, p)$), set-up times ($\mathbf{ST}(r, p)$) and machine batch sizes ($\mathbf{PP}(r, p)$). Looking more closely at the data of location $j = 2$, it

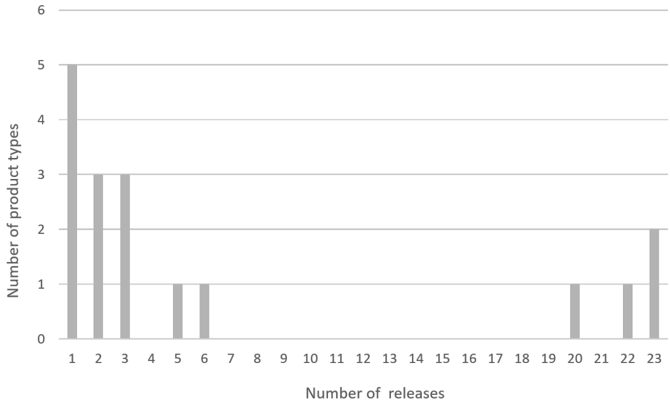

Figure 6.1: Frequency distribution of the products under consideration with regard to the number of approvals they have

is to be noted that due to a different machine concept, there are some cases of significantly longer set-up times and processing times compared to the other locations. Also, it must be taken into account that both the setting-up and the resetting to the initial state must be considered in order to ensure that the normal production plan can be continued as originally planned. The (product-independent and resource-specific) set-up times stored in $\mathbf{ST}(r,p)$ therefore indicate the time required for two changeover operations. In chapter 6.2.4, we will come back to the topic of set-up times and present a further alternative modelling approach.

Looking at the approvals, figure 6.1 shows in a histogram how many parallel releases the products under consideration have. Remarkably, there are some products (23.5%) that are released on quite a lot resources (≥ 20). Those flexible product types are used as load balancers allowing the plants of the network to shift the load between their resources. On the other hand, there is also a large amount of products (29.4%) that are only released on one resource, which is caused by the fact that parallel releases are associated with higher costs and efforts.

In addition, we received information on the product-specific filling quantities of the containers ($\mathbf{QP}(p)$) and on the container weight ($\mathbf{WP}(p,i)$). With regard to the container weight, we would like to note that we have broken down the given weights of the full pallets evenly to the individual containers using the given numbers of containers per pallet. Moreover, we assume the same weight for the raw material stage and the machining stage of the parts, since weight information was only available for the (slightly heavier) raw material stage.

Transport-Related: The transport-related data was provided by the Transport Betz GmbH. The data on **direct non-stop transports** can be found in appendix B.3. The attached data table contains the provided input data on capacities ($\mathbf{PSV}(v)$) and weight restrictions ($\mathbf{LC}(v)$) of the different vehicle classes, as well as the associated minimum transport costs ($\mathbf{MCT}(v)$) and the kilometre-based cost rates ($\mathbf{CT}(v)$).

For the **groupage service**, the freight forwarder has provided a customized tariff table for the transport relations under consideration, which reveals the transport costs ($\mathbf{BC}(j,l)$ and $\mathbf{CS}(j,l)$) depending on the distance ($\mathbf{D}(j,l)$) and the number of pallets to be shipped. The table can be found in appendix B.4.

In addition to that, we were provided with estimated travel times ($\mathbf{TT}(j,l,v)$) required for the different transport relations when using the different forms of transportation. That data can be found in appendix B.3 for the direct transport and in appendix B.4 for the groupage service. Since there is a Sunday driving ban in Germany for trucks over 7.5 tons, we have furthermore set the corresponding values in $\mathbf{PB}(s,v)$ to 0 for transport forms to which this applies - including the groupage service, where we assume a 40-ton truck - in order to prevent driving on these days.

The calculated values for the transport capacity per pallet slot ($\mathbf{MCP}(p,v)$), which can be found in appendix B.5, are based on a pallet stacking factor of 1. For most transport forms, the value of $\mathbf{MCP}(p,v)$

corresponds to the number of containers contained in a full pallet. Only when using a Caddy ($v = 2$), the weight restriction of the vehicle prohibits to transport a full pallet. For this vehicle class, the value of $\mathbf{MCP}(p, v)$ has been calculated from the rounded-off ratio of the maximum permissible loading weight of the vehicle and the container weight.

Dynamic Properties

The dynamic input data was extracted from the levelled MRP-derived **production plans** of the 3 plants provided by the Robert Bosch GmbH. With these plans, together with the provided data on processing times and set-up times and the net production time of the machines, which is calculated from the available time by subtracting the OEE losses of the machines, the free capacity per day ($\mathbf{AC}(r, t)$) can be calculated according to the following formula:

$$\text{Free capacity [min]} = \text{Net production time [min]} - \\ \left(\frac{\text{Production quantity } \cdot \text{Processing time [min]}}{\text{Machine batch size}} + \text{Set-up time [min]}\right) \quad (6.1)$$

With the production plans provided, it was additionally possible to ascertain the values of $\mathbf{SH}(r, t, p)$, indicating the product types already scheduled in the periods under consideration. The determined values for $\mathbf{AC}(r, t)$ and $\mathbf{SH}(r, t, p)$, as well as the assigned period types ($\mathbf{PH}(t)$), can be found in appendix B.7. As illustrated in figure 2.18, the calculated free capacity values result both from unused time blocks within a planned shift in the sense of a proactively planned buffer and from previously unplanned shifts that can be exploited in the sense of a time-based adjustment measure. In the case of a unplanned shift, we have included the total net production time of the shift as free capacity. In the production network considered, locations $j = 1$ and $j = 3$ work with 15 shifts per week with a free Saturday and Sunday. Location $j = 2$ follows a 20-shift model with one free shift at the weekend.

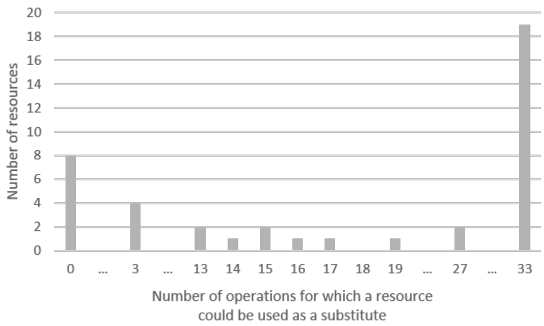

Figure 6.2: Frequency distribution of the resources according to the number of operations for which they could be used as a substitute in case these operations are disrupted

To get a more profound impression of the as-is situation, we will below present some more in-depth descriptive analyses of the dynamic production data:

First of all, we note that in the planning horizon considered a total of 89 operations are performed at plant $j = 1$, which is used to simulate the event of a disruption. As an operation, we understand the processing of one product type on a resource within one day. If 2 different products are manufactured at a resource on one day or a product is manufactured on two consecutive days, this results in 2 different operations. To get a feeling for the importance of the different resources in the event of a disruption, fig. 6.2 shows the frequency distribution of the resources according to the number of operations for which they could be used as a substitute based on the underlying approvals in case these operations are disrupted.

8 of the 41 resources, all being located at plant $j = 3$, have no approvals at all for the products manufactured during the planning horizon. On the other hand, there are 19 resources that could be used for 33 operations and 2 resources that could be used for 27 operations. At the same time, there are no alternative resources for 14 of the 89 operations due

to missing parallel approvals. The group of resources suitable for 27 and 33 operations each, together covers more than 77% (58 out of 75) of the distributable operations, which is why we call them *key replacement resources*. All those key replacement resources are located at plant $j = 2$. Looking at the plant level, the 4 resources at plant $j = 1$ could be used in 49 of the 75 operations (65%), the 25 resources at plant $j = 2$ could be used in 61 operations (81%), and the 4 remaining resources at plant $j = 3$ could be used in 28 operations (37%).

Figure 6.3 shows the average utilisation rates of the resources and the aggregated number of day slots in which the resources have more free capacity than the required (double) set-up time, which makes them directly eligible for the platform. Due to the long set-up time on some machines and the associated low number of usable day slots, we consider, in addition to the real set-up time, a second scenario, in which all set-up times are as short as the shortest set-up time in the network. That is, all machines having a set-up time of 30 min for one changeover operation. In our analyses, we separately look at the 3 locations, the whole network and the key replacement resources. Not included are the 8 resources that cannot be used at all. Besides, we have broken down the results into weekdays, weekends and the entire planning horizon (weekend + weekdays).

Across all locations, the utilisation rate is approx. 90% on weekdays, approx. 53% on weekends and approx. 80% over the entire planning horizon. Furthermore, there are a total of 131 day slots (out of a maximum of 924 (=28 days · 33 resources)) with a sufficient amount of free capacity for the CM platform based on the real (double) set-up time. As to be expected, a shorter set-up time increases this number significantly. However, it should be noted that in both cases, a large part of these slots account for the weekend. In addition to that, it can be seen that the key replacement resources show a high utilisation rate (in total at approx. 88%) and provide only 6 of the 131 day slots despite the high number of resources. This is accompanied by the plant-related data. Due to the 15-shift model, the plants $j = 1$ and $j = 3$ indi-

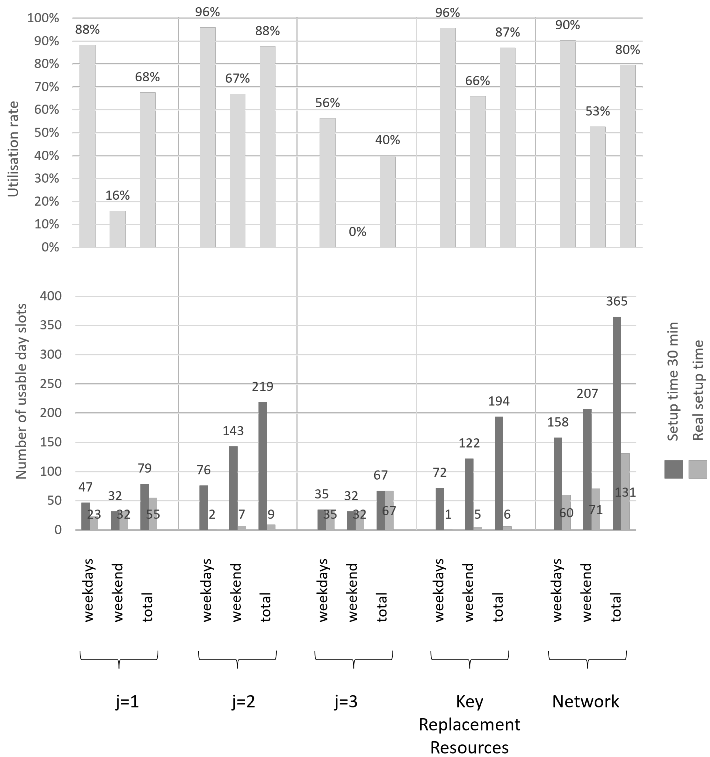

Figure 6.3: Utilisation rates of the resources and aggregated number of day slots in which the resources have more free capacity than required for set-up

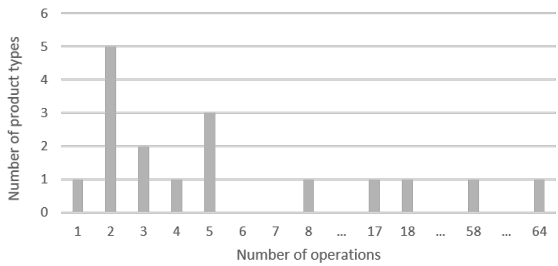

Figure 6.4: Frequency distribution of the product types under consideration with regard to the number of operations they account to throughout the network

cate a significant lower overall capacity utilisation[1] than plant $j = 2$. Plant $j = 3$, which is utilised as a flexible external location, has the lowest overall capacity utilisation - even on weekdays due to partially completely unused resources. In that regard, it is noticeable that the resources at location $j = 1$ are less heavily utilised during a planned shift, resulting in about the same number of available slots on weekdays as at location $j = 3$, where only the completely unused shifts are available. With location $j = 2$, which largely corresponds to the key replacement resources, not only the high utilisation rate but also the significantly longer set-up times contributes to the limited number of usable slots. In return, however, location $j = 2$ and the key replacement resources benefit most from a shorter changeover time.

With regard to $\mathbf{SH}(r, t, p)$, which helps us to plan in a set-up-optimised way, fig. 6.4 shows the frequency distribution of the 17 product types with respect to the number of operations they account for throughout the network.

As can be seen in the diagram, there is a large amount of low runner products, which are processed only in a few operations. If these

[1] The marginal capacity utilisation on weekends at site $j = 1$ results from overlapping shifts. Thus, the night shift on Friday runs to Saturday morning at 6 a.m.

products are affected by a disruption, it is rather difficult to find a period in which the products are already manufactured to save the set-up time. The right side of the diagram shows the high runners, which are produced in large quantities. With these products, it is much easier to plan set-up-optimised. Not surprisingly, the 4 products that account for ≥ 17 operations also already cover 63% (47 of 75) of the distributable and potentially disrupted operations at location $j = 1$ and 81% (47 of 58) of the operations a key replacement resource could be used for.

In terms of the second important dynamic input parameter, the **inventory data** ($\mathbf{IP}(p, i, j, t)$), no data has been provided. We therefore assume that only the raw material quantities released by the disruption are available at the affected site from the time of the disruption.

6.1.3 Design of Experiments

In order to obtain a comprehensive picture of the effects of the CM usage, we have systematically carried out experiments based on the provided production plan of the lead factory (cf. appendix B.7) by simulating various breakdown scenarios. The following two subchapters describe the factors used to set up the experimental design and the test scenarios derived from it.

Factors

To assess the performance of the CM platform in different situations, we have varied the factors **order size** and **size of the solution space** within the scope of the conducted study. The size of an order is thereby characterised by the *shortfall volume*, represented by the sum of production days affected by a disruption, and the *product range*, i.e. the number of different product types that are required to be rescheduled via the CM platform ($\hat{P}_{max}$). The size of the solution space is characterised by the *number of suitable resources* for an order ($\hat{R}_{max}$), as this, in combination with the resulting number of qualified day slots, has a decisive influence on the number of permissible solutions.

In order to be able to vary those factors systematically in the experimental design, we have divided them into different factor levels, which we will discuss below.

With regard to the factor **shortfall volume**, we distinguish 4 factor levels, which cover a wide range of possible disruptions. However, please note that the provided (frozen) planning horizon of 4 weeks defines an upper limit, as disruptions that cannot be rescheduled within this period are not considered. In the case of a *small* shortfall volume, a single resource is down for one day. The *medium* level covers, for example, disruptions where the whole production of the lead factory (4 resources) is down for one day or alternatively the case of one single resource being down for a whole week. The category *large* includes the breakdown of a single resource for two weeks and also the case of all 4 resources being down simultaneously for 3 days. An example of a disruption causing a *major* shortfall volume is the breakdown of the whole production for one week.

- Small: 1 Day
- Medium: 4-5 Days
- Large: 10-12 Days
- Major: 20 Days

To ensure that there is enough capacity for rescheduling, we only simulate breakdowns that occur within the first two weeks of the planning horizon. Within this period, the maximum possible number of affected product types is 9 for the disruption types defined in the previous section. We therefore take this value as the upper limit for the factor **product range** and divide the scale into three equally sized ranges capturing all possible scenarios.

- Small: 1-3 Product Types
- Medium: 4-6 Product Types

- Large: 7-9 Product Types

Looking at the number of suitable resources, there are two larger clusters with reference to figure 6.1. If products with only a few approvals ($\leq$6) are affected by a disruption, the total number of eligible resources remains low. In the two-week period considered, the maximum possible number of suitable resources is 6 if only these product types are affected. If products from the cluster with many approvals ($\geq$20) are involved, a lot of suitable resources ($\geq$20) result. Based on this argumentation, the following two factor levels for the factor **number of suitable resources** were taken into account:

- Small: $\leq$6 Resources
- Large: $\geq$20 Resources

Test Scenarios

To obtain a picture that is as multi-faceted as possible, we used a full-factorial test design to generate the test scenarios. By combining all possible factor levels of the 3 criteria, theoretically, $4 \cdot 3 \cdot 2 = 24$ scenarios result. However, since not all combinations are feasible in the considered production plan within the considered time frame, we had to exclude impossible scenarios and obtained a remaining set of 13 scenarios possible. As such, it is, for example, not possible to find a scenario with a medium or large product range if the shortfall volume is small. On the other hand, a large product range is only possible in the case of a large or major shortfall volume combined with a large number of suitable resources.

The 13 scenarios considered are summarised in table 6.1. The scenarios were selected in a way to ensure a large degree of variance in terms of the resources and product types affected.

The table shows for the different scenarios, which resources are assumed to be down for which period of time (column 2+3). Using scenario 9 as an example, we can see that resources 2 and 4 are assumed to be down during the first week (Monday up to and including Sunday). Column 4 shows the affected product types and the respective quantities that should have been produced during this period and that are now to be rescheduled via the CM platform. With regard to the shortfall volume, please note that we only count the number of production days lost, i.e. the number of downtime weekdays of the two resources. In addition, the product range and the number of suitable resources together with the respective classification as well as the number of suitable day slots are shown. In total, there are 5 suitable resources for the 4 product types affected in the regarded scenario. In case we use the real set-up time (ST), 44 day slots offer more free capacity than required to conduct two changeover operations. If we use the minimum set-up time of 30 minutes for all resources, 71 eligible day slots result. In both cases, we count only those day slots that date later than or equal to the start date of the downtime. The slots of the affected resources themselves are not available during the downtime period. Last but not least, the number of plants owning a suitable resource ($|\hat{\mathcal{J}}|$) is given. In the example of scenario 9, two plants need to be considered when solving the SLSP. As can be seen, there are also cases (scenario 1 and scenario 3) in which only the lead factory needs to be taken into account.

6.1.4 Analyses

Approach

The analyses within this chapter were performed with the base model version of the SLSP, extended by the transport cost modelling described in chapter 5.4.1 (SLSP-B-TC). All calculations were conducted under a 64 bit Windows 10 operating system equipped with an Intel i7-7500 CPU (2.7 GHz, 2 kernels) and a working memory of 16 GB. The models were implemented in Java using the IBM CPLEX library (version 12.9) in its default setting.

Based on the described input data, we have solved the SLSP according to the explanations in chapter 5.3.3 for each scenario with the weighting

Scenario	Affected Resources	Affected Periods	Affected Quantity	Shortfall Volume		Product Range		Number of Suitable Resources		Number of Suitable Day Slots		Number of Plants
				#Days	Class.	$\hat{P}_{max}$	Class.	$\hat{R}_{max}$	Class.	ST real	ST 30min	$\lvert\hat{\mathcal{J}}\rvert$
1	$r = 2$	$t = 3$	$p = 9 : 355$ pc.	1	Small	1	Small	2	Small	30	30	1
2	$r = 1$	$t = 3$	$p = 1 : 480$ pc.	1	Small	1	Small	23	Large	65	252	3
3	$r = 2$	$t = 1$ to $t = 7$	$p = 11 : 372$ pc. $p = 9 : 1420$ pc.	5	Medium	2	Small	2	Small	29	29	1
4	$r = 1$	$t = 1$ to $t = 7$	$p = 3 : 216$ pc. $p = 1 : 2000$ pc.	5	Medium	2	Small	23	Large	66	259	3
5	$r = 1$ $r = 2$ $r = 3$ $r = 4$	$t = 12$	$p = 5 : 315$ pc. $p = 6 : 340$ pc. $p = 7 : 150$ pc. $p = 8 : 135$ pc. $p = 12 : 410$ pc.	4	Medium	5	Medium	6	Small	40	62	2
6	$r = 1$ $r = 2$ $r = 3$ $r = 4$	$t = 1$	$p = 3 : 216$ pc. $p = 11 : 330$ pc. $p = 13 : 270$ pc. $p = 17 : 340$ pc.	4	Medium	4	Medium	25	Large	73	271	3
7	$r = 4$	$t = 1$ to $t = 14$	$p = 6 : 2530$ pc. $p = 17 : 536$ pc.	10	Large	2	Small	5	Small	44	71	2
8	$r = 3$	$t = 1$ to $t = 14$	$p = 12 : 775$ pc. $p = 13 : 3030$ pc.	10	Large	2	Small	22	Large	26	204	3
9	$r = 2$ $r = 4$	$t = 1$ to $t = 7$	$p = 6 : 1135$ pc. $p = 9 : 1420$ pc. $p = 11 : 372$ pc. $p = 17 : 536$ pc.	10	Large	4	Medium	5	Small	44	71	2

Scenario	Affected Resources	Affected Periods	Affected Quantity	Shortfall Volume		Product Range		Number of Suitable Resources		Number of Suitable Day Slots		Number of Plants
				#Days	Class.	$\hat{P}_{max}$	Class.	$\hat{R}_{max}$	Class.	ST real	ST 30min	$\lvert\hat{\mathcal{J}}\rvert$
10	$r = 2$	$t = 1$ to $t = 14$	$p = 7 : 315$ pc. $p = 8 : 250$ pc. $p = 9 : 1590$ pc. $p = 10 : 850$ pc. $p = 11 : 372$ pc.	10	Large	5	Medium	23	Large	30	218	2
11	$r = 1$ $r = 2$ $r = 3$ $r = 4$	$t = 1$ to $t = 3$	$p = 1 : 880$ pc. $p = 3 : 216$ pc. $p = 6 : 345$ pc. $p = 9 : 595$ pc. $p = 11 : 372$ pc. $p = 13 : 1080$ pc. $p = 17 : 536$ pc.	12	Large	7	Large	29	Large	124	332	3
12	$r = 1$ $r = 2$ $r = 3$ $r = 4$	$t = 1$ to $t = 7$	$p = 1 : 2000$ pc. $p = 3 : 216$ pc. $p = 6 : 1135$ pc. $p = 9 : 1420$ pc. $p = 11 : 372$ pc. $p = 13 : 2025$ pc. $p = 17 : 536$ pc.	20	Major	7	Large	29	Large	116	320	3
13	$r = 1$ $r = 3$	$t = 1$ to $t = 12$	$p = 1 : 2000$ pc. $p = 2 : 520$ pc. $p = 3 : 216$ pc. $p = 5 : 995$ pc. $p = 12 : 775$ pc. $p = 13 : 3030$ pc.	20	Major	6	Medium	25	Large	82	267	3

Table 6.1: Test scenarios

$\lambda_1 = 0.99$ (cost-optimised), $\lambda_1 = 0.01$ (time-optimised) and $\lambda_1 = 0.5$ (equally weighted). To evaluate the computational time behaviour with regard to practical applicability in a bottleneck situation, we ran each scenario several times by gradually limiting the computing time to 5 min, 15 min and 30 min. The analyses were embedded in three test series conducted under different test conditions. In **test series 1**, we used the real data as provided. In **test series 2**, we looked at the influence of the set-up time and therefore made use of the reduced set-up times, as discussed in the previous chapters. In **test series 3**, we investigated the effects of similar production costs at the different sites of the network by using the cost rates of site $j = 1$ for all plants. To assess the effectiveness of the CM usage, we furthermore compared the results to a heuristic approach oriented towards the practical way of handling disruptions.

The **heuristic approach** developed for the purpose of comparison follows the procedure described in the production guidelines of the Robert Bosch GmbH. According to these guidelines, production orders affected by a disruption are to be put on hold, i.e. to be moved into the backlog, so that the planned pattern can be continued as originally planned. This logic is used if the bottleneck on the affected day is that large that it cannot be reduced by decreasing the production quantity of a high-runner product. As soon as more capacity is available in the upcoming days than is needed according to the plan, the deferred production orders can be brought back into production until the shortfall quantity is reduced.

Follow this logic, we have implemented a *successive planning procedure* that successively proceeds through the periods (including the weekend) and examines whether free capacities are available at the approved production resources at the affected location. If this is the case, the deferred production orders are taken from the backlog according to their number of parallel releases and are scheduled into the free slots. Products with no or only a few parallel releases are accordingly produced first. The reason for applying this dispatching rule is to prevent products that can only be processed on one resource from having to wait because the respective resource is blocked with parts that could also be processed on other resources. For the sake of simplicity, we have furthermore assumed that the inserted backlog orders are either produced at the beginning of a day or ,if possible, are included to already scheduled production orders of the same product type.

In simplified terms, the heuristic approach follows the (pseudocode) procedure described in algorithm 3.

Algorithm 3: Heuristic approach for shortage reduction

```
Data: production plan, inventory data, shortfall quantities, approval matrix
Result: updated production plan
Determine the sequence in which the backlogged product types are to be
  manufactured for each resource of the affected location. Use the number of
  parallel releases on the resources of the affected site as primary and the part ID
  as secondary sorting criterions and start with the product types with the fewest
  number of releases and smallest part ID;
Select day 1 of the planning horizon;
while shortfall quantities are not resolved and end of planning horizon is not
  yet reached do
    if working day then
        Go successively (by ascending resource ID) through the resources of the
          affected site and schedule as much of the shortfall quantities of the
          affected product types in the specified order as possible, taking into
          account the free capacities, available stocks and approvals. Either
          schedule the quantities at the beginning of the day, taking the
          upstream and downstream product types into consideration when
          determining the set-up time, or if the same product type is already
          scheduled that day, then add to this quantity;
        Reduce the shortfall quantities and the available capacities;
    if regular non-working day then
        Go successively (by ascending resource ID) through the resources of the
          affected site and schedule as much of the shortfall quantities of the
          affected product types in the specified order until the regular
          non-working day(s) (including the available capacity of the next
          working day) are completely full, taking into account the available
          stock, approvals, upstream and downstream products for set-up time
          calculation;
        Reduce the shortfall quantities and the available capacities;
    Go one day further;
```

Results

Quality of the Solutions: Tables 6.2 - 6.4 show for the three test series the goodnesses of the solutions calculated under different time limits.

The time limits define after how many seconds the solution algorithm of the solver is going to stop, outputting the current best solution. The tables contain for each scenario and for each of the 3 weightings described, the computing time (CT) required to solve the given optimisation problem and the resulting optimality gap. The optimality gap indicates the relative deviation from the best known bound and is determined by CPLEX according to the following formula (IBM 2025):

$$\text{Gap} = \left(\frac{|\text{Best Bound - Best Integer}|}{|\text{Best Integer}| + 10^{-10}}\right) \tag{6.2}$$

The *best integer* value represents the best feasible objective function value found so far. The *best bound* value marks the best known lower bound (in the case of a minimisation problem) determined by solving the LP relaxations of the problem within the Branch & Cut algorithm used by CPLEX.

As can be seen from the data, especially the combination of a large or major shortfall volume together with a medium or large-sized product range leads to longer computing times (cf. scenarios 9-13). On the other hand, problems that do not involve any of these combinations (cf. scenarios 1-8) could be solved in all test series in a short amount of time with a maximum of 41 seconds. Looking more closely at the scenarios 9-13 having the longest computing times, not all problem instances could be solved with proven optimality within the maximum time limit of 1800 seconds. Nevertheless, we were able to find a feasible solution in all test runs. Within test series 1, those solutions were indicating only small optimality gaps of at most 0.33%. Within test series 2, the maximum optimality gap amounts to 2.07%, with scenarios 12 and 13 showing slightly increased numbers. In test series 3, this value decreases to 0.62%. But also with shorter time limits, a good solution quality could be achieved. In fact, the solutions found after 300 seconds already show an optimality gap of less than 2.50% within test series 1, of less than 3.30% within test series 2 and of less than 1.0% within test series

Scenario	Time Limit: 300 sec.						Time Limit: 900 sec.						Time Limit: 1800 sec.					
	$\lambda_1 = 0.99$		$\lambda_1 = 0.01$		$\lambda_1 = 0.5$		$\lambda_1 = 0.99$		$\lambda_1 = 0.01$		$\lambda_1 = 0.5$		$\lambda_1 = 0.99$		$\lambda_1 = 0.01$		$\lambda_1 = 0.5$	
	CT [sec.]	Gap [%]	CT [sec.]	Gap [%]	CT [sec.]	Gap [%]	CT [sec.]	Gap [%]	CT [sec.]	Gap [%]	CT [sec.]	Gap [%]	CT [sec.]	Gap [%]	CT [sec.]	Gap [%]	CT [sec.]	Gap [%]
1	<1	<0.01	<1	<0.01	<1	<0.01	-	-	-	-	-	-	-	-	-	-	-	-
2	4	<0.01	<1	<0.01	<1	<0.01	-	-	-	-	-	-	-	-	-	-	-	-
3	<1	<0.01	<1	<0.01	<1	<0.01	-	-	-	-	-	-	-	-	-	-	-	-
4	28	<0.01	<1	<0.01	8	<0.01	-	-	-	-	-	-	-	-	-	-	-	-
5	<1	<0.01	<1	<0.01	<1	<0.01	-	-	-	-	-	-	-	-	-	-	-	-
6	7	<0.01	2	<0.01	2	<0.01	-	-	-	-	-	-	-	-	-	-	-	-
7	<1	<0.01	<1	<0.01	<1	<0.01	-	-	-	-	-	-	-	-	-	-	-	-
8	40	<0.01	4	<0.01	12	<0.01	-	-	-	-	-	-	-	-	-	-	-	-
9	235	<0.01	4	<0.01	26	<0.01	-	-	-	-	-	-	-	-	-	-	-	-
10	8	<0.01	2	<0.01	2	<0.01	-	-	-	-	-	-	-	-	-	-	-	-
11	300	0.38	300	0.37	46	<0.01	900	0.35	900	0.22	-	-	1800	0.33	1800	0.05	-	-
12	300	0.41	300	0.02	300	0.51	900	0.23	401	<0.01	900	0.49	1800	0.15	-	-	1800	0.33
13	300	2.44	72	<0.01	300	0.3	900	1.51	-	-	900	0.05	1800	0.21	-	-	1800	0.03

Table 6.2: Computing times and optimality gaps within test series 1 under different weightings and time limits using the CPLEX default relative MIP gap tolerance of 0.01%

Scenario	Time Limit: 300 sec.						Time Limit: 900 sec.						Time Limit: 1800 sec.					
	$\lambda_1 = 0.99$		$\lambda_1 = 0.01$		$\lambda_1 = 0.5$		$\lambda_1 = 0.99$		$\lambda_1 = 0.01$		$\lambda_1 = 0.5$		$\lambda_1 = 0.99$		$\lambda_1 = 0.01$		$\lambda_1 = 0.5$	
	CT [sec.]	Gap [%]	CT [sec.]	Gap [%]	CT [sec.]	Gap [%]	CT [sec.]	Gap [%]	CT [sec.]	Gap [%]	CT [sec.]	Gap [%]	CT [sec.]	Gap [%]	CT [sec.]	Gap [%]	CT [sec.]	Gap [%]
1	<1	<0.01	<1	<0.01	<1	<0.01	-	-	-	-	-	-	-	-	-	-	-	-
2	4	<0.01	<1	<0.01	<1	<0.01	-	-	-	-	-	-	-	-	-	-	-	-
3	<1	<0.01	<1	<0.01	<1	<0.01	-	-	-	-	-	-	-	-	-	-	-	-
4	33	<0.01	6	<0.01	6	<0.01	-	-	-	-	-	-	-	-	-	-	-	-
5	2	<0.01	<1	<0.01	<1	<0.01	-	-	-	-	-	-	-	-	-	-	-	-
6	11	<0.01	2	<0.01	2	<0.01	-	-	-	-	-	-	-	-	-	-	-	-
7	5	<0.01	<1	<0.01	3	<0.01	-	-	-	-	-	-	-	-	-	-	-	-
8	37	<0.01	6	<0.01	16	<0.01	-	-	-	-	-	-	-	-	-	-	-	-
9	300	0.29	19	<0.01	17	<0.01	900	0.2	-	-	-	-	1800	0.05	-	-	-	-
10	257	<0.01	2	<0.01	251	<0.01	-	-	-	-	-	-	-	-	-	-	-	-
11	300	0.3	300	0.25	188	<0.01	900	0.29	900	0.14	-	-	1800	0.29	1287	<0.01	-	-
12	300	1.13	300	0.09	300	2.3	900	0.87	900	0.06	900	1.62	1800	0.85	1800	0.06	1800	1.52
13	300	3.22	300	0.1	300	0.31	900	2.59	900	0.08	900	0.29	1800	2.07	1800	0.06	1800	0.29

Table 6.3: Computing times and optimality gaps within test series 2 under different weightings and time limits using the CPLEX default relative MIP gap tolerance of 0.01%

Scenario	Time Limit: 300 sec.						Time Limit: 900 sec.						Time Limit: 1800 sec.					
	$\lambda_1 = 0.99$		$\lambda_1 = 0.01$		$\lambda_1 = 0.5$		$\lambda_1 = 0.99$		$\lambda_1 = 0.01$		$\lambda_1 = 0.5$		$\lambda_1 = 0.99$		$\lambda_1 = 0.01$		$\lambda_1 = 0.5$	
	CT [sec.]	Gap [%]	CT [sec.]	Gap [%]	CT [sec.]	Gap [%]	CT [sec.]	Gap [%]	CT [sec.]	Gap [%]	CT [sec.]	Gap [%]	CT [sec.]	Gap [%]	CT [sec.]	Gap [%]	CT [sec.]	Gap [%]
1	<1	<0.01	<1	<0.01	<1	<0.01	-	-	-	-	-	-	-	-	-	-	-	-
2	4	<0.01	<1	<0.01	<1	<0.01	-	-	-	-	-	-	-	-	-	-	-	-
3	<1	<0.01	<1	<0.01	<1	<0.01	-	-	-	-	-	-	-	-	-	-	-	-
4	41	<0.01	2	<0.01	5	<0.01	-	-	-	-	-	-	-	-	-	-	-	-
5	2	<0.01	<1	<0.01	<1	<0.01	-	-	-	-	-	-	-	-	-	-	-	-
6	11	<0.01	2	<0.01	2	<0.01	-	-	-	-	-	-	-	-	-	-	-	-
7	<1	<0.01	<1	<0.01	<1	<0.01	-	-	-	-	-	-	-	-	-	-	-	-
8	5	<0.01	3	<0.01	5	<0.01	-	-	-	-	-	-	-	-	-	-	-	-
9	270	<0.01	3	<0.01	4	<0.01	-	-	-	-	-	-	-	-	-	-	-	-
10	10	<0.01	3	<0.01	14	<0.01	-	-	-	-	-	-	-	-	-	-	-	-
11	46	<0.01	300	0.28	35	<0.01	-	-	535	<0.01	-	-	-	-	-	-	-	-
12	300	0.92	50	<0.01	300	0.14	900	0.7	-	-	900	0.14	1800	0.62	-	-	1800	0.14
13	300	0.44	45	<0.01	300	0.4	900	0.27	-	-	900	0.2	1800	0.14	-	-	1800	0.13

Table 6.4: Computing times and optimality gaps within test series 3 under different weightings and time limits using the CPLEX default relative MIP gap tolerance of 0.01%

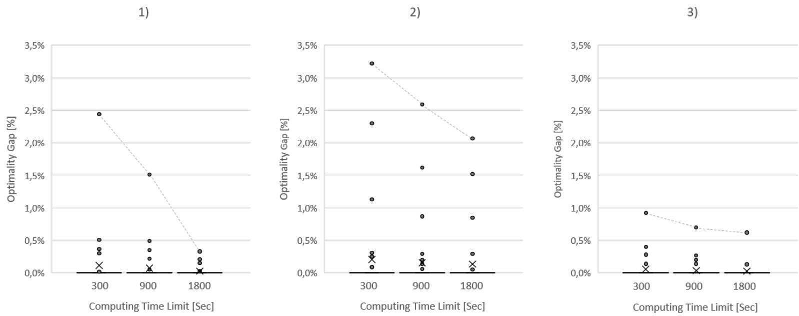

Figure 6.5: Boxplots showing the distribution of the optimality gaps as well as the decrease of the maximum values under different computing time limits within test series 1,2 and 3

3. After 900 seconds, those numbers go down to 1.60%, 2.60% and 0.7%, respectively.

From the data, which is graphically summarised in fig. 6.5, it can be concluded that the larger number of day slots within test series 2 produces only minor differences in the resulting optimality gap in most scenarios when compared to test series 1. In the scenarios with the largest shortfall volumes, however, the optimality gap increases, leading to a larger maximum gap. A comparison of test series 1 and 3, on the other hand, reveals slightly better values for test series 3 in most cases. Moreover, it can be observed throughout all test series that the optimality gap decreases most at the beginning of the calculation and improves only slowly with longer computing times.

Since the time limit of 900 seconds therefore appears to be an acceptable compromise between a reasonable runtime behaviour in a bottleneck situation and the resulting optimality gap - in the worst case without considering multi-threading, this results in a computing time of 75 min for the 5 runs required - we have performed the further evaluations based on this limit.

Calculation Results: Fig. 6.6 displays for the three test series the resulting **costs** of the solutions found in relation to the situation if the disruption had not occurred. The figure shows for the different scenarios and weightings how much additional costs are caused by the disruption, expressed in absolute figures as well as in relative numbers referring to the costs that would have been incurred without the disruption. However, please note that the big bucket optimisation model of this work, which does not preserve the set-up state between two periods, only provides a worst-case calculation of the resulting costs due to the potentially doubled inclusion of the set-up time. By reviewing the calculated production plans, we have therefore additionally indicated the cost values that can be deducted in order to display the real costs. For example, if a certain product type is produced on 2 consecutive days during the weekend, there is no need to retool at the end of day 1 and to set-up again on day 2. We can neglect those set-up costs accordingly [2].

Looking first at *test series 1*, the costs are always highest for the time-optimised solution, as to be expected. In particular, the frequent use of transports between the network locations causes the costs to increase, which can be seen in scenarios 4,8,11,12 and 13. Likewise, it can be observed that the cost-optimised solutions generate rather low additional costs. The resulting costs increase with regard to the calculated worst-case costs on average with 4.3%, as shown in the boxplot in fig 6.7. In terms of additional real costs induced, even a cost decrease of on average -1.7% can be monitored, which is caused by the fact that the lower production costs at the other two sites of the network actually enable costs to be saved. This is the case in scenarios 4,8,11,12 and 13. Looking at the weighting $\lambda_1 = 0.5$, additional costs of on average

[2] To determine the real costs, we made the simplifying assumption that the quantities scheduled by the CM Platform are always produced at the beginning of a day (except for when the product is already regularly scheduled in the production plan). By going through the periods one after the other, we obtained the deductible costs of unneeded set-up operations by comparing what is produced before and after each product scheduled by the CM platform. If multiple products were scheduled by the CM platform within the same day, we arranged those products within that day in a set-up-optimised way.

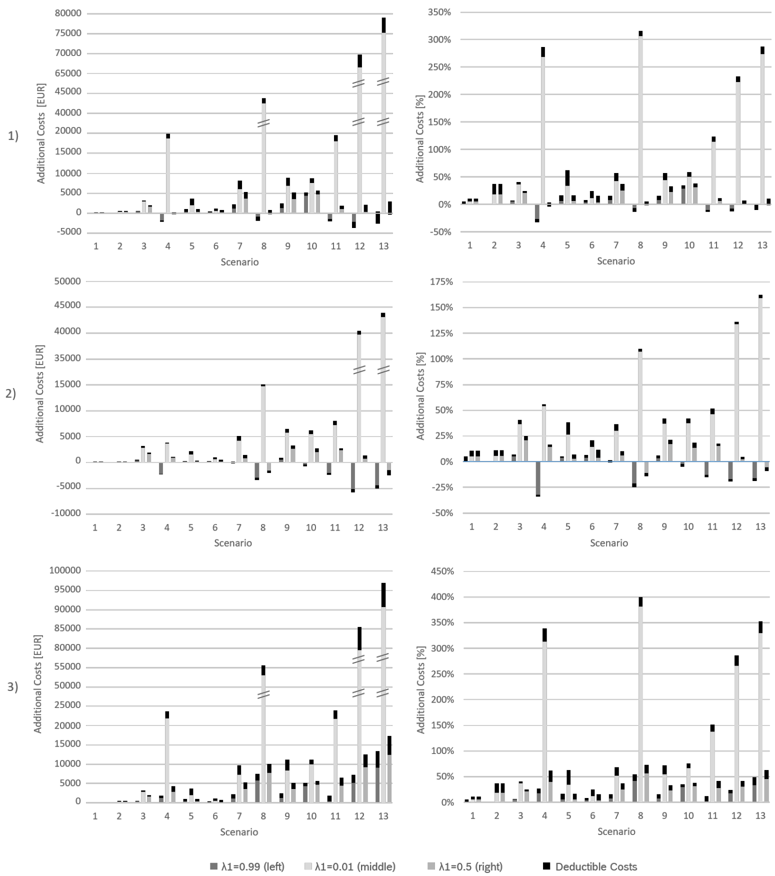

Figure 6.6: Resulting additional absolute (left) and relative (right) costs in relation to the situation if the disruption had not occurred for the different scenarios and weightings within test series 1,2 and 3

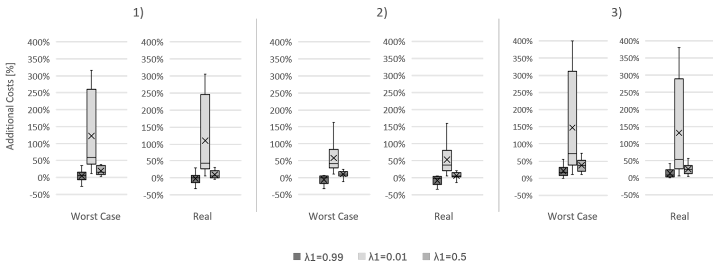

Figure 6.7: Boxplots showing the distribution of the resulting additional costs for the different weightings within test series 1,2 and 3. Plotted are both the real costs and the worst case values

19.42% can be observed with regard to the calculated worst-case costs. Referring to the real costs, additional costs of on average 10.38% result, with scenarios 4,8 and 13 leading to small cost savings.

Within *test series 2*, the additional costs decrease in most scenarios when compared to test series 1, both in absolute and relative figures. For a better comparability, please note that we have adjusted the point of reference within this test series by calculating the costs occurring without any disruption with the reduced set-up times as well. The average cost increase of the cost-optimised solutions amounts to -5.4% when referring to the calculated worst-case costs and to -7.8% when addressing the real costs. In the case of $\lambda_1 = 0.5$, these rates average 10.56% and 6.4%. When looking at the time-based optimisation, the maximum cost values of the transport-intensive scenarios 4,8,11,12 and 13 diminish noticeably as well. In general, the lower additional costs within test series 2 can be explained, on the one hand, by the fact that the shorter set-up time allows a larger quantity to be produced at once, which reduces the number of set-up operations required. On the other hand, the shorter set-up times enable the low-cost location $j = 2$, which provides all key replacement resources and which is located more closely to the lead factory, to be included more intensively, especially in the scenarios with a larger shortfall volume. Besides, we can observe a smaller deviation between worst-case costs and real costs, what can also be explained by the shorter set-up times that need to be included as a precaution to ensure the feasibility of a calculated plan.

In *test series 3*, the additional costs are higher than in the other two test series, as to be expected. In the case of the cost-based optimisation, additional costs of 20.82% can be observed when looking at the calculated worst-case costs. When looking at the real costs, additional costs of 13.23% are obtained. In the equally weighted case, these values increase to 38.05% and 25.72%, respectively. Compared to test series 1, as will be seen more clearly in the following chapter, the increased cost values are caused in particular by scenarios 4,8,11,12 and 13, which no longer benefit from the more favourable production costs of the other network locations.

Fig. 6.8 furthermore shows for the three test series the average number of days by which the parts to be rescheduled are **delayed** compared to when they actually should have been finished. Not surprisingly, the cost-optimised solutions show the greatest numbers in this case, with maximum delay values of 17.96, 19.66 and 17.59 days within test series 1,2 and 3, respectively, as illustrated in fig. 6.9. The average value across all scenarios is the lowest for test series 3 with 11.62 days of delay when compared to test series 1 and 2, indicating 11.86 and 12.60 days of delay. The time-optimised solutions, on the other hand, manage to reduce a shortfall quantity relatively quickly with maximum delay values of 10.3, 8.85 and 10.3 days and average values of 5.74, 5.09 and 5.74 days with reference to test series 1, 2 and 3, respectively. With the weighting $\lambda_1 = 0.5$, the maximum values amount to 11.28, 10.95 and 10.84 days and the average values across all scenarios amount to 7.25, 6.55 and 6.95 days when looking at test series 1,2 and 3.

A comparison of the values presented shows that the results of the different test series are not that far apart from each other. The shorter set-up time in test series 2 leads to a small acceleration in comparison to test series 1 when looking at the time-optimised and the equally weighted solutions. With regard to the cost-optimised solutions, the

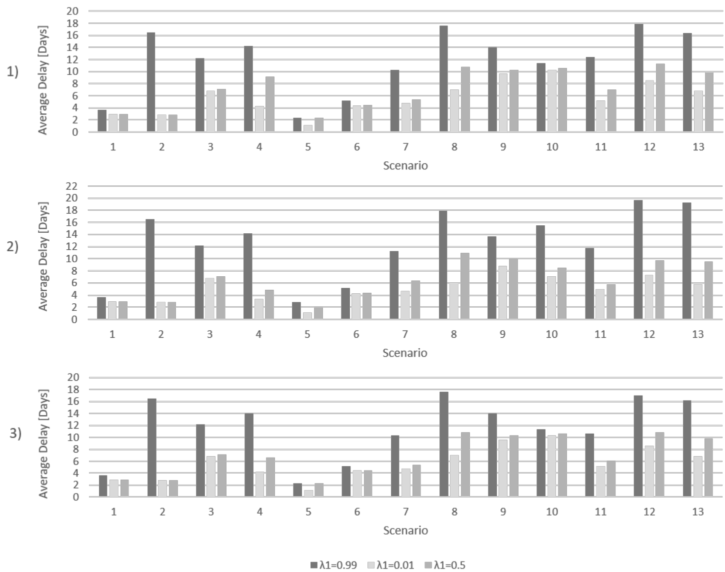

Figure 6.8: Resulting average delays in relation to the situation if the disruption had not occurred for the different scenarios and weightings within test series 1,2 and 3

delay time increases slightly. The delay times of test series 1 and 3 are very similar, especially in the cost-based and time-based cases.

Summarising the results, it can be seen that the time-optimised solution achieves in many scenarios only minor time advantages compared to the weighting $\lambda_1 = 0.5$ but causes significantly higher costs. The solutions calculated according to the weighting $\lambda_1 = 0.5$ therefore might represent a reasonable substitute for the time-optimised solutions under the scenarios considered. When focusing on the cost factor, the cost-optimised solutions are clearly beneficial since the delivery delays are kept within limits, and substantial cost advantages emerge when compared to the other weightings. At the end of the day, however, it is up to the planner to decide how to weight the different target di-

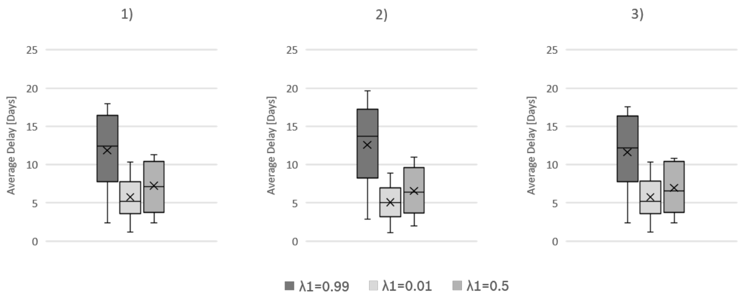

Figure 6.9: Boxplots showing the distribution of the resulting average delays within test series 1,2 and 3

mensions. The comparison of the three test series furthermore showed that a short set-up time is advantageous for the CM usage. The resulting costs are lower for all three weightings within test series 2 when compared to test series 1. Test series 3, on the other hand, leads to an increase in the resulting costs, as to be expected. Notwithstanding this, only minor differences could be found between the different test series with regard to the delay times.

Detailed Analysis: In the following, we will take a closer look at the solutions calculated. Fig. 6.10 shows for each of the three weightings the *share of the ordered volume that is assigned to the different plants* under the different scenarios within test series 1, 2 and 3.

Throughout all test series and weightings, it can be seen that in all scenarios with a small or medium shortfall volume, except for scenario 4, the order volume is fully allocated to the affected site $j = 1$. In test series 1 and 3, which show very similar data, it can furthermore be observed that in scenarios with a large or major shortfall volume, site $j = 3$ is primarily added to take over some portion of the order volume. Low-cost location $j = 2$, with its longer set-up times, is only marginally used in the context of the time-based optimisation, although located more closely to the affected site. The shorter set-up times within

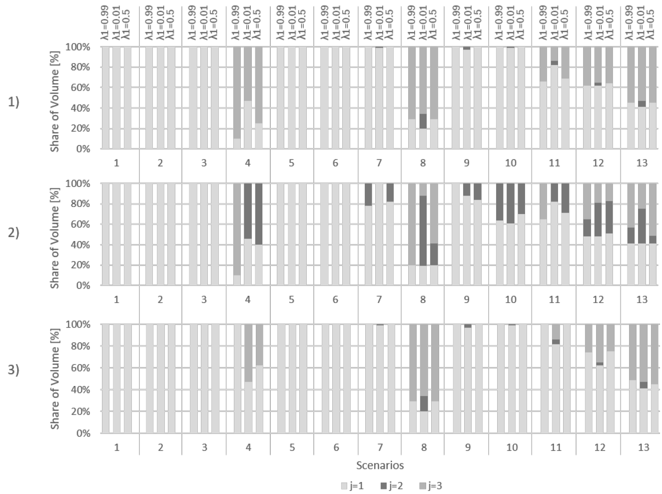

Figure 6.10: Share of the volume to be rescheduled that is assigned to the different plants under different scenarios and weightings within test series 1, 2 and 3

test series 2, however, enable location $j = 2$ to be included in the cases of large or major shortfall volumes more intensively throughout all weightings. Along with this, the portion of the volume being shifted away from the affected plant to other locations rises in most of these scenarios within test series 2 as well.

With regard to the calculated production plans and the associated *distribution of the ordered volume to different period types*, which is shown in fig. 6.11, several aspects can be observed. As can be seen from the data, the cost-optimised solutions make use of (the more expensive) Sunday shifts much less intensively than the other two weightings in most cases, especially in scenarios showing a small or medium shortfall volume. In the case of time-based optimisation, on the other hand, Sunday work is used to a high degree, except for small-volume scenarios 1 and 2. The figure also shows that the distribution of the ordered volume among the different period types changes for the most part only slightly

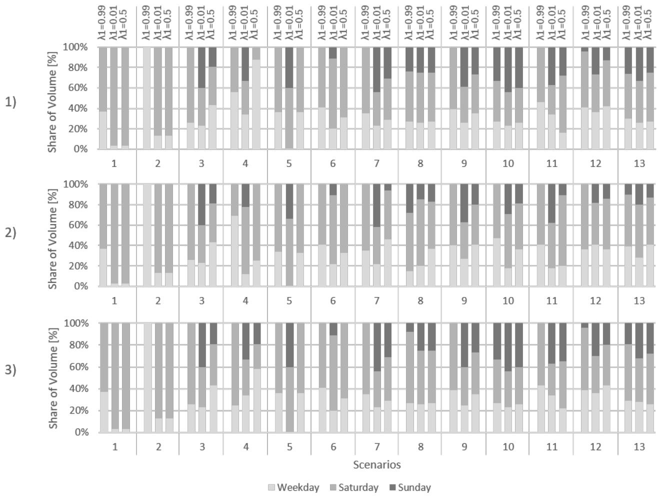

Figure 6.11: Time-based distribution of the volume to be rescheduled under different scenarios and weightings within test series 1, 2 and 3

between the 3 test series. Although, it can be observed that there is less work on Sunday in test series 2 within most scenarios. Notwithstanding this, the ratio between weekdays and weekends remains relatively constant at (1/3):(2/3) throughout the three test series. Additional weekend shifts are thus utilised quite intensively. In this regard, we would like to note that the weekday share also includes the Monday portion of Sunday night shifts used. Caused by the high capacity utilisation, as shown in fig. 6.3, free gaps during the week therefore only account for a small proportion of the ordered volume.

In order to be able to assess the *complexity of the calculated solutions*, taking into account that we have not used minimum lot sizes within this study, we have illustrated in fig. 6.12 the statistical distribution of the factor by which the number of operations, as defined in chapter 6.1.2, increases. As can be seen in the diagram, the number of operations rises on average by a factor of 2-3 when compared to the situation without a disruption. Using smaller lot sizes, the execution

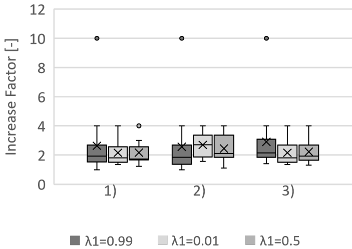

Figure 6.12: Increase of the number of operations in relation to the situation without a disruption under different weightings within test series 1,2 and 3

of the production plan thus becomes more complex. At the same time, it can be seen that the values of the different test series and weightings are very similar, with the larger outliers occurring in the case of smaller shortfall volumes, which are distributed over several periods when optimising cost-oriented.

In terms of *transport*, it can be observed that the time-based solutions mainly use direct transports, especially when transporting the processed materials back to the affected site (cf. fig. 6.13). This causes the costs to rise as small volumes are transported with a high frequency, which is exaggerated by the fact that the raw materials are becoming available in stages. Beyond that, it is noticeable that the smaller set-up times within test series 2 partially increase the volume to be transported, which allows the use of larger vehicles. With regard to the cost-optimised solutions and the equally-weighted solutions, the slower but less expensive groupage service is utilised in the vast majority of cases with a low frequency and on the basis of a consolidated transport volume. Direct transports with large vehicles are only being employed within test series 2 but in far fewer cases. In addition, transport consolidations between the sites of the network can be observed. For example, materials are transported via groupage service from site $j = 3$ to site $j = 2$ and from there jointly to site $j = 1$. Last but not least, it was found that in some cases slightly more materials are transported than necessary. This effect can occur when there are enough materials in the

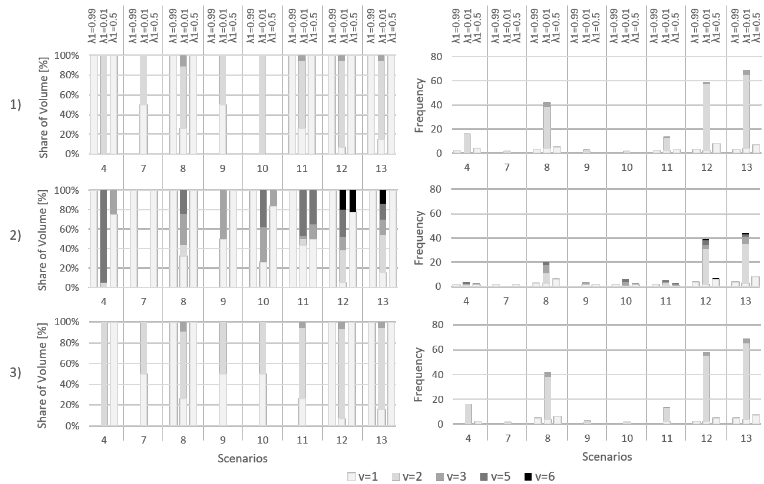

Figure 6.13: Share of different transport forms relative to the total transport volume (left) and number of transports planned (right) under different transport-affected scenarios and weightings within test series 1-3

stock and the additional transport quantities do not increase the transport costs (e.g. when a pallet is filled up), resulting in an indifferent objective function value.

Comparison to the Heuristic Approach: In figures 6.14 and 6.15, we compare the presented results that were obtained by solving the SLSP-B-TC with the solutions found when using the introduced heuristic approach (cf. algorithm 3).

Two different settings are examined. In Fig. 6.14, we consider the case where the heuristic approach aims at finding a rather fast solution taking into account all available slots, including Sunday shifts (*setting 1*). The obtained results are compared with the time-oriented ($\lambda_1 = 0.01$) and the equally-weighted ($\lambda_1 = 0.5$) SLSP solutions. In Fig. 6.15, we investigate a more cost-oriented setting where the heuristic approach skips the more expensive Sunday shifts (*setting 2*) and compare the results with the cost-oriented ($\lambda_1 = 0.99$) and the equally-weighted ($\lambda_1 = 0.5$) SLSP solutions.

The two figures illustrate for each of the three test series the differences of the solution values under different scenarios. A negative sign indicates that the heuristic solution provides the better, i.e. smaller value. A positive sign, on the other hand, indicates that the solution calculated with the SLSP shows the lower additional costs or delay value. With regard to the cost values, we have listed both the absolute cost difference and the relative cost difference in relation to the costs occurring without a disruption using the reduced real costs.

As can be seen in the figures, not all scenarios could be solved with the heuristic approach due to an insufficient amount of free capacity usable inside the planning horizon. In the second setting, we were not able to find a solution in scenarios 8,10,12 and 13, showing a large or major shortfall volume. In the first setting, where more capacity was available to be used due to the inclusion of Sunday work, no solutions were found in scenarios 8 and 13.

Looking more closely at the results of the time-oriented **setting 1** shown in fig. 6.14, it can be seen that the heuristic approach achieved time advantages over the *equally-weighted* SLSP solutions in most scenarios. In return, the SLSP approach generated the lower cost values in most cases. Overall, the equally-weighted SLSP solutions performed best with short set-up times (test series 2) with a total of 5 scenarios in which the heuristic results were Pareto-dominated. On the other hand, the equally-weighted SLSP solutions performed worst in test series 3, where the cost advantages of the other locations could not be exploited. The resulting cost and delay values of the *time-optimised* SLSP solutions are, in most scenarios, very similar to the heuristic results. Nevertheless, in some scenarios, time advantages could be achieved - mostly accompanied by higher transport costs. In addition, there are also a few scenarios (e.g. scenarios 6 and 9 in test series 1 and 3) in which the time-optimised SLSP solution is Pareto-dominated. This phenomenon can be explained by the fact that the heuristic approach was able to

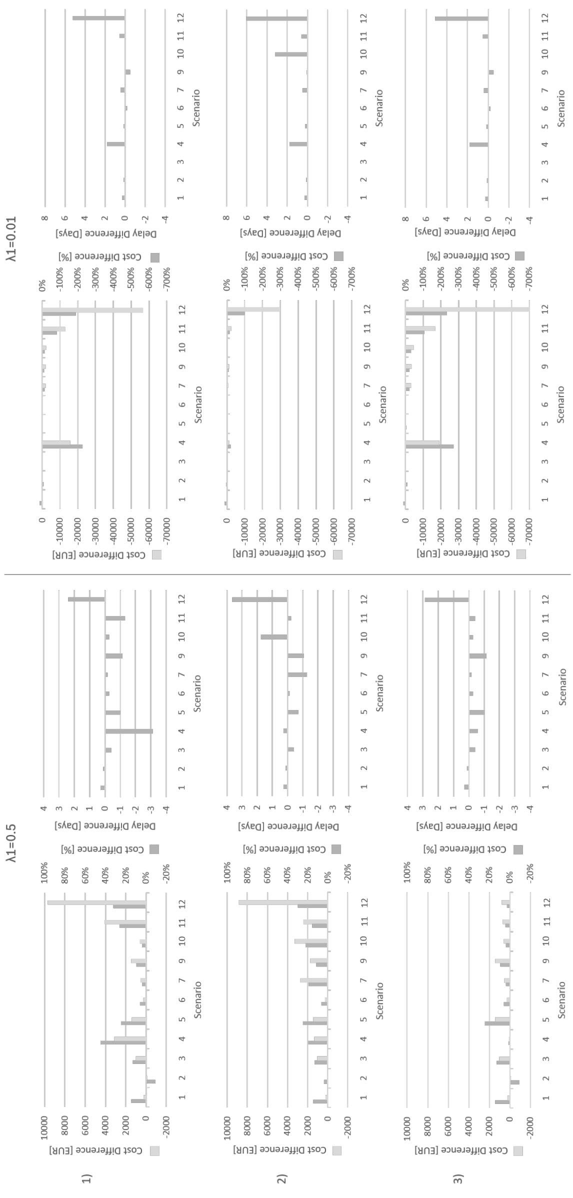

Figure 6.14: Cost differences (absolute and relative) and delay differences between the solutions calculated according to the heuristic approach (setting 1) and the solutions calculated according to the weightings $\lambda_1 = 0.5$ and $\lambda_1 = 0.01$ under different scenarios within test series 1, 2 and 3

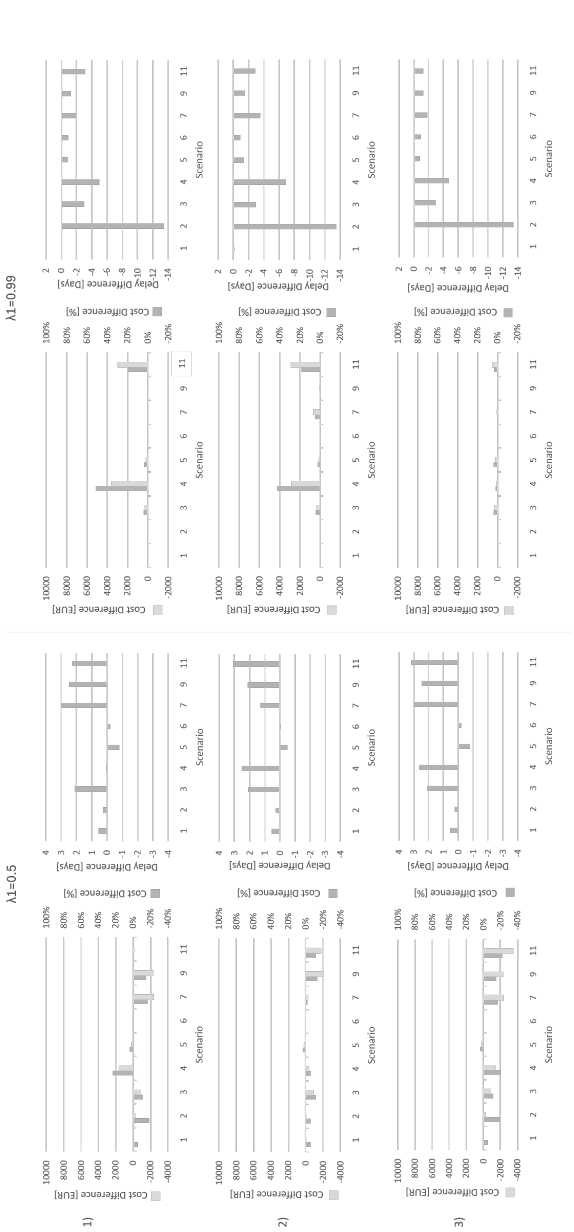

Figure 6.15: Cost differences (absolute and relative) and delay differences between the solutions calculated according to the heuristic approach (setting 2) and the solutions calculated according to the weightings $\lambda_1 = 0.5$ and $\lambda_1 = 0.99$ under different scenarios within test series 1, 2 and 3

save set-up time due to the known information about which products are produced upstream and downstream. As explained earlier, and as we will be discussed in more detail in the next section, the set-up time is considered twice in the SLSP without knowing what is produced before and afterwards to ensure that the determined plan is feasible, which causes the negative deviation.

As can be seen in fig. 6.15, in the cost-oriented **setting 2**, the heuristic approach achieved in most scenarios lower cost values than the *equally-weighted* SLSP solution, but in return produced the longer delays. The *cost-oriented* SLSP solution, on the other hand, indicates clear cost advantages in several scenarios when compared to the heuristic approach but induces longer delay times. Again, in some scenarios (e.g. in scenario 2), the phenomenon occurs that the SLSP solution is Pareto dominated by the heuristic result due to the explained set-up time handling and the resulting larger delay values.

To sum up, it can be stated that when the target criteria were weighted one-sidedly, the SLSP solutions indicated in the majority of the scenarios the better solution values. However, the heuristic results then mostly revealed advantages in the other target dimension. In order to be able to make a concluding statement about the suitability of SLSP optimisation compared to the heuristic approach when both target dimensions are considered simultaneously, we have compared in fig. 6.16 the normalised, summed-up objective function values. A positive sign indicates that the SLSP solution provides the better, i.e. smaller, value. A negative sign indicates the opposite.

As can be seen in the figure, the SLSP approach performed better in most scenarios. Especially when Sunday work was taken into account, the heuristic results indicate negative deviations for the most part, although more scenarios could be solved in this case. The SLSP approach achieved the best results when the set-up times were short (test series 2) and the worst results when the production costs were the same at all locations (test series 3). Besides, it can be seen that due to the more targeted set-up planning, there are also some scenarios in which

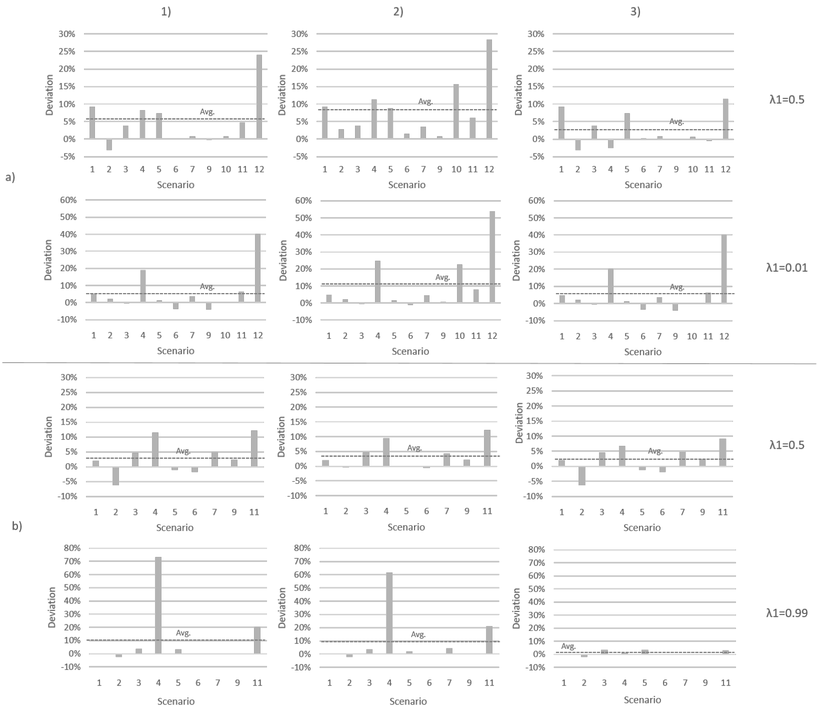

Figure 6.16: Deviation (in %) of the heuristic solutions determined with setting 1 (a) and setting 2 (b) from the SLSP solutions based on the added-up, normalised objective function value under different weightings within test series 1,2 and 3

the heuristic approach was able to generate the better result. It is thus highly recommended to take the heuristic approach into account as well when selecting a solution to handle a disruption.

Set-up Time Reduction

The analyses carried out in the last sections were based on the assumption that the set-up time is taken into account twice in the parameter $\mathbf{ST}(r, p)$ when solving the SLSP. This assumption is particularly useful if, as in the use case considered, there are only very few set-up operations and the same product types are manufactured over several days with no set-up operations taking place in between. Considering the set-up time twice ensures that the original plan can be continued without any interruption if a CM order has been scheduled, but can result in poorer results. On the other hand, if set-up operations are carried out very frequently, also within one day, it seems plausible to assume that after inserting a CM order, another product type will be manufactured anyhow. The set-up time then only has to be taken into account once in the parameter $\mathbf{ST}(r, p)$, which can lead to an improvement in the solution quality.

Below, we will present a model extension for the first case described above, i.e. when facing only a few set-up operations as in the regarded use case, that allows reducing the number of set-up operations considered. The objective of the model extension is thus to save set-up time in order to be able to use more of the offered capacity for production.

The model extension is based on the assumption that when at least one set-up operation is scheduled in the underlying production plan on a given day, this stop is used to insert a scheduled CM order. Accordingly, there is no need to plan a further retooling operation in the CM platform since a changeover to another product type will be made afterwards anyhow. As opposed to this, in our previous modelling, the planner was given the choice to schedule a CM order within the planned day at the time that suits him best. For example, if there was a scheduled changeover at shift start to a new product type that is going to be produced uninterruptedly for several days, the planner was still able to insert the CM order only at the end of the shift for reasons known to him. With the assumption described, this flexibility is no longer given and the CM order would have to be produced right at the beginning of the shift in this example.

To reflect this limiting assumption in the model, we redefine the parameter $\mathbf{SH}(r, t, p)$:

$$\mathbf{SH}(r,t,p) := \begin{cases} 1 & \text{if product } p \text{ is scheduled to be produced} \\ & \text{in period } t \text{ on resource } r \\ 0.5 & \text{if product } p \text{ is not scheduled to be produced} \\ & \text{in period } t \text{ on resource } r \text{ but there is at least} \\ & \text{one set-up operation in period } t \text{ on resource } r \\ 0 & \text{otherwise} \end{cases}$$

The parameter $\mathbf{ST}(r,p)$ still contains the double set-up time. The redefined parameter $\mathbf{SH}(r,t,p)$ ensures that in the formula 5.15 only one set-up operation is considered on days on which at least one changeover operation is going to take place anyhow. Thus, more of the offered capacity can be used for production. However, due to the big-bucket approach followed in this work, the period transitions can still lead to deviations between the real costs and the calculated worst-case costs. For example, in the case of a free weekend shift, the set-up time is planned twice, since it is unknown what will happen the next day. If the same product is manufactured the next day or if a changeover process takes place at the beginning of the next day, the real set-up costs decrease accordingly.

		(Worst Case) Costs [EUR]	(Real) Costs [EUR]	Delay [Days]
$\lambda_1 = 0.01$	Base Model	11056.58	10754.78	10.05
	Adapted	10988.32	10547.92	9.95
$\lambda_1 = 0.5$	Base Model	9818.98	9517.18	10.41
	Adapted	9614.98	9353.98	10.26
$\lambda_1 = 0.99$	Base Model	8412.64	8290.24	15.47
	Adapted	8371.84	8290.24	15.41

Table 6.5: Comparison of the results with and without set-up time optimisation using the example of scenario 3 within test series 1

As can be seen in table 6.5, using the example of scenario 3 within test series 1, the presented model extension can help to improve both the real and calculated worst-case costs, as well as the delay time when compared to the results presented in figures 6.6 and 6.8.

6.1.5 Conclusion

In the following section, we will summarise and critically discuss the results of our study.

Based on a real-world example for a single-stage production-process, our aim in this chapter was to investigate what results the CM platform can deliver in the event of a breakdown. For this purpose, we looked at different breakdown scenarios within 3 test series, in which we both used the real data as well as varied the set-up times and the production costs.

In a first step, we took a closer look at the computing times and the resulting optimality gaps. It was shown that solutions with at least 95% optimality could be found with acceptable computing times, even in cases of large shortfall volumes. However, optimality could not be proven in all cases. Since the optimality gap also decreases only very slowly in these cases, a limitation of the computation time seems to be reasonable for the application case of the CM platform.

Furthermore, the resulting costs and delays were examined in comparison to the situation without a disruption. It was shown that also in cases of large breakdowns, rescheduling with the CM platform is possible with acceptable delay values and acceptable cost increases without having to completely recalculate the existing production plan. In this respect, the equally weighted approach seems to be a reasonable compromise, as it achieved comparatively close results in both target dimensions to those obtained when optimising only according to this criterion. The best results were found when we assumed a reduced set-up time since this increases the planning flexibility. But even without this variation, in some cases, a breakdown actually saved costs due to the cost structure in the regarded network. Under the assumption of equal production costs, this phenomenon obviously no longer occurs.

A more detailed look at the calculated production plans additionally revealed that rescheduling to the other locations of the network is mostly done only in cases of larger shortfall volumes. Beyond that, the free weekend shifts were utilised to a high degree due to the high utilisation rate during the week. With regard to the transport side, it was shown that groupage services are used to a large extent, especially when optimising cost-oriented or equally-weighted. In the time-based optimisation, on the other hand, direct transports were mostly used.

A comparison with a successive planning heuristic that is based on the practical way of proceeding further showed in which cases the use of the platform might be reasonable. The SLSP approach was able to find the better solution in most scenarios taking into account different target weightings. The advantages were again highest when the set-up times were short and lowest when we assumed the production costs to be the same throughout the network. The results of the heuristic approach improved when Sunday work was omitted.

On the other hand, some limitations of the CM approach could be identified as well. Thus, it is not possible to plan in a sequence-optimal way within a period and also between periods due to the big-bucket approach of this work. The optimisation approach in this case study was therefore based on a worst-case calculation, in which the set-up time is always considered twice for setting up and then setting back again in order to ensure an undisturbed continuing of the original plan. This resulted in a deviation between the calculated worst-case costs and the real costs, as some of those set-up operations included were not necessary and could therefore be neglected. Additionally, a better solution possibly could have been achieved in this case if the planned but unused set-up time had been used for production. This phenomenon could also be observed in the comparison with the successive planning heuristic, which was able to outperform the SLSP approach in a few scenarios due to the better set-up planning. The heuristic approach should therefore be taken into account as well when selecting a solution for handling a disruption. The problem arises especially when changeover operations are carried out infrequently and with long set-up times. An improvement can be achieved by extending the optimisation model in a way that reduces the planning flexibility on days when changeover operations take place anyway, so that CM orders are required to be scheduled in between those changeover operations.

A further point of discussion arises with regard to practical feasibility. For example, it depends on the company whether only partially utilised shifts at the weekend, as it might be suggested by the CM platform, can be scheduled realistically in this way. This is accompanied by the question of minimum lot sizes, which were not considered in this study. Accordingly, the calculated production plans are more complex to execute when compared to the original plan, also due to partly smaller batches, which has been shown by the number of operations to be conducted. On the other hand, setting minimum lot sizes would limit the planning flexibility, which could lead to a deterioration of the results.

To sum up, we draw the conclusion that the presented approach offers advantages, especially in cases of medium and large-scale shortfall volumes. The use of the CM platform seems to make sense in particular in situations when the urgency level is that high that the shortfall volume cannot be postponed to the next planning period. As an upper limit, however, the volume should still be small enough to allow a scheduling within the planning horizon. Apart from that, the complexity level above which a complete rescheduling of the production plan seems to be more reasonable defines a further upper threshold level for the shortfall volume to be handled.

6.2 Multi-Stage Production Process

Having addressed the single-stage case in the last chapter, we will now look at the multi-stage production process. The chapter starts with an introduction to the general problem setting. Afterwards, we will take a closer look at the data used and the defined test scenarios. In the last subchapter, we will present the results of the analysis and discuss the implications derived from them.

6.2.1 Problem Setting

Using again the example of the Robert Bosch GmbH, we will conduct our investigations in this chapter based on the multi-stage production process shown in fig. 2.8. In contrast to the previous chapter, however, we will now focus on **excess quantities**, assuming that additional order quantities required to pass through the entire process need to be scheduled. The main objective of this chapter is not to evaluate the calculated results content-related but to analyse the computation times. We will therefore take a closer look at the runtime behaviour of both the MILP formulation of the SLSP as well as of the LP reformulation in different scenarios. The evaluations are again based on a provided real-world data set, which will be discussed in the following.

6.2.2 Data Base

Below, we will describe how we have prepared the data provided by the Robert Bosch GmbH and by the Transport Betz GmbH in order to be usable for the CM platform, addressing the basic quantities and the static and dynamic properties.

Basic Quantities

Our analyses in this chapter are based on the multi-stage production process illustrated in fig. 2.8. Since, in analogy to the previous chapter, only the bottleneck steps need to be considered, we have limited the scope to the bottleneck steps of the 4 planning areas, i.e. $\mathcal{I} = \{1, ..., 4\}$ applies. In terms of network size, the problem expands to $\mathcal{J} = \{1, ..., 5\}$ locations with two additional externally operated process plants in Germany ($j = 4$) and in the Czech Republic ($j = 5$) (cf. fig. 2.5). Taken together, these locations provide a total of $\mathcal{R} = \{1, ..., 60\}$ resources throughout the network. 41 of those resources, located at the plants $j = 1 - j = 3$, belong to step $i = 1$, as described in the preceding chapter. Step $i = 2$ is performed at the two external sites $j = 4$ and $j = 5$, for which no detailed production data are available. We have therefore created two dummy resources for representation purposes, which will be discussed in more detail in the next subchapter. For the steps $i = 3$ and $i = 4$, the lead factory $j = 1$ provides 3 and 4 resources, respectively, and the source factory $j = 2$ provides 4 and 6 resources, respectively.

In terms of products, we limit the analyses to two representative product types $\mathcal{P} = \{1, 2\}$. Building on figures 6.1 and 6.4, $p = 1$ represents a flexible product type with many releases and a high number of operations. Product $p = 2$, on the other hand, is a low-runner product with only a few releases. Each product type incorporates 9 different purchased components that are added to the processed parts in the assembly step. This results in a total number of $\mathcal{C} = \{1, ..., 18\}$ component types that need to be considered in the planning of the CM platform. Moreover, we include the two finished goods container types $\mathcal{F} = \{1, 2\}$ into which the finished parts are packed.

With respect to the planning horizon, period types and transport, $\mathcal{T} = \{1, ..., 28\}$, $\mathcal{S} = \{1, ..., 7\}$ and $\mathcal{V} = \{1, ..., 7\}$ applies, as in the previous chapter.

Static Properties

Analogous to the previous chapter, we have mapped the provided data to the static production- and transportation-related input variables of our model. Where data was missing, we have supplemented it with reasonable, realistic assumptions. However, in order to protect the confidentiality of the data over the entire production process and due to the focus on a computational evaluation, we have not listed them in detail in the appendix this time. Nevertheless, we would like to point out some aspects with regard to the two external sites $j = 4$ and $j = 5$.

Since no information was available on the number of resources, processing times and set-up times, and since coordination with the other sites in the network is based on lead times, we modelled these two sites as two dummy resources with marginal processing times and set-up times. As a standard, we have assumed a lead time of 7 days. During the first 7 days of the planing horizon, the capacity at the two sites was therefore set to 0. Accordingly, no production is possible within this time frame. From day 8, the capacity was assumed to be unlimited what makes a delivery possible at any time. Since there was also no cost information available, we set those values to 0 as well. This assumption is especially plausible if the two locations operate at approximately the same cost level so that these costs can be neglected in the decision making. The selection is then only based on the distance.

Dynamic Properties

To consider the varying production-related conditions at the other locations of the network, we generated the values of $\mathbf{AC}(r,t)$ and $\mathbf{SH}(r,t,p)$, which indicate the free capacities and the scheduled products in the production plan, stochastically this time. In terms of the inventory data ($\mathbf{IP}(p,i,j,t)$, $\mathbf{IC}(c,j,t)$ and $\mathbf{IF}(f,j,t)$), we distinguished the two cases that all materials are available at the beginning of the planning horizon or that the materials are provided in a staggered manner.

In the following, we will discuss this in more detail when presenting the test scenarios considered.

6.2.3 Test Scenarios

In order to obtain a comprehensive picture when analysing the performance of the CM platform, we defined various test scenarios reflecting problem instances of different sizes. Below, we will introduce the underlying factors of the experimental setting and describe the test scenarios considered.

Factors

The different test scenarios are built around the idea of using the CM platform to schedule additional, different-sized **order quantities** in different **order compositions** with respect to the two reference products.

Looking at the factor **order quantity**, we distinguish the following two levels:

- Small: 1 Day
- Large: 5 Days

In the category *small*, the additional order quantity to be scheduled with the platform equals the quantity that can be produced in a complete day (3 shifts). Since this is a comparatively small amount, we assume that all required materials are available at the beginning of the planning horizon. In the case of a *large* order, the ordered quantity corresponds to the quantity that can be produced in a complete week (15 shifts). Due to the larger amount, we assume in this case a staggered supply of the required materials.

In terms of the factor **order composition**, we distinguish whether product $p = 1$, product $p = 2$ or both product types together are ordered:

- Product $p = 1$
- Product $p = 2$
- Products $p = 1$ and $p = 2$

Product $p = 1$ is a so-called flexi-type that is released on many resources. If this product is ordered, a large problem instance is created, which includes a total of 30 available resources distributed across all 5 locations. More specifically, the problem encompasses 23 resources at 3 locations ($j = 1, j = 2, j = 3$) for step $i = 1$, 2 resources at 2 locations ($j = 4, j = 5$) for step $i = 2$, 2 resources at 2 locations ($j = 1, j = 2$) for step $i = 3$ and 3 resources at 2 locations ($j = 1, j = 2$) for step $i = 4$. At the same time, product $p = 1$ is a high-runner product that is frequently produced in the network. Product $p = 2$, on the other hand, is only released on 5 resources located at 2 sites. All steps except for step $i = 2$ are performed in the lead factory, with only step $i = 1$ offering 2 alternative resources. Step $i = 2$ is conducted at site $j = 4$. Moreover, product $p = 2$ is a low-runner product that is produced much less frequently.

Modelling

Using the factors presented, we have compiled a total of 5 test scenarios based on a full-factorial test design, which are shown in table 6.6. We disregarded, however, the rather unusual scenario of combining a small order quantity with multiple ordered products. To illustrate the dimensions of the problem instances considered, the table additionally provides the sizes of the basic quantities after the prefiltration step.

Sc.	Order Qty.	Order Comp.	$\hat{P}_{max}$	$\hat{R}_{max}$	$\lvert\hat{\mathcal{J}}\rvert$	$\hat{C}_{max}$	$\hat{F}_{max}$	$\hat{I}_{max}$	$\hat{S}_{max}$	$\hat{V}_{max}$	$\hat{T}_{max}$
1	Small	$p = 2$	1	5	2	9	1	4	7	7	28
2	Small	$p = 1$	1	30	5	9	1	4	7	7	28
3	Large	$p = 2$	1	5	2	9	1	4	7	7	28
4	Large	$p = 1$	1	30	5	9	1	4	7	7	28
5	Large	$p = 1$, $p = 2$	2	32	5	18	2	4	7	7	28

Table 6.6: Test Scenarios

For the implementation of the test scenarios, we made use of the following modelling assumptions:

We assumed the lead factory to be the ordering plant and used the production data of this plant for step $i = 1$ as a reference point for determining the **order quantity** ($\mathbf{Q}(p, i)$). In the case of a *small* order quantity, we have thus taken the quantity of the considered product that the lead factory is able to process in one day on one resource when conducting step $i = 1$. In the case of scenario 5, where both product types are ordered simultaneously, we have divided the respective quantity that would have been ordered if the product had been ordered alone by 2.

In terms of the **inventory** provisioning ($\mathbf{IP}(p, i, j, t)$, $\mathbf{IC}(c, j, t)$ and $\mathbf{IF}(f, j, t)$), we have assumed that the required materials are made available exclusively at the lead factory - either at the beginning of the planning horizon (*small* order quantity) or in a staggered manner (*large* order quantity). In the case of a staggered provisioning, we based our modelling on the assumption that about 1/3 of the required quantity is already available at the beginning of the planning horizon, and the second and last thirds are being delivered after 7 and 14 days, respectively.

To create the underlying **production patterns**, we randomly selected days on which the products are scheduled in the production plan ($\mathbf{SH}(r,t,p)$). For the high runner product, we assumed a selection probability per day and approved resource of 7/28, indicating that the product type is usually processed on 7 out of 28 days. For the low-runner product, we assumed a rather lower selection probability of 2/28.

To determine the **free capacities** $\mathbf{AC}(r,t)$, we made use of the normal distribution ($\mathcal{N}(\mu,\, \sigma^2)$). Using the net production time and the utilisation rate, we utilised the following formula to calculate the needed expectation values:

$$\mu := \text{Net production time [min]} \cdot (1 - \text{Utilisation[\%]}) \tag{6.3}$$

6.2.4 Analyses

After having introduced different test scenarios, we will now present and analyse the results of our investigations. We will first look at the findings obtained with the extended base model version of the SLSP, incorporating both the enhanced transport cost modelling as well as secondary material resources (SLSP-B-TC-SMR). Afterwards, we will discuss the outcomes achieved with the LP reformulation extended to include the planning of components (SLSP-LP-SMR/C). Both test series were performed with the same computing system as in the previous chapter.

SLSP-B-TC-SMR

Runtime Behaviour: To get a detailed insight into the computation time behaviour when solving the SLSP-B-TC-SMR, we first looked at how the solution quality evolves over time, which is shown in fig. 6.17. Establishing a base for comparison, we created for each of the 5 scenarios problem instances to be solved with all three weightings using the CPLEX default setting while limiting the computation time to a maximum of 28800 seconds (8 h) per run. For each scenario, we used the same dynamic production data ($\mathbf{SH}(r,t,p)$ and $\mathbf{AC}(r,t)$), pseudo-randomly generated with the Java random number generator according to the probability distributions described in the previous section. With regards to $\mathbf{AC}(r,t)$, we calculated with the utilisation rates of the lead factory documented in fig. 6.3, i.e. 88% during the week and 16% on weekends at all locations and resources. For the standard deviation, we chose $\sigma = 60$.

As can be seen in fig. 6.17, the problem instances related to scenarios 1 and 3 could be solved optimally in a short amount of time for all three weightings. On the other hand, we were not able to solve scenarios 2, 4 and 5 with proven optimality within the defined time limit in most cases.

This relationship is also reflected in the sizes of the problem instances solved, which are shown in table 6.7.

	Scenario				
	1	2	3	4	5
Number of Variables	26183	160096	26183	160096	311315
Number of Constraints	24556	126037	24556	126037	234713

Table 6.7: Sizes of the problem instances used to analyse the runtime behaviour when solving the SLSP-B-TC-SMR

Looking at the large-scale scenarios 2,4 and 5 in more detail, the best results were obtained when optimising time-based, where good solutions could already be found at the beginning of the solution procedure. The cost-based optimisation, on the opposite, resulted in the largest gaps with a maximum value of 19.02% when reaching the computation time limit. With regard to the equally weighted case, it is important to note that the normalisation of the objective function is based on the best-

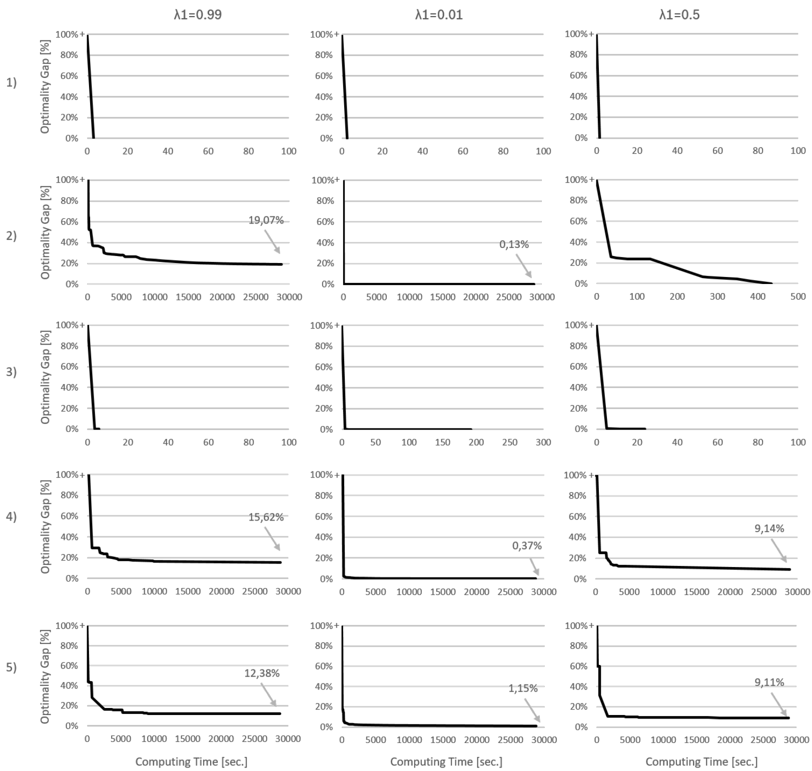

Figure 6.17: Development of the optimality gap when solving the test instances for scenarios 1-5

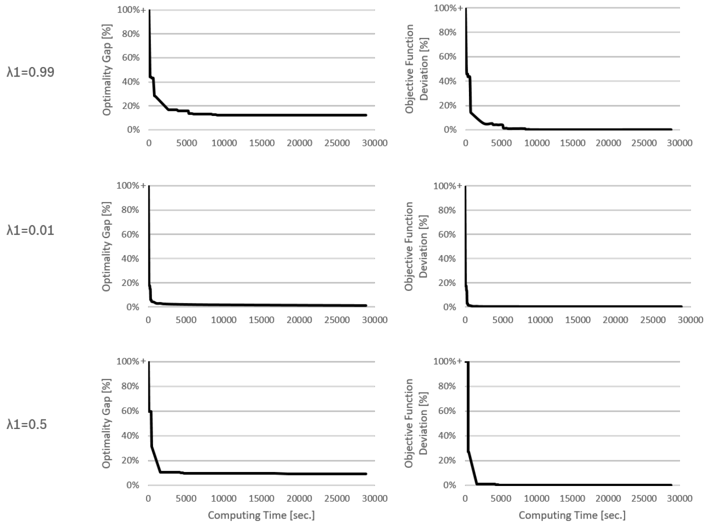

Figure 6.18: Comparison of the development of the optimality gap (left) with the development of the objective function related to the best value found when the optimisation was terminated (right), using scenario 5 as an example

found values for the mono-criteria problems, which may not have been optimal, resulting in a bias in the preference weighting.

In addition to that, it could be observed throughout all test runs that the optimality gap always decreased the fastest at the beginning of the solution procedure. Further improvements with longer computation times were achieved only very slowly. This relationship is also noticeable when comparing the development of the optimality gap with the development of the objective function, as exemplified in fig. 6.18 for scenario 5. It can be seen that both curves developed highly synchronously, with the objective function improving only in small steps for longer computation times. Finding a tighter lower bound to reduce the gap, thus played only a minor role in the solution method.

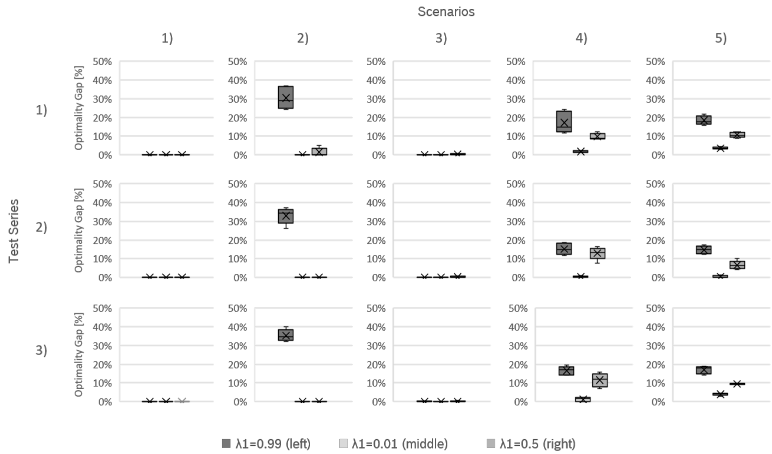

Figure 6.19: Resulting optimality gaps within test series 1, 2 and 3 based on 5 test runs per scenario. The test runs were stopped after 1800 seconds

Impact of the Dynamic Production Data: To further investigate the impact of varying production data ($\mathbf{SH}(r,t,p)$ and $\mathbf{AC}(r,t)$) on the runtime behaviour, we compared the resulting optimality gaps of multiple test runs, setting the maximum computation time per run to a practical value of 1800 seconds.

To create a base for comparison, we performed 5 test runs for each of the scenarios, each with different random numbers generated according to the probability distributions described. In order to simulate the impact of the capacity utilisation, we additionally embedded the test runs in 3 test series in which we varied the expected values for the free capacities. In **test series 1**, we calculated with utilisations rates of 88% and 16% already used in the last section. In **test series 2**, we assumed a significantly lower utilisation rate throughout the network and took the values of plant $j = 3$, i.e. 56% on weekdays and 0% on weekends (cf. fig. 6.3). In **test series 3**, we simulated a higher utilisation rate and set the values to 90% and 53%, which corresponds to the average utilisation rate in fig. 6.3.

As can be seen in fig. 6.19, the results obtained confirm the findings of the last section. The optimality gaps were largest for the problem instances of scenarios 2, 4, and 5, especially in the cost-based optimisation runs and somewhat smaller in the equally weighted-case. The time-based solutions, on the other hand, revealed comparatively low gaps across all scenarios. The best results were obtained for the small-scale problems of scenarios 1 and 3, regardless of the order quantity. In addition to that, it could be observed that there were only minor deviations in the resulting optimality gaps between the test runs, both within and between the test series. A strong influence of varying production data could therefore not be detected.

Impact of the Model Extensions: In order to analyse the influence of the model extensions on the runtime behaviour in large-scale scenarios 2,4 and 5, we additionally compared the results obtained with the SLSP-B-TC-SMR with the results obtained when neglecting the model extensions. For comparison, we used the SLSP-B-TC disregarding the secondary material resources and the SLSP-B-SMR disregarding the transport cost extension. To ensure comparability of results, we performed the evaluations with the same random numbers as in the analysis above (fig. 6.17) while limiting the computation time per run to a maximum of 7200 seconds (2 h).

As can be seen in figures 6.20 and 6.21, the runtime behaviour improved significantly when the two extensions were neglected.

		Scenario		
		2	4	5
Nb. of Variables	SLSP-B-TC	60506	60506	112135
	SLSP-B-SMR	155196	155196	306415
Nb. of Constraints	SLSP-B-TC	54847	54847	92333
	SLSP-B-SMR	107137	107137	205313

Table 6.8: Sizes of the problem instances used to analyse the runtime behaviour when solving the SLSP-B-TC and the SLSP-B-SMR

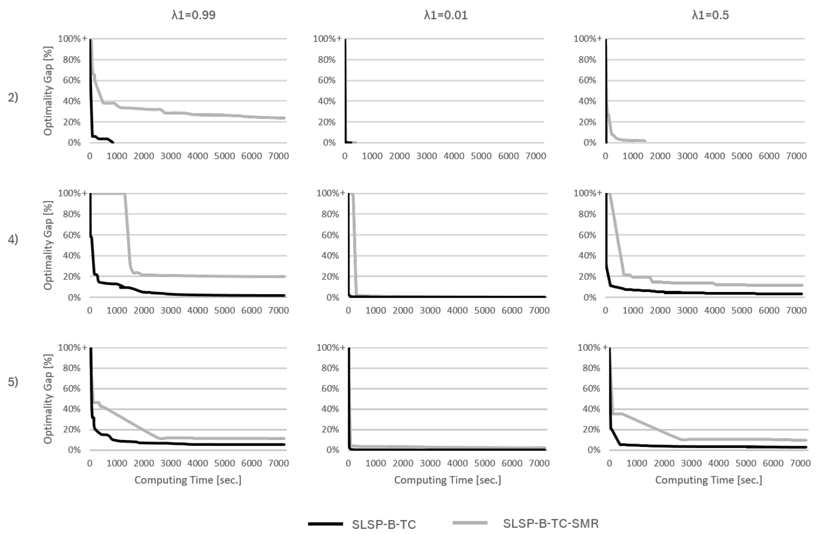

Figure 6.20: Runtime behaviour when solving the SLSP-B-TC-SMR compared to when solving the SLSP-B-TC in large-scale scenarios 2,4 and 5

In the case of the SLSP-B-TC, the better runtime performance achieved by neglecting the secondary material resources was accompanied by a significantly reduced model size, as illustrated in table 6.8. It thus seems to be a reasonable approach to keep the number of materials considered in the model as small as possible by focusing on A-components that are not available in large quantities at all relevant sites. At the same time, it is advisable to neglect any material that is on hand at the relevant plants in sufficient numbers.

Looking at the SLSP-B-SMR, neglecting the transport cost extension, it can be seen that the model size changed only marginally. Accordingly, the better runtime behaviour was mainly achieved by not forcing the consolidation of transportation due to the missing fixed costs part. However, it should be taken into account that if no corresponding tariff tables are offered by the freight forwarders, only an approximate transportation cost calculation is made in this case.

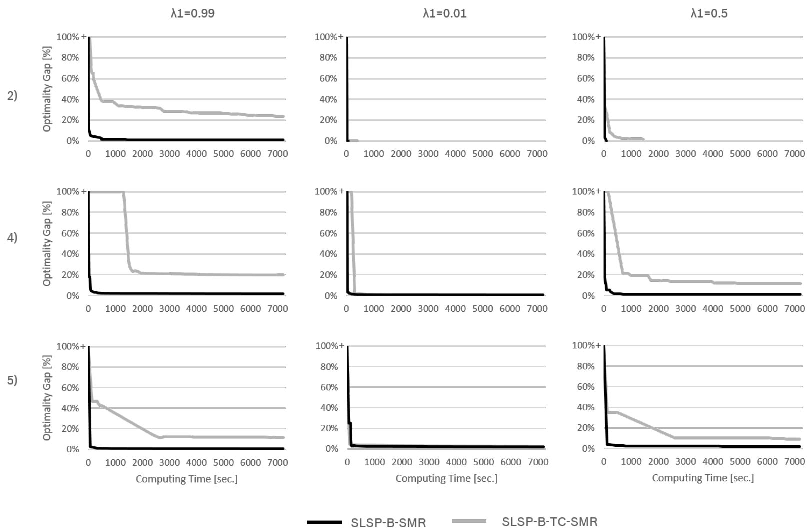

Figure 6.21: Runtime behaviour when solving the SLSP-B-TC-SMR compared to when solving the SLSP-B-SMR in large-scale scenarios 2,4 and 5

In both cases, it could furthermore be observed that despite the better runtime behaviour, which led to small gaps already after a short amount of time, in most cases, still no proven optimal solution could be found within the defined time limit.

SLSP-LP-SMR/C

Due to the fact that most large-scale MILP problems could not be solved proven optimal, we further looked at the performance of the less complex LP reformulation. To do so, we again performed 5 runs each for the individual scenarios embedded in the 3 test series described.

As can be seen in table 6.9, all problem instances could be solved in less than 1 second (with a lower bound of 0.022 seconds). Using the LP reformulation, we were thus able to find (optimal) solutions very quickly, even for large problems.

	Scenario				
	1	2	3	4	5
Number of Variables	2521	12671	2521	12671	25453
Number of Constraints	2774	8752	2774	8752	16831
Max. Computation Time [sec.]	0.079	0.296	0.091	0.23	0.444

Table 6.9: Sizes of the problem instances solved with the SLSP-LP-SMR/C and maximum computation time required throughout all test runs within the 3 test series

It should be noted, however, that the use of the LP reformulation and the (optimal) solutions found with it involve several assumptions:

Based on the restrictions described in chapter 5.5, we subtracted the maximum possible set-up times (including setting up and setting down) from the free capacities, which were again randomly generated, in advance to ensure the feasibility of all solutions possible. This approach seems to be reasonable if the set-up times are short. If, on the other hand, many products with long set-up times are eligible for a resource, the solution quality may deteriorate due to the large amount of blocked time that may not be needed depending on the calculated solution. In addition to that, it must be taken into account that in the LP reformulation, no set-up-optimised planning is carried out with respect to the existing production plan as well as with regard to the upstream and downstream period. Since the set-up time is also not considered in the objective function, these two points likewise lead to the fact that the solution quality may deteriorate. All in all, a permissible solution can be generated by subtracting the set-up time in the forefront, but for large set-up times, the lack of consideration in the optimisation can lead to suboptimal results in the overall picture.

In the context of the use case under consideration, it therefore seems to be reasonable to restrict the use of the LP-reformulation to steps $i = 2$ to $i = 4$, which require a significantly shorter set-up time than most resources in step $i = 1$. The inclusion of step $i = 1$ seems to make sense only in cases where just the resources with shorter set-up times are included.

Looking at the transport costs, it is worth noting that only groupage services are included. As can be seen in fig. 6.13, this restriction seems to be acceptable especially for the cost-based and equally-weighted case. For the time-based solution, on the other hand, the solution space is noticeably restricted. At this point, we would like to recall that we calculate the transport costs in the LP reformulation depending on the freight weight, without considering any fixed costs, which negates the need for transport consolidation. If the freight forwarders offer corresponding tariffs, this form of modelling is accurate. Otherwise, as in our study, transportation costs are included only approximately in the objective function, which can also lead to distortions.

Last but not least, we would like to emphasise that the modelling of the LP reformulation is based on continuous variables. On the one hand, we therefore do not consider the finished goods containers in the LP reformulation, which are integer entities in our model. On the other hand, this causes continuous results to be generated for the remaining variables. For large container filling quantities, it might be possible to approximate those values. However, for smaller filling quantities and in practical implementation, it is quite possible that deviations from the optimal plan will occur at this point.

6.2.5 Conclusion

Having presented the results of the analysis, we will now summarise and critically discuss the findings of our study.

Our aim in this chapter was to analyse the use of the CM platform in a multi-stage production process. The investigations primarily focused on the evaluation of the computing time behaviour rather than on content analysis. For this purpose, various test scenarios were considered, representing different use cases in which additional quantities of selected representative product types ordered at short notice were to schedule. The investigations were based on provided static real-world data, partly supplemented by reasonable assumptions. The dynamic production data, derived from the underlying production plan, was generated stochastically.

In a first step, we looked at the progression of the optimality gap when solving the SLSP-B-TC-SMR. It became apparent that there is a noticeable difference between large-scale and smaller problem instances. As such, we were able to solve the smaller problem instances optimally in a short amount of time. For the larger problem instances, a proven optimal solution could not be found within the defined time limit in most cases. The best computation time behaviour was yet achieved in the time-based optimisation case. The largest gaps occurred in the cost-based optimisation runs.

To further investigate the influence of varying dynamic production data, we varied the stochastically generated production data in a second analysis. A strong influence on the computation time behaviour could not be detected, however.

In addition to that, we investigated the impact of the two model extensions. Both the SLSP-B-TC and the SLSP-B-SMR, neglecting the secondary material resources and the transport cost extension, respectively, could be solved with significantly smaller gaps, but still mostly not proven optimal within the defined time limit.

In the last analysis, we took a closer look at the LP reformulation. The less complex modelling of the SLSP-LP-SMR/C allowed a fast problem solving with a maximum computation time of less than 1 second throughout all test instances.

Taken together, it was shown that we were able to find feasible solutions for realistic problem sizes with different model variants in an acceptable amount of time. The achieved solution quality depended in particular on the problem size and the model variant used. Especially for the MILP models, it is recommended to keep the problems as small as possible, e.g. by limiting the number of secondary material resources to be considered. However, we would like to emphasise that even a reasonably good solution can result in an improvement over the actual state in practice. It does not always necessarily require the proven optimal solution, especially if only achievable with exorbitant computing times. We therefore believe that the more complex MILP models still provide an acceptable solution quality in a reasonable amount of time to be helpful in a practical context in cases of larger problem instances. On the other hand, if proven optimal solutions are sought in a short time, and the formulated constraints are considered acceptable, the use of the LP reformulation is recommended.

Taking a closer look at the limitations of the different model variants, several aspects are worth mentioning. Firstly, the continuous variables in the LP reformulation, but also the component-related continuous variables of the extended MILP models (SLSP-B-SMR, SLSP-B-TC-SMR) may assume non-integer values making an exact real-world implementation difficult. Simplifying assumptions with regard to the fixed-costs in transport modelling can further lead to the fact that the transport costs are only considered approximately, without any constraint for consolidation. Notwithstanding this, the limitations formulated in the last chapter continue to apply, especially with regard to set-up times, which is particularly of concern in the LP reformulation.

Last but not least, it should be noted that the concrete computation time always depends on the concrete problem structure. Causal relationships are therefore difficult to generalise. Nevertheless, we are confident that the results presented provide a good impression of the computational time behaviour to be expected in different situations.

7 Conclusions

Believe you can and you're
halfway there.
-T. Roosevelt

This chapter summarises the main contributions and outcomes of the thesis and provides an outlook on further research topics.

7.1 Summary

The motivation for this thesis was derived from the fact that there are hardly any planning tools available in practice that enable cross-site coordination at the short-term level. In the event of disruptions, however, this coordination can be beneficial and is even necessary in some cases. Due to the complexity and the resulting manual efforts, though, the network potentials are often not exploited as much as it could be possible. The goal of this work was thus to develop a cloud manufacturing (CM) approach that can be used in internal production networks as a short-term cross-location planning tool allowing for event-based rescheduling in cases of disruptions. The concept is based on the idea of using existing resources (machines and material) in the network, which are offered on a private CM platform together with different forms of transport as services to be used, to generate a short-term ad-hoc value stream that can be integrated into the existing production plans in the network without having to change them. The core aspect of the CM platform is the optimisation problem referred to in the literature as the service selection problem (SSP), which aims to combine the resources offered in terms of time and quantity in such a way that the most suitable value stream possible is generated for the customer placing the order, i.e. the plant affected by the disruption.

In the following, we will summarise the main contributions of this thesis taking into account the defined research segments:

First Segment: As part of the first segment, we looked at how a concept for a private CM Platform can look like, both in terms of its use as an event-based rescheduling tool as well as in terms of its functional aspects. The main results are listed below:

- Building the foundation of the CM platform, we firstly designed a comprehensive data model that captures the real-world requirements for use in an internal production network from a production and transportation perspective, based on the guiding example of a German multinational automotive supplier, the Robert Bosch GmbH.
- On this basis, we then developed a framework that provides guidance on how the platform can be used in different disruption situations, incorporating existing concepts for production-related disruptions. Core aspect of this framework is the distinction between shortfall quantities and excess quantities.
- In the last step, the developed approaches were transferred into a concept for the functioning of the CM platform under consideration of the status quo in the field of cloud manufacturing, which formed the basis for the prototype platform implemented in this work. The concept includes an architectural pattern as well as a specified order processing procedure. Core aspect of this procedure is a multi-stage service composition process, as part of which the SSP is solved.

Second Segment: The main contributions worked out in the context of answering research question 2, which dealt with the modelling of the SSP, are as follows:

- Based on given framework conditions and existing circumstances in practice, we firstly compiled the requirements for the modelling of the SSP. These requirements served as a guideline for a literature research on status quo modelling approaches. As a result of the literature search, it was found that, to the best of our knowledge, there is not yet a lot-sizing-based approach to solve the problem, which served us as a starting point for defining the service-oriented lot-sizing problem (SLSP).
- The SLSP is a big-bucket model aiming to allocate production quantities to available resources on a period-by-period basis, taking into account various transport alternatives and material requirements in order to fulfil a customer order while considering time and cost criteria. We have designed both a basic version of the SLSP as a multi-objective mixed-integer linear program (MOMILP) and a simplified linear programming-based (LP) reformulation. Furthermore, several extension possibilities were presented.

Third Segment: In the last research segment, we looked at how to apply the designed methods and models to a real-world example using the data provided by the considered automotive supplier:

- Based on the example of a single-stage production process, we investigated in a first step the effects of applying the developed models in different machine breakdown scenarios. It was shown that the approach is suitable for practical use. The best results were achieved with short set-up times, as this increases the planning flexibility. In addition, it could be observed that rescheduling to other locations was mostly beneficial when larger volumes were affected. Using the developed concepts in a simplified single-plant approach can therefore already be helpful in cases of smaller volumes, too. These findings were also reflected in a comparison with a heuristic approach oriented towards the successive practical procedure, where it could be shown that the use of the CM platform was worthwhile in most scenarios. In a few cases, though, the heuristic approach outperformed the CM approach, which is why we recommend to consider the successive planning heuristic in the decision-making when reacting to a disruption as well. Another interesting outcome that contradicts the prevailing practice was that direct transports were only preferred in cases of pure time optimisation. In cases where the criteria costs and time were equally weighted, which turned out to be a reasonable alternative, groupage services were predominantly used.

- In a second study, we looked at the computing time behaviour when facing a multi-stage production process using the example of additional order quantities to be scheduled at short notice. As to be expected, the computing time increased with the size of the problem. As such, we were not able to solve larger problem instances proven optimal in an acceptable amount of time. Depending on the application case, however, accepting a feasible good solution still often already provides an improvement over the actual situation in practice. Notwithstanding this, it could be shown that significant computational time improvements were possible both by omitting the model extensions and by using the LP reformulation.
- Both studies also revealed some limitations of the approach. Most importantly, due to the big bucket approach, no sequence-optimal planning is carried out. Especially in the case of long and infrequent set-up operations and in particular with the LP reformulation, this can lead to deviations in the solution quality, as it could be observed in some scenarios in the comparison with the heuristic approach.

Altogether, this work contributes to the literature on cloud manufacturing, both through the lot-sizing-based approach for modelling the SSP as well as by applying the CM concept to an internal network in order to be used as an event-based rescheduling instrument. The second point furthermore provides a contribution to the disruption management literature in the context of production networks. In addition to that, we were able to demonstrate the practical feasibility of the approach. Both in terms of the results obtained and if certain limitations in the model complexity or in the solution quality can be accepted, also in terms of solvability.

7.2 Outlook

After having summarised the results and contributions of the thesis, we conclude this chapter by addressing the boundaries of the work with the purpose of deriving possible research topics for further investigations.

The first aspect to be mentioned relates to the topic of set-up-optimised planning. Due to the big-bucket approach followed, no sequence-accurate planning is carried out within this work, which prevents us from taking into account upstream and downstream set-up states. Considering those set-up states in the optimisation model could be a possible starting point for further work, e.g. by recording the available capacity in the form of time windows with defined predecessor and successor products rather than planning on the basis of period buckets.

Furthermore, a comparison with approaches in which a complete rescheduling of the production plan is carried out, both site-related and across sites, as implemented in the work of Opritescu (2018), for example, would be interesting. In this way, the relationship between rescheduling effort and the resulting system nervousness and solution quality could be worked out more precisely.

In order to improve the solution quality when solving larger problem instances with more complex model variants, further research with regard to the solution algorithm seems to be reasonable. A possible starting point could be to problem-specifically adapt the employed Branch & Cut algorithm.

Likewise, it appears to be interesting to transfer the SLSP to a public cloud manufacturing platform. On the one hand, this results in higher requirements towards the computing time performance as larger networks need to be considered. Addressing the transport planning initially only in a simplified form, as in the LP reformulation, for example, and subsequently optimising the transport network in a separate step may be a promising starting point. At the same time, this is accompanied by changing modelling requirements. Thus, due to the expected higher frequency of planning, online optimisation approaches may provide useful guidance.

In addition, public CM platforms usually assume unknown products, which leads to significant increases in complexity in the upstream requirements engineering and prefiltration steps. The assumption of unknown products can also be transferred to the internal use case, e.g. to plan the production of special parts network-wide at short notice.

From a practical point of view, it is crucial that the required data is available in good quality, which requires interfaces to the company systems, such as the ERP system. Looking ahead, the ongoing digitalisation of production with networked machines and processes within the framework of Industry 4.0 will offer even new possibilities for data provisioning. For example, the machines themselves could recognise their free capacities and offer them on the CM platform to enable automated rescheduling to other machines in the network in the event of machine breakdowns.

Glossary of Notation

Abbreviations

ABC	Artificial Bee Colony	83
ACO	Ant Colony Optimisation	82
API	Application Programming Interface	120
APS	Advanced Planning System	31
BBO	Biogeography based Optimisation	83
BOM	Bill of Materials	21
C2C	Consumer-To-Consumer	3
CAD	Computer-Aided Design	124
CEP	Courier, Express and Parcel Service	40
CLSP	Capacitated Lot-Sizing Problem	71
CM	Cloud Manufacturing	3
CSEP	Composite Service Execution Path	78
FTL	Full Truck Load	39
GA	Genetic Algorithm	83
HTTP	Hypertext Transfer Protocol	120
ILP	Integer Linear Programming	137
IoT	Internet of Things	57
KPI	Key Performance Indicator	5
LP	Linear Programming	6
LSP	Logistics Service Provider	38
LTL	Less Than Truck Load	39
MILP	Mixed-Integer Linear Programming	83

MIP	Mixed-Integer Programming	73
MLCLSP	Multi-level Capacitated Lot-Sizing Problem	73
MOEA	Multi-Objective Evolutionary Algorithm	83
MOLP	Multiobjective Linear Programming	167
MOMILP	Multi-Objective Mixed-Integer Linear Programming	6
MPLSP	Multi-plant Lot-Sizing Problem	73
MPS	Master Production Schedule	29
MRP	Material Requirements Planning	29
MRP II	Manufacturing Resource Planning	27
NSGA II	Non-dominated Sorting Genetic Algorithm	83
OEE	Overall Equipment Effectiveness	101
OEM	Original Equipment Manufacturer	25
PSO	Particle Swarm Optimisation	83
QoS	Quality of Service	77
REST	Representational State Transfer	120
SAW	Simple Additive Weighting	77
SC	Service candidate	61
SCOS	Service Composition and Optimal Selection	77
SFLA	Shuffled Frog-Leaping Algorithm	83
SLSP	Service-oriented Lot-sizing Problem	4
SMR	Secondary Material Resources	170
SMR/C	Secondary Material Resources (only Components)	170
SSOS	Service Selection Optimisation and Scheduling	77
SSP	Service Selection Problem	4
ST	Set-up Time	187
ST	Subtask	61
TC	Transport Costs	170
TQM	Total Quality Management	50

TW	Time Windows based Delivery	170
UML	Unified Modeling Language	122
VDA	German Association of the Automotive Industry	40

Literature Review

a_k	Capacity needed to produce one item of product k	72
$C(S_{i,x_i})$	Resulting costs when performing subtask ST_i with service candidate S_{i,x_i}	78
C_p	Available capacity in period p	72
$d_{k,p}$	Demand for product k in period p	72
h_k	Holding costs per item of product k for one period	72
i	Index of a subtask	78
$I_{k,0}$	Initial inventory of product k	72
$I_{k,p}$	Inventory of product k at the end of planning period p	72
j	Index of a service candidate	78
k	Index of a product	72
M	Large number	72
m_i	Number of service candidates for subtask ST_i	78
$Norm()$	Normalised value	79
p	Index of a period	72
q	Index of a QoS criterion	79
$Q(S_{i,x_i})$	Quality value of service candidate S_{i,x_i} when performing subtask ST_i	78
r	Number of subtasks	78
S_i	Set of service candidates for subtask ST_i	78
s_k	Set-up costs for product k	72

$S_{i,j}$	Service candidate j for subtask ST_i	78
ST_i	Subtask i	78
$T(S_{i,x_i})$	Required time to perform subtask ST_i with service candidate S_{i,x_i}	78
TK	Task	78
$U^C(X)$	Costs of CSEP X	78
$U^Q(X)$	Quality value of CSEP X	78
$U^T(X)$	Time of CSEP X	78
$U^{q,max,0}$	Predefined upper bound of QoS criterion q	80
$U^{q,max}$	Maximum value of QoS criterion q among all possible CSEP X	79
$U^{q,min,0}$	Predefined lower bound of QoS criterion q	80
$U^{q,min}$	Minimum value of QoS criterion q among all possible CSEP X	79
w_q	Weight of a QoS criterion q	80
X	Composite Service Execution Path	78
x_i	Number of the selected service candidate for subtask ST_i in CSEP X	78
$x_{k,p}$	Production quantity of product k in period p	72
$z_{k,p}$	Binary set-up variable of product k in period p	72

Modelling of the CM Platform

α	Weighting of the decision criterion *costs*. The weighting of the criterion *time* results from $(1-\alpha)$	110
$\mathcal{C}$	Set of component types	93
$\mathcal{F}$	Set of finished goods container types	93
$\mathcal{I}$	Set of production steps	93
$\mathcal{J}$	Set of plants	93
$\mathcal{P}$	Set of product types	93

$\mathcal{R}$	Set of production resources . . . 93
$\mathcal{S}$	Set of different period types . . . 93
$\mathcal{T}$	Set of periods . . . 93
$\mathcal{V}$	Set of transport forms . . . 93
$\mathbf{AC}(r,t)$	Available capacity (in minutes) of a resource r in a period t . . . 101
$\mathbf{A}(r,p)$	Approval matrix, indicating whether a production resource r is approved for a product p (1) or not (0) . . . 94
$\mathbf{BC}(j,l)$	Basic costs of a groupage service between locations j and l . . . 98
$\mathbf{B}(i,p,c)$	Number of components of type c that are incorporated in production step i when processing a part of type p . . . 94
$\mathbf{CP}(r,p,s)$	Production cost rate (in $\frac{€}{\text{min}}$) for processing a part of type p on resource r in a period of type s . . . 94
$\mathbf{CS}(j,l)$	Increase rate in transport costs per pallet space when using a groupage service between locations j and l . . . 98
$\mathbf{CT}(v)$	Vehicle cost rate per freight kilometre when using transport form v . . . 98
$\mathbf{CW}(j,l)$	Increase rate in transport costs per freight kilogram when using a groupage service between locations j and l . . . 98
$\mathbf{D}(j,l)$	Distance in kilometres between plant j and plant l . . . 99
$\mathbf{IC}(c,j,t)$	Number of full containers with components of type c being available form period t on at location j in order to be used by the CM platform . . . 105
$\mathbf{IF}(f,j,t)$	Number of empty finished goods containers of type f being available from period t on at

	location j in order to be used by the CM platform	105
$\mathbf{IP}(p, i, j, t)$	Number of full containers with parts of type p, that have passed through production step i, i.e. raw materials ($i = 0$), semi-finished products ($i > 0 \wedge i < I_{max}$) or finished goods ($i = I_{max}$), and which are available from period t on at location j in order to be used by the CM platform	105
$\mathbf{IQ}(p, i)$	Number of full containers with parts of type p being buffered before a production step i	109
$\mathbf{LC}(v)$	Maximum load capacity (in kg) of a vehicle within transport form v	97
$\mathbf{L}(r)$	Plant, in which a production resource r is located	94
$\mathbf{MCC}(c, v)$	Maximum possible number of containers with components of type c per pallet space in a vehicle within transport form v	97
$\mathbf{MCF}(f, v)$	Maximum possible number of empty finished goods containers f per pallet space in a vehicle within transport form v	97
$\mathbf{MCPF}(p, v)$	Maximum possible number of containers with finished goods of a product type p per pallet space in a vehicle within transport form v	97
$\mathbf{MCP}(p, v)$	Maximum possible number of containers with raw materials or semi-finished parts of a product type p per pallet space in a vehicle within transport form v	97
$\mathbf{MCT}(v)$	Minimum cost rate per vehicle when using transport form v	98
$\mathbf{ML}(r)$	Minimum lot size of a production resource r	94
$\mathbf{PB}(s, v)$	Indicates whether transport form v is allowed to be operated in a period of type s (1) or not (0)	99

$\mathbf{PF}(p)$	Finished goods container type assigned to product type p	95
$\mathbf{PH}(t)$	Period type of a planning period t	101
$\mathbf{PP}(r, p)$	Machine batch size when processing parts of type p on a resource r	94
$\mathbf{PSV}(v)$	Number of pallet spaces of a vehicle within transport form v	97
$\mathbf{PS}(r)$	Production step of a resource r	94
$\mathbf{PT}(r, p)$	Processing time (in minutes) per part of type p on production resource r	94
$\mathbf{QC}(c)$	Holding capacity of a container with components of type c	95
$\mathbf{QPF}(p)$	Holding capacity of the finished goods container of product type p	95
$\mathbf{QP}(p)$	Holding capacity of the production container of product type p	95
$\mathbf{Q}(p, i)$	Number of full containers with parts of type p that have passed through production step i ordered on the CM platform	108
$\mathbf{SH}(r, t, p)$	Indicates whether a product p is produced in a period t on resource r (1) or not (0)	101
$\mathbf{SQ}(p)$	Number of full containers with parts of type p being produced less than originally planned during the duration of a disruption in the affected production step	109
$\mathbf{ST}(r, p)$	Sequence-independent set-up time (in minutes) for product type p on production resource r	94
$\mathbf{TE}(p, i)$	Earliest period in which an order with parts of type p that have passed through production step i is allowed to be delivered	110
$\mathbf{TL}(p, i)$	Latest period in which an order with parts of type p that have passed through production step i is allowed to be delivered	110

$\mathbf{TR}(j, l, v, t)$ Actual transport time (in periods) of a transport from location j to location l with transport form v that arrived at location l in period t 130

$\mathbf{TT}(j, l, v)$ Number of periods required for a transport between locations j and l when utilising transport form v 99

$\mathbf{T}(j, l, v, t)$ Actual transport time (in periods) from a location j to a location l when starting in period t when utilising transport form v 130

$\mathbf{WC}(c)$ Weight (in kg) of a full container with components of type c 95

$\mathbf{WF}(f)$ Weight (in kg) of an empty finished goods container f 95

$\mathbf{WP}(p, i)$ Weight (in kg) of a full container with parts of type p after having passed production step i 95

$\tilde{\mathcal{C}}_T$ Tuple, containing the elements of $\tilde{\mathcal{C}}$ ascendingly ordered 127

$\tilde{\mathcal{C}}$ Filtered out set of production resources to be considered during optimisation 127

$\tilde{\mathcal{F}}_T$ Tuple, containing the elements of $\tilde{\mathcal{F}}$ ascendingly ordered 127

$\tilde{\mathcal{F}}$ Filtered out set of finished goods containers to be considered during optimisation 127

$\tilde{\mathcal{I}}_T$ Tuple, containing the elements of $\tilde{\mathcal{I}}$ ascendingly ordered 125

$\tilde{\mathcal{I}}$ Filtered out set of production steps to be considered during optimisation 125

$\tilde{\mathcal{J}}$ Filtered out set of plants to be considered during optimisation 127

$\tilde{\mathcal{J}}_{T \setminus j_0}$ Tuple, containing the elements of $\tilde{\mathcal{J}} \setminus j_0$ ascendingly ordered 127

$\tilde{\mathcal{P}}_T$ Tuple, containing the elements of $\tilde{\mathcal{P}}$ ascendingly ordered 126

$\tilde{\mathcal{P}}$	Filtered out set of product types to be considered during optimisation ... 126
$\tilde{\mathcal{R}_T}$	Tuple, containing the elements of $\tilde{\mathcal{R}}$ ascendingly ordered ... 126
$\tilde{\mathcal{R}}$	Filtered out set of production resources to be considered during optimisation ... 126
c	Index of a component type ... 93
C_{max}	Number of component types ... 93
f	Index of a finished good container type ... 93
F_{max}	Number of finished goods container types ... 93
i	Index of a production step ... 93
i_0	Production step, from which on a rescheduling is to be made ... 109
i_t	Production step, triggering a disruption ... 109
I_{max}	Number of production steps ... 93
i_{max}	Production step, up to which a rescheduling is to be made ... 125
j	Index of a plant ... 93
j_0	Ordering plant ... 110
J_{max}	Number of plants ... 93
l	Index of a plant ... 93
p	Index of a product type ... 93
P_{max}	Number of product types ... 93
$Pos_{\tilde{\mathcal{J}}_{T\setminus j_0}}$	Position of a plant $j \in \tilde{\mathcal{J}} \setminus j_0$ in $\tilde{\mathcal{J}}_{T\setminus j_0}$ ... 127
$Pos_{\tilde{\mathcal{C}_T}}(c)$	Position of component $c \in \tilde{\mathcal{C}}$ in $\tilde{\mathcal{C}_T}$ ... 127
$Pos_{\tilde{\mathcal{F}_T}}(f)$	Position of finished goods container $f \in \tilde{\mathcal{F}}$ in $\tilde{\mathcal{F}_T}$ ... 127
$Pos_{\tilde{\mathcal{I}_T}}(i)$	Position of a production step $i \in \tilde{\mathcal{I}}$ in $\tilde{\mathcal{I}_T}$ ... 125
$Pos_{\tilde{\mathcal{P}_T}}(p)$	Position of a product type $p \in \tilde{\mathcal{P}}$ in $\tilde{\mathcal{P}_T}$ ... 126
$Pos_{\tilde{\mathcal{R}_T}}(r)$	Position of a production resource $r \in \tilde{\mathcal{R}}$ in $\tilde{\mathcal{R}_T}$ ... 126
r	Index of a production resource ... 93

R_{max}	Number of production resources 93
s	Index of a period type 93
S_{max}	Number of different period types 93
t	Index of a period 93
T_{max}	Number of periods 93
v	Index of a transport form 93
V_{max}	Number of transport forms 93

Modelling of the SLSP

ϵ	Small number 147
$\hat{\imath}$	Index referring to a production step i via $Pos^{-1}_{\tilde{\mathcal{I}}_T}(\hat{\imath})$ 125
$\hat{\jmath}$	Index referring to a plant $j \neq j_0$ via $Pos^{-1}_{\tilde{\mathcal{J}}_{T \setminus j_0}}(\hat{\jmath})$ if $\hat{\jmath} \neq 0$ or to the customer j_0 if $\hat{\jmath} = 0$ 127
$\hat{c}$	Index referring to component c via $Pos^{-1}_{\tilde{\mathcal{C}}_T}(\hat{c})$ 127
$\hat{C}_{max}$	Maximum value of index set $\hat{\mathcal{C}}$ 132
$\hat{f}$	Index referring to finished goods container f via $Pos^{-1}_{\tilde{\mathcal{F}}_T}(\hat{f})$ 127
$\hat{F}_{max}$	Maximum value of index set $\hat{\mathcal{F}}$ 132
$\hat{I}_{max}$	Maximum value of index set $\hat{\mathcal{I}}$ 132
$\hat{J}_{max}$	Maximum value of index set $\hat{\mathcal{J}}$ 132
$\hat{l}$	Index referring to a plant $l \neq j_0$ via $Pos^{-1}_{\tilde{\mathcal{J}}_{T \setminus j_0}}(\hat{l})$ if $\hat{l} \neq 0$ or to the customer j_0 if $\hat{l} = 0$ 127
$\hat{p}$	Index referring to a product type p via $Pos^{-1}_{\tilde{\mathcal{P}}_T}(\hat{p})$ 126
$\hat{P}_{max}$	Maximum value of index set $\hat{\mathcal{P}}$ 132

$\hat{r}$	Index referring to a production resource r via $Pos^{-1}_{\tilde{\mathcal{R}}_T}(\hat{r})$	126
$\hat{R}_{max}$	Maximum value of index set $\hat{\mathcal{R}}$	132
$\hat{t}$	Index referring to a planning period with $\hat{t} \in \hat{\mathcal{T}}$	132
$\hat{T}_{max}$	Maximum value of index set $\hat{\mathcal{T}}$	132
$\hat{v}$	Index referring to a transport form with $\hat{v} \in \hat{\mathcal{V}}$	132
$\hat{V}_{max}$	Maximum value of index set $\hat{\mathcal{V}}$	132
λ_k	Weight of objective function k	142
$\hat{\mathbf{AC}}(\hat{r}, \hat{t})$	Available capacity (in minutes) of a resource $\hat{r}$ in period $\hat{t}$	136
$\hat{\mathbf{A}}(\hat{r}, \hat{p})$	Approval matrix, indicating whether a production resource $\hat{r}$ is approved for a product type $\hat{p}$ (1) or not (0)	136
$\hat{\mathbf{BC}}(\hat{\jmath}, \hat{l})$	Basic costs of a groupage service between locations $\hat{\jmath}$ and $\hat{l}$	136
$\hat{\mathbf{B}}(\hat{\imath}, \hat{p}, \hat{c})$	Number of components of type $\hat{c}$ that are incorporated in production step $\hat{\imath}$ when processing a part of type $\hat{p}$	136
$\hat{\mathbf{CP}}(\hat{r}, \hat{p}, \hat{t})$	Production cost rate (in $\frac{€}{\text{min}}$) for processing a part of type $\hat{p}$ on resource $\hat{r}$ in period $\hat{t}$	136
$\hat{\mathbf{CS}}(\hat{\jmath}, \hat{l})$	Increase rate in transport costs per pallet space when using a groupage service between locations $\hat{\jmath}$ and $\hat{l}$	136
$\hat{\mathbf{CT}}(\hat{v})$	Vehicle cost rate per freight kilometre when using transport form $\hat{v}$	136
$\hat{\mathbf{CW}}(\hat{\jmath}, \hat{l})$	Increase rate in transport costs per freight kilogram when using a groupage service between locations $\hat{\jmath}$ and $\hat{l}$	136
$\hat{\mathbf{D}}(\hat{\jmath}, \hat{l})$	Distance in kilometres between plant $\hat{\jmath}$ and plant $\hat{l}$	136
$\hat{\mathbf{IC}}(\hat{c}, \hat{\jmath}, \hat{t})$	Number of full containers with components of type $\hat{c}$ being available form period $\hat{t}$ on at	

	location $\hat{\jmath}$ in order to be used by the CM platform	136
$\hat{\mathbf{IF}}(\hat{f}, \hat{\jmath}, \hat{t})$	Number of empty finished goods containers of type $\hat{f}$ being available from period $\hat{t}$ on at location $\hat{\jmath}$ in order to be used by the CM platform	136
$\hat{\mathbf{IP}}(\hat{p}, \hat{\imath}, \hat{\jmath}, \hat{t})$	Number of full containers with raw materials or semi-finished products of a product type $\hat{p}$ being available for the CM platform from period $\hat{t}$ on at location $\hat{\jmath}$ in order to be processed in a production step $\hat{\imath}$	136
$\hat{\mathbf{LC}}(\hat{v})$	Maximum load capacity (in kg) of a vehicle within transport form $\hat{v}$	136
$\hat{\mathbf{L}}(\hat{r})$	Plant, in which a production resource $\hat{r}$ is located	136
$\hat{\mathbf{MCC}}(\hat{c}, \hat{v})$	Maximum possible number of containers with components of type $\hat{c}$ per pallet space in a vehicle within transport form $\hat{v}$	136
$\hat{\mathbf{MCF}}(\hat{f}, \hat{v})$	Maximum possible number of empty finished goods containers $\hat{f}$ per pallet space in a vehicle within in transport form $\hat{v}$	136
$\hat{\mathbf{MCPF}}(\hat{p}, \hat{v})$	Maximum possible number of containers with finished goods of a product type $\hat{p}$ per pallet space in a vehicle within transport form $\hat{v}$	136
$\hat{\mathbf{MCP}}(\hat{p}, \hat{v})$	Maximum possible number of containers with raw materials or semi-finished products of type $\hat{p}$ per pallet space in a vehicle within transport form $\hat{v}$	136
$\hat{\mathbf{MCT}}(\hat{v})$	Minimum cost rate per vehicle when using transport form $\hat{v}$	136
$\hat{\mathbf{ML}}(\hat{r})$	Minimum lot size of a production resource $\hat{r}$	136
$\hat{\mathbf{PB}}(\hat{t}, \hat{v})$	Indicates whether transport form $\hat{v}$ is allowed to be operated in period $\hat{t}$ (1) or not (0)	136

$\hat{\mathbf{PF}}(\hat{p})$	Finished goods container type assigned to product type $\hat{p}$	136
$\hat{\mathbf{PP}}(\hat{r},\hat{p})$	Machine batch size when processing parts of type $\hat{p}$ on a resource $\hat{r}$	136
$\mathbf{P\hat{S}V}(\hat{v})$	Number of pallet spaces of a vehicle within transport form $\hat{v}$	136
$\hat{\mathbf{PS}}(\hat{r})$	Production step of a resource $\hat{r}$	136
$\hat{\mathbf{PT}}(\hat{r},\hat{p})$	Processing time (in minutes) per part of type $\hat{p}$ on production resource $\hat{r}$	136
$\hat{\mathbf{QC}}(\hat{c})$	Holding capacity of a container with components of type $\hat{c}$	136
$\mathbf{Q\hat{P}F}(\hat{p})$	Holding capacity of the finished goods container of product type $\hat{p}$	136
$\hat{\mathbf{QP}}(\hat{p})$	Holding capacity of the production container of product type $\hat{p}$	136
$\hat{\mathbf{Q}}(\hat{p},\hat{\imath})$	Number of full containers with parts of type $\hat{p}$ that have passed through production step $\hat{\imath}$ to be planned with the SLSP	136
$\hat{\mathbf{SH}}(\hat{r},\hat{t},\hat{p})$	Indicates whether a product $\hat{p}$ is already produced on resource $\hat{r}$ in a period $\hat{t}$ (1) or not (0)	136
$\hat{\mathbf{ST}}(\hat{r},\hat{p})$	Sequence-independent set-up time (in minutes) for product type $\hat{p}$ on production resource $\hat{r}$	136
$\hat{\mathbf{TE}}(\hat{p},\hat{\imath})$	Earliest period in which an order with parts of type $\hat{p}$ that have passed through production step $\hat{\imath}$ is allowed to be delivered	136
$\hat{\mathbf{TL}}(\hat{p},\hat{\imath})$	Latest period in which an order with parts of type $\hat{p}$ that have passed through production step $\hat{\imath}$ is allowed to be delivered	136
$\hat{\mathbf{TR}}(\hat{\jmath},\hat{l},\hat{v},\hat{t})$	Actual transport time (in periods) of a transport from location $\hat{\jmath}$ to location $\hat{l}$ with transport form $\hat{v}$ that arrived at location $\hat{l}$ in period $\hat{t}$	136

$\hat{\mathbf{T}}(\hat{\jmath}, \hat{l}, \hat{v}, \hat{t})$	Actual transport time (in periods) from a location $\hat{\jmath}$ to a location $\hat{l}$ when starting in period $\hat{t}$ utilising transport for $\hat{v}$ 136
$\hat{\mathbf{WC}}(\hat{c})$	Weight (in kg) of a full container with components of type $\hat{c}$ 136
$\hat{\mathbf{WF}}(\hat{f})$	Weight (in kg) of an empty finished goods container $\hat{f}$ 136
$\hat{\mathbf{WP}}(\hat{p}, \hat{\imath})$	Weight (in kg) of a full container with parts of type $\hat{p}$ after having passed production step $\hat{\imath}$ 136
$\hat{\mathcal{C}}$	Index set of $\hat{c}$ with $\hat{c} \in \hat{\mathcal{C}}$ 127
$\hat{\mathcal{F}}$	Index set of $\hat{f}$ with $\hat{f} \in \hat{\mathcal{F}}$ 127
$\hat{\mathcal{I}}$	Index set of $\hat{\imath}$ with $\hat{\imath} \in \hat{\mathcal{I}}$ 125
$\hat{\mathcal{J}}$	Index set of $\hat{\jmath}, \hat{l}$ with $\hat{\jmath}, \hat{l} \in \hat{\mathcal{J}}$ 127
$\hat{\mathcal{P}}$	Index set of $\hat{p}$ with $\hat{p} \in \hat{\mathcal{P}}$ 126
$\hat{\mathcal{R}}$	Index set of $\hat{r}$ with $\hat{r} \in \hat{\mathcal{R}}$ 126
$\hat{\mathcal{T}}$	Index set of $\hat{t}$ with $\hat{t} \in \hat{\mathcal{T}} = \mathcal{T}$ 132
$\hat{\mathcal{V}}$	Index set of $\hat{v}$ with $\hat{v} \in \hat{\mathcal{V}} = \mathcal{V}$ 132
$\tilde{g}$	Aggregated objective function 142
$b^{LP}_{\hat{\imath},\hat{p},\hat{\jmath},\hat{l},\hat{t},\hat{v}}$	Number of full containers ($\in \mathbb{R}_{\geq 0}$) with parts of type $\hat{p} \in \hat{\mathcal{P}}$ that have passed step $\hat{\imath} \in \hat{\mathcal{I}} \cup \{0\}$, and which are being shipped from location $\hat{\jmath} \in \hat{\mathcal{J}}$ to location $\hat{l} \in \hat{\mathcal{J}}$ in period $\hat{t} \in \hat{\mathcal{T}} \setminus \{0\}$ using a groupage service 166
$b_{\hat{\imath},\hat{p},\hat{\jmath},\hat{l},\hat{t},\hat{v}}$	Number of containers with parts of type $\hat{p} \in \hat{\mathcal{P}}$ having passed step $\hat{\imath} \in \hat{\mathcal{I}} \cup \{0\}$ that are to be shipped from location $\hat{\jmath} \in \hat{\mathcal{J}}$ to location $\hat{l} \in \hat{\mathcal{J}}$ in period $\hat{t} \in \hat{\mathcal{T}} \setminus \{0\}$ using transport form $\hat{v} \in \hat{\mathcal{V}}$ 140
$b_{\hat{c},\hat{\jmath},\hat{l},\hat{t},\hat{v}}$	Number of full containers with components of type $\hat{c} \in \hat{\mathcal{C}}$ that are being shipped from location $\hat{\jmath} \in \hat{\mathcal{J}}$ to location $\hat{l} \in \hat{\mathcal{J}}$ in period $\hat{t} \in \hat{\mathcal{T}} \setminus \{0\}$ using transport form $\hat{v} \in \hat{\mathcal{V}}$............ 157

$b_{\hat{f},\hat{\jmath},\hat{l},\hat{t},\hat{v}}$	Number of empty finished containers of type $\hat{f} \in \hat{\mathcal{F}}$ that are being shipped from location $\hat{\jmath} \in \hat{\mathcal{J}}$ to location $\hat{l} \in \hat{\mathcal{J}}$ in period $\hat{t} \in \hat{\mathcal{T}} \setminus \{0\}$ using transport form $\hat{v} \in \hat{\mathcal{V}}$ 158
g	Objective function vector 141
g_1	Cost function of the SLSP 144
g_2	Time function of the SLSP 145
g_k	Objective function k 141
g_k^*	Optimal value of objective function k 141
$H_{\hat{\jmath},\hat{p},\hat{t}}$	Number of containers with finished goods of type $\hat{p} \in \hat{\mathcal{P}}$ being filled in period $\hat{t} \in \hat{\mathcal{T}} \setminus \{0\}$ at location $\hat{\jmath} \in \hat{\mathcal{J}}$ 158
K	Number of objective functions 141
k	Index of an objective function 141
$NP_{\hat{\imath},\hat{p},\hat{\jmath},\hat{l},\hat{t},\hat{v}}$	Number of pallets slots required for transporting parts of type $\hat{p} \in \hat{\mathcal{P}}$ that have passed step $\hat{\imath} \in \hat{\mathcal{I}} \cup \{0\}$ from location $\hat{\jmath} \in \hat{\mathcal{J}}$ to location $\hat{l} \in \hat{\mathcal{J}}$ in period $\hat{t} \in \hat{\mathcal{T}} \setminus \{0\}$ using transport form $\hat{v} \in \hat{\mathcal{V}}$ 139
$NP_{\hat{c},\hat{\jmath},\hat{l},\hat{t},\hat{v}}$	Number of pallet slots required for transporting components of type $\hat{c} \in \hat{\mathcal{C}}$ from location $\hat{\jmath} \in \hat{\mathcal{J}}$ to location $\hat{l} \in \hat{\mathcal{J}}$ in period $\hat{t} \in \hat{\mathcal{T}} \setminus \{0\}$ using transport form $\hat{v} \in \hat{\mathcal{V}}$ 157
$NP_{\hat{f},\hat{\jmath},\hat{l},\hat{t},\hat{v}}$	Number of pallet slots required for transporting empty finished goods containers of type $\hat{f} \in \hat{\mathcal{F}}$ from location $\hat{\jmath} \in \hat{\mathcal{J}}$ to location $\hat{l} \in \hat{\mathcal{J}}$ in period $\hat{t} \in \hat{\mathcal{T}} \setminus \{0\}$ using transport form $\hat{v} \in \hat{\mathcal{V}}$ 158
$NV_{\hat{\jmath},\hat{l},\hat{t},\hat{v}}$	Number of vehicles to be employed to conduct a direct non-stop transport form location $\hat{\jmath} \in \hat{\mathcal{J}}$ to location $\hat{l} \in \hat{\mathcal{J}}$ in period $\hat{t} \in \hat{\mathcal{T}} \setminus \{0\}$ when utilising transport form $\hat{v} \in \hat{\mathcal{V}} \setminus \{1\}$ 139
q	Parameter of the L_q metric 143

$Q^{LP}_{\hat{\imath},\hat{p},\hat{\jmath},\hat{t}}$	Stock of containers ($\in \mathbb{R}_{\geq 0}$) with parts $\hat{p} \in \hat{\mathcal{P}}$ that have passed stage $\hat{\imath} \in \hat{\mathcal{I}} \cup \{0\}$ at location $\hat{\jmath} \in \hat{\mathcal{J}}$ at the end of period $\hat{t} \in \hat{\mathcal{T}}$ 166
$q^{LP}_{\hat{r},\hat{p},\hat{t}}$	Number of full containers ($\in \mathbb{R}_{\geq 0}$) of product $\hat{p} \in \hat{\mathcal{P}}$ to be processed on resource $\hat{r} \in \hat{\mathcal{R}}$ in period $\hat{t} \in \hat{\mathcal{T}} \setminus \{0\}$ 166
$Q_{\hat{\imath},\hat{p},\hat{\jmath},\hat{t}}$	Stock of containers with parts $\hat{p} \in \hat{\mathcal{P}}$ that have passed stage $\hat{\imath} \in \hat{\mathcal{I}} \cup \{0\}$ at location $\hat{\jmath} \in \hat{\mathcal{J}}$ at the end of period $\hat{t} \in \hat{\mathcal{T}}$ 140
$Q_{\hat{c},\hat{\jmath},\hat{t}}$	Inventory stock of containers with components of type $\hat{c} \in \hat{\mathcal{C}}$ at location $\hat{\jmath} \in \hat{\mathcal{J}}$ at the end of period $\hat{t} \in \hat{\mathcal{T}}$ 157
$Q_{\hat{f},\hat{\jmath},\hat{t}}$	Inventory stock of empty finished goods containers of type $\hat{f} \in \hat{\mathcal{F}}$ at location $\hat{\jmath} \in \hat{\mathcal{J}}$ at the end of period $\hat{t} \in \hat{\mathcal{T}}$ 158
$q_{\hat{r},\hat{p},\hat{t}}$	Number of full containers of product $\hat{p} \in \hat{\mathcal{P}}$ to be processed on resource $\hat{r} \in \hat{\mathcal{R}}$ in period $\hat{t} \in \hat{\mathcal{T}} \setminus \{0\}$ 139
$TCD_{\hat{\jmath},\hat{l},\hat{t},\hat{v}}$	Resulting transport costs of a direct transport from location $\hat{\jmath} \in \hat{\mathcal{J}}$ to location $\hat{l} \in \hat{\mathcal{J}}$ in period $\hat{t} \in \hat{\mathcal{T}} \setminus \{0\}$ using transport form $\hat{v} \in \hat{\mathcal{V}} \setminus \{1\}$ 154
X	Feasible set of a problem 141
x	Solution of a problem with $x \in X$ 141
x^{par}	Pareto optimal solution of a problem with $x^{par} \in X$ 141
$x_{\hat{r},\hat{p},\hat{t}}$	Binary variable to $q_{\hat{r},\hat{p},\hat{t}}$ that assumes value 1 if $q_{\hat{r},\hat{p},\hat{t}} > 0$ and 0, otherwise 140
$y_{\hat{\jmath},\hat{l},\hat{t}}$	Binary variable that assumes value 1 if materials are to be transported from location $\hat{\jmath} \in \hat{\mathcal{J}}$ to location $\hat{l} \in \hat{\mathcal{J}}$ in period $\hat{t} \in \hat{\mathcal{T}} \setminus \{0\}$ using a groupage service and 0, otherwise 154

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A Demonstrator

In the following, several pages of the frontend application of the prototypical demonstrator developed in the context of this thesis at the Robert Bosch GmbH are presented. The demonstrator builds on the work of Laensitalo (2020), who implemented the basic framework for communicating on the pilot platform within his master's thesis supervised by the author of this work. The prototype platform was deployed on the Bosch intranet, being accessible via a browser to log in as a production or transport user.

Fig. A.1 shows how a logged-in user of a plant can enter a new order into the platform.

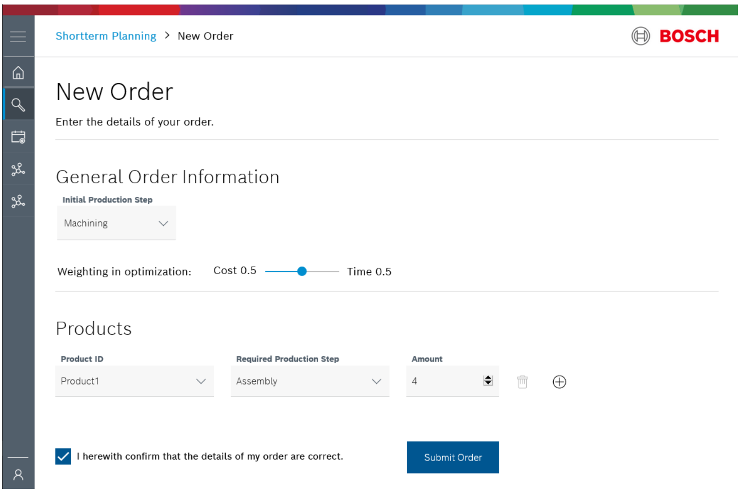

Figure A.1: Entering a new order

Fig. A.2 shows how the calculated production and transport plans are presented to the orderer for selection.

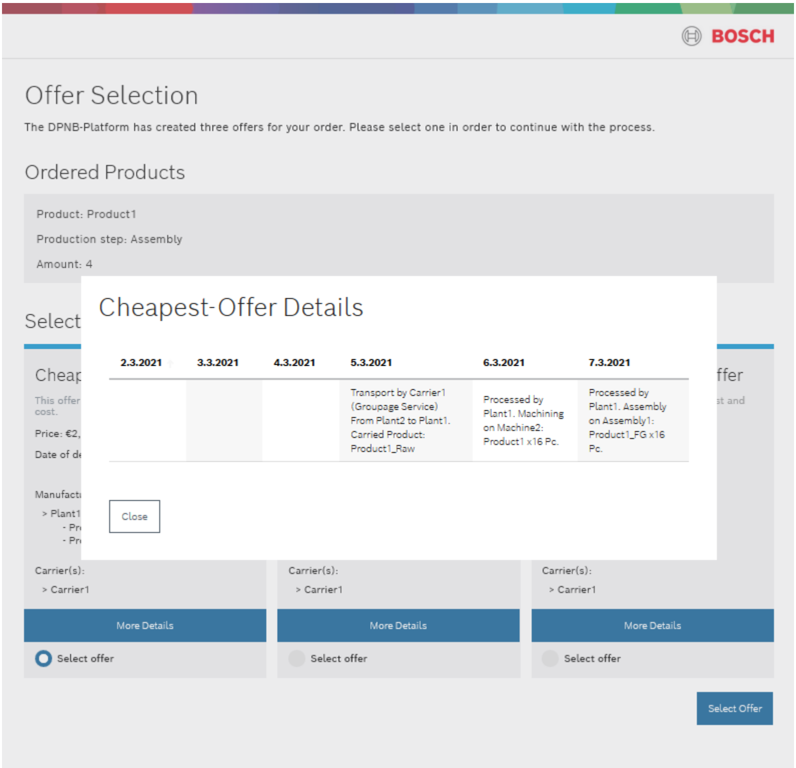

Figure A.2: Presentation of the calculated plans

Fig. A.3 shows how the input data can be maintained via the graphical user interface, using the example of the free capacity data. Likewise, all other static and dynamic production- and transport-related data as well as the basic quantities can be created, changed and deleted by the users.

The plants participating on the platform are able to look at the production orders assigned to them, which is shown in fig. A.4. Similarly, the

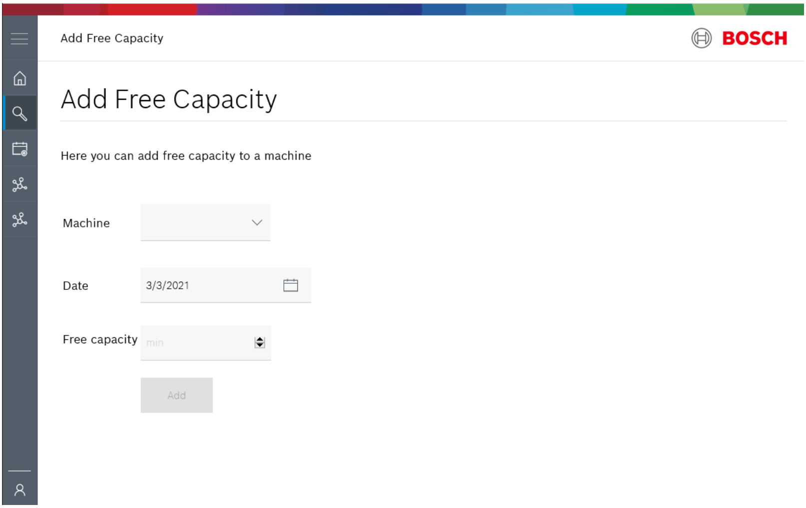

Figure A.3: Maintaining the data

participating freight forwarder receives the transport orders assigned to him and can access the corresponding order details.

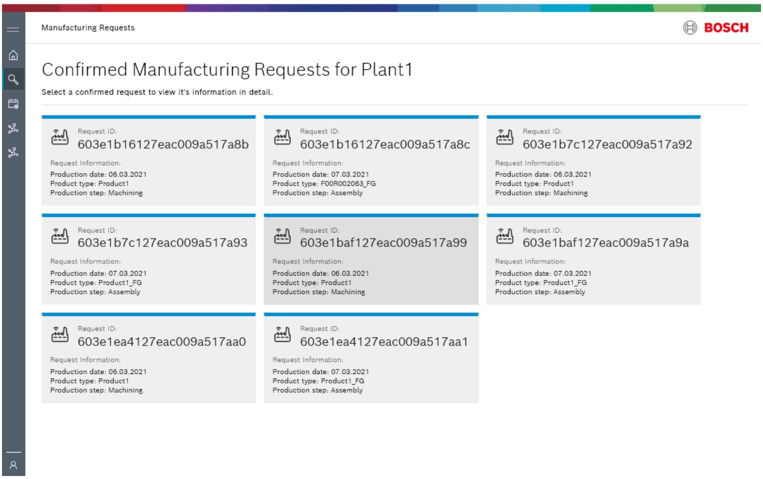

Figure A.4: Production orders assigned to a plant

B Input Data

This section presents the input data used within the case study on the single-stage production process based on data sets provided by the Robert Bosch GmbH and the Transport Betz GmbH.

B.1 Resources

Table B.1 contains the resource-related input data.

r	$\mathbf{L}(r)$	$\mathbf{PS}(r)$	$\mathbf{ML}(r)$	$\mathbf{CP}(r,p,s)$, $s \in \{1,...,6\}$, $p \in \{1,...,17\}$	$\mathbf{CP}(r,p,s)$, $s = 7$, $p \in \{1,...,17\}$
1	1	1	0	1.36	2.31
2	1	1	0	1.36	2.31
3	1	1	0	1.36	2.31
4	1	1	0	1.36	2.31
5	2	1	0	0.45	0.77
6	2	1	0	0.45	0.77
7	2	1	0	0.45	0.77
8	2	1	0	0.45	0.77
9	2	1	0	0.45	0.77
10	2	1	0	0.45	0.77
11	2	1	0	0.45	0.77
12	2	1	0	0.45	0.77
13	2	1	0	0.45	0.77
14	2	1	0	0.45	0.77
15	2	1	0	0.45	0.77
16	2	1	0	0.45	0.77
17	2	1	0	0.45	0.77
18	2	1	0	0.45	0.77
19	2	1	0	0.45	0.77
20	2	1	0	0.45	0.77
21	2	1	0	0.45	0.77
22	2	1	0	0.45	0.77
23	2	1	0	0.45	0.77
24	2	1	0	0.45	0.77
25	2	1	0	0.45	0.77

26	2	1	0	0.45	0.77
27	2	1	0	0.45	0.77
28	2	1	0	0.45	0.77
29	2	1	0	0.45	0.77
30	3	1	0	0.45	0.77
31	3	1	0	0.45	0.77
32	3	1	0	0.45	0.77
33	3	1	0	0.45	0.77
34	3	1	0	0.45	0.77
35	3	1	0	0.45	0.77
36	3	1	0	0.45	0.77
37	3	1	0	0.45	0.77
38	3	1	0	0.45	0.77
39	3	1	0	0.45	0.77
40	3	1	0	0.45	0.77
41	3	1	0	0.45	0.77

Table B.1: Resource-related input data

B.2 Products

Table B.2 contains the product-related input data. Column 2 lists the set of resources r, which are approved for the manufacturing of a product p. Columns 3,4 and 5 record the corresponding processing times, set-up times and machine batch sizes of that set of resources. In the case of several consecutive resource IDs in column 2, we have summarized them by a hyphen notation and accordingly listed them only once in columns 3, 4 and 5.

p	$H_p := \{r \in \mathcal{R} \mid \mathbf{A}(r,p) = 1\}$	$\{\mathbf{PT}(r,p) \mid r \in H_p\}$	$\{\mathbf{ST}(r,p) \mid r \in H_p\}$	$\{\mathbf{PP}(r,p) \mid r \in H_p\}$	$\mathbf{QP}(p)$	$\mathbf{WP}(p,i)$ $i \in \{0,1\}$
1	1,3,9-24,25-27,31,34	2.25,2.25,4.68,3.77,2.25,2.25	200,200,1536,1152,200,200	1,1,1,1,1,1	8	14.3567
2	1	2.367	200	1	8	15.8767
3	1,3	2.0167,2.0167	200,200	1,1	8	15.3167
4	1	2.7167	200	1	8	19.2367
5	1	3.467	200	1	4	15.3967
6	1,2,4,28,29	3.067,3.4167,3.4167,6.2,6.2	200,60,60,768,768	1,1,1,1,1	4	15.9167
7	2,28,29	3.267,5.35,5.35	60,768,768	1,1,1	4	16.9967
8	2,28,29	3.267,6.63,6.63	60,768,768	1,1,1	4	12.0767
9	2,4	3.167,3.167	60,60	1,1	5	20.4967
10	2,9-24,25-27	3.1,5.58,4.1	60,1536,1152	1,1,1	5	17.8967
11	2,4	3.38,3.38	60,60	1,1	5	17.8967
12	3	2.6167	100	1	8	18.63
13	3,9-24,25-27,38,41	2.67,5.58,4.1,2.67,2.67	200,1536,1152,200	1,1,1,1	8	19.7967
14	1,3,5-8	2.167,2.167,2.33	200,200,768	1,1,1	5	11.0967
15	2,4,9-24,25-27,28,29	3.9,3.9,6.78,4.88,6.52,6.52	60,60,1536,1152,768,768	1,1,1,1,1,1	4	25.91
16	4,28,29	3.5,5.8167,5.8167	60,768,768	1,1,1	4	15.9167
17	4	3.25	60	1	4	17

Table B.2: Product-related input data

B.3 Direct Transports

Table B.3 contains the input data on direct transports.

v	Name	**PSV**(v)	**LC**(v)	**CT**(v)	**MCT**(v)	**TT**(j,l,v)
2	Caddy	1	300	0.75	85	$j=1,l=2$: 1 $j=2,l=1$: 1 $j=1,l=3$: 2 $j=3,l=1$: 2 $j=2,l=3$: 1 $j=3,l=2$: 1
3	Transporter	4	1200	1	100	$j=1,l=2$: 1 $j=2,l=1$: 1 $j=1,l=3$: 3 $j=3,l=1$: 3 $j=2,l=3$: 2 $j=3,l=2$: 2
4	Tarpaulin transporter	8	1000	1.25	125	$j=1,l=2$: 1 $j=2,l=1$: 1 $j=1,l=3$: 3 $j=3,l=1$: 3 $j=2,l=3$: 2 $j=3,l=2$: 2
5	7.5-ton truck	15	2100	1.45	185	$j=1,l=2$: 1 $j=2,l=1$: 1 $j=1,l=3$: 3 $j=3,l=1$: 3 $j=2,l=3$: 2 $j=3,l=2$: 2
6	12-ton truck	15	5250	2	245	$j=1,l=2$: 1 $j=2,l=1$: 1 $j=1,l=3$: 3 $j=3,l=1$: 3 $j=2,l=3$: 2 $j=3,l=2$: 2
7	40-ton truck	34	24000	2.5	485	$j=1,l=2$: 1 $j=2,l=1$: 1 $j=1,l=3$: 3 $j=3,l=1$: 3 $j=2,l=3$: 2 $j=3,l=2$: 2

Table B.3: Direct transport-related input data

B.4 Groupage Services

Table B.4 contains the groupage service-related input data.

j, l	$\mathbf{D}(j,l)$	$\mathbf{BC}(j,l)$	$\mathbf{CS}(j,l)$	$\mathbf{TT}(j,l,1)$
1,2	735	432.85	10.97	2
2,1	735	432.85	10.97	2
1,3	1631	534.85	46.68	3
3,1	1631	534.85	46.68	3
2,3	970	573.75	28.60	2
3,2	970	573.75	28.60	2

Table B.4: Groupage service-related input data

B.5 Transport Capacity

Table B.5 contains the input data on the transport capacity derived from the vehicle capacity and the container data provided.

p	$\mathbf{MCP}(p,v)$ $v \in \mathcal{V} \setminus \{2\}$	$\mathbf{MCP}(p,v)$ $v = 2$
1	36	20
2	36	18
3	36	19
4	36	15
5	36	19
6	36	18
7	36	17
8	36	24
9	36	14
10	36	16
11	36	16
12	32	16
13	36	15
14	36	27
15	28	11
16	36	18
17	36	17

Table B.5: Transport capacity-related input data

B.6 Dynamic Data

Table B.6 contains the dynamic input data. The table shows the period types ($\mathbf{PH}(t)$) of the planning periods (first row) as well as the free capacity ($\mathbf{AC}(r,t)$) of the (approved) resources and the product types being produced on them ($\mathbf{H}(r,t,p)$). The values of $\mathbf{AC}(r,t)$ and $\mathbf{H}(r,t,p)$ are displayed together in the same cells separated by a semicolon. To simplify the visualization of $\mathbf{H}(r,t,p)$, we only illustrate the set of products $p \in \mathcal{P}$ for which $\mathbf{H}(r,t,p) = 1$ applies.

B.7 Production Plan

Table B.7 contains the production plan of the lead factory.

r \ t	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
PH_t	1	2	3	4	5	6	7	1	2	3	4	5	6	7	1	2	3	4	5	6	7	1	2	3	4	5	6	7
1	616;6,3	152;1	72;1	72;1	72;1	792	1152	531;2	169;2,5	40;5	60;5	60;5	788	1152	525;5,4	0;4,1	72;1	72;1	72;1	792	1152	432;1	72;1	72;1	72;1	72;1	792	1152
2	35;11	220;11,9	28;9	28;9	28;9	788	1152	584;9	36;10	36;10	180;10,7	191;7,8	776	1152	400;8	41;8	196;8,11	36;11	36;11	779	1152	394;9	28;9	28;9	165;6	0;6	759	1152
3	432;13	72;13	72;13	72;13	72;13	792	1152	432;13	72;13	172;13	0;12	79;12	799	1152	0;14	0;14	0;14	172;13	72;13	792	1152	432;13	72;13	48;13	72;13	72;13	792	1152
4	47;17	229;17,6	0;6	0;6	0;6	776	1152	383;6	0;6	0;6	0;6	0;6	776	1152	575;6	67;16	230;16	47;17	206;15	782	1152	411;15	165;6	0;6	0;6	0;6	776	1152
5	16	16	16	16	16	475	16	16	16	16	16	16	475	814	16	16	16	16	16	475	16	16	16	16	16	16	475	16
6	65	38	0	0	0	357	0	357	0;14	0;14	503	0	357	755	0	0	0	0	0	357	0	0	0	0	0	0	357	0
7	0	0	0	0	0	410	0	0	0	0	0	0	410	792	0	0	0	0	0	410	0	0	1062	0	0	0	410	0
8	0	0	0	0	0	424	189	0	0	0	0	0	357	755	0	0	0	0	0	357	0	0	0	0	0	0	522	0
9	100	100	100	100	100	538	100	100	100	100	100	100	538	889	100	100	100	100	100	538	100	100	100	100	100	100	538	538
10	100	100	100	100	100	538	100	100	100	100	100	100	538	889	100	100	100	100	100	538	100	100	100	100	100	100	538	538
11	49	49	49	49	49	435	49	49	49	49	49	49	435	821	49	49	49	49	49	435	49	49	49	49	49	49	435	49
12	49	49	49	49	49	435	49	49	49	49	49	49	435	821	49	49	49	49	49	435	49	49	49	49	49	49	435	49
13	0;15	0;15	0;15	0;15	0;15	406;15	0;15	0;15	0;15	0;15	0;15	0;15	406;15	745;15	0;15	0;15	0;15	0;15	0;15	406;15	0;15	0;15	0;15	0;15	0;15	0;15	474;15	0;15
14	0;15	0;15	0;15	0;15	0;15	406;15	0;15	0;15	0;15	0;15	0;15	0;15	406;15	745;15	0;15	0;15	0;15	0;15	0;15	406;15	0;15	0;15	0;15	0;15	0;15	0;15	474;15	0;15
15	0	4	4	4	4	435	4	4	4	4	4	4	435	817	4	4	4	4	4	435	435	4	4	4	4	4	435	100
16	47	47	47	47	47	515	47	47	47	47	47	47	387	855	47	47	5	5	5	515	5	5	5	5	5	5	1110	5
17	0	4	4	4	4	435	4	4	4	4	4	4	435	817	4	4	4	4	4	435	435	4	4	4	4	4	435	100
18	0	0	0	0	0	0	0	0	0	0	0	0	415	817	0	0	0	0	0	415	13	0	0	0	0	0	415	13
19	0	0	0	0	0	415	13	0	0	0	0	0	415	750	0	0	0	0	0	415	13	0	0	0	0	0	415	13
20	0;13	0;13	0;13	0;13	0;13	370;13	0;13	0;13	0;13	0;13	0;13	0;13	370;13	761;13	0;13	0;13	0;13	199;13	8;13	437;13	8;13	8;13	8;13	8;13	8;13	8;13	437;13	8;13
21	0;13	0;13	0;13	0;13	0;13	370;13	0;13	0;13	0;13	0;13	0;13	0;13	370;13	761;13	0;13	0;13	0;13	199;13	8;13	437;13	8;13	8;13	8;13	8;13	8;13	8;13	437;13	8;13
22	83	0	0	0	0	415	13	0	0	0	0	0	415	750	0	0	0	0	0	415	13	0	0	0	0	281	415	13
23	83	0	0	0	0	415	13	0	0	0	0	0	415	750	0	0	0	0	0	415	13	0	0	0	0	281	415	13
24	47	47	47	47	47	515	47	47	47	47	47	47	387	855	47	47	5	5	5	515	5	5	5	5	5	5	1110	5
25	0	0	0	0	0	474	662	0	122	47	47	0	818	818	27	27	27	27	68	1152	1152	576	209	209	164	209	455	209
26	0	0	0	0	0	418	0	0	0	0	0	0	919	1152	1152	535	0	0	0	329	0	0	0	287	1152	230	461	461
27	0	576	102	224	0	365	0	845	0	0	0	0	485	818	652	143	0	0	0	385	0	0	518	0	0	0	203	0
28	0	616	0	0	0	437	571	768	986	0	0	0	488	820	0	0	0	0	662	728	0	0	0	0	0	0	421	421
29	0	0	0	0	0	802	1152	768	0	0	0	0	494	853	65	0	0	0	0	550	0	0	0	0	0	210	860	627
31	1152	1152	1152	1152	1152	1152	1152	0	0	0	0	0	1152	1152	1152	1152	1152	1152	1152	1152	1152	1152	1152	1152	1152	1152	1152	1152
34	0;1	0;1	0;1	0;1	0;1	1152	1152	1152	1152	1152	1152	1152	1152	1152	1152	1152	1152	1152	1152	1152	1152	1152	1152	1152	1152	1152	1152	1152
39	1152	1152	0;13	0;13	1152	1152	1152	1152	1152	0;13	0;13	0;13	1152	1152	0;13	0;13	0;13	0;13	0;13	1152	1152	0;13	0;13	0;13	0;13	0;13	1152	1152
41	0	0	0	0	0	1152	1152	0	0	0	0	0	1152	1152	0	0	0	0	0	1152	1152	0	0	0	0	0	1152	1152

Table B.6: Dynamic input data

p	r	t: 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
1	1		400	480	480	480	160										240	480	480	480	160		320	480	480	480	480	160	
2	1								220	300																			
3	1	216																											
4	1															60	190												
5	1									50	210	315	315	105		105													
6	2																									280	345	115	
7	2											165	150																
8	2												135	115		230	340	135											
9	2		240	355	355	355	115		170														230	355	355				
10	2									360	360	130																	
11	2	330	42															30	330	330	110								
12	3											230	410	135															
13	3	270	405	405	405	405	135		270	405	330								330	405	135		270	405	270	405	405	135	
14	3															133	133	133											
6	4		75	270	340	340	110		225	190	190	340	340	110		160								280	340	340	340	110	
15	4																			235	95		190						
16	4																310	255											
17	4	340	196																340										

Table B.7: Production plan of the lead factory

List of Publications

Treber, S., C. Bubeck, G. Lanza (2018). Investigating Causal Relationships between Disruptions, Product Quality and Network Configurations in Global Production Networks. In *Procedia CIRP*, 78, pp. 202-207

Bauer, C. et al. (2021). *Abschlussbericht des Forschungsprojekts "Broker für Dynamische Produktionsnetzwerke"*.
https://doi.org/10.5445/IR/1000141238