Two-Level Capacitated Lot Sizing in Production Control to Guarantee Availability, Considering Multidimensional Restrictions

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For Janet-Lucia

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Abbreviations and Symbols

Sets:

$TM := (TM, \sqsubseteq)$	Time-Periods: Mid-Term Planning
$TS := (TS, \sqsubseteq)$	Time-Periods: Short-Term Planning
CP_p	Set of products which are produced in coupled production with $p \in P$
C	Coils
D	Dies
LE	Loading Equipment
M	Machines
P	Products
$P_{ST} \subseteq P$	Subset of products, relevant for short-term planning
R	Raw Materials
S	Shifts

Parameters and Variables:

$bcM_{m,p,tm} \in \mathbb{N}^0$	Counting variable for completed batches at machine $m \in M$, product $p \in P$ finished during mid-term planning time-period $tm \in TM$
$binS^{mtnc}_{m,p,ts} \in \{0,1\}$	=1, if maintenance of product $p \in P$ is activated in short-term period $ts \in TS$
$binS^{cw}_{m,ts} \in \{0,1\}$	=1, if a coil is being changed at machine $m \in M$ during short-term period $ts \in TS$ (0, otherwise)
$binS^{prod}_{m,ts} \in \{0,1\}$	=1, if machine $m \in M$ is producing during short-term period $ts \in TS$ (0, otherwise)
$binS^{r}_{m,ts} \in \{0,1\}$	=1, if machine $m \in M$ is being set up during short-term period $ts \in TS$ (0, otherwise)
$binmM_{m,p,tm} \in \{0,1\}$	=1, if die for machine $m \in M$, product $p \in P$ is maintained during mid-term planning time-period $tm \in TM$ (0, otherwise)
$binsM_{m,p,tm} \in \{0,1\}$	=1, if set-up is executed to produce product $p \in P$ at machine $m \in M$ during mid-term planning time-period $tm \in TM$ (0, otherwise)
$binsrM_{m,p,tm} \in \{0,1\}$	=1, if a set-up with low effort is executed to produce product $p \in P$ at machine $m \in M$ during mid-term planning time-period $tm \in TM$ (0, otherwise)
$binxM_{m,p,tm} \in \{0,1\}$	=1, if machine $m \in M$ produces product $p \in P$ during mid-term planning time-period $tm \in TM$ (0, otherwise)
bs_p	Batch size of product $p \in P$
btM_{tm}	Break time in mid-term planning time-period $tm \in TM$

chw_p	Charge weight of product $p \in P$
$cM_{d,tm}^{mtnc}$	Maintenance cost of die $d \in D$ in mid-term planning time-period $tm \in TM$
cM^{ir}	Interest rate for capital commitment for a mid-term time-period
$cM_{p,tm}^{prod}$	Production costs of product $p \in P$ in mid-term planning time-period $tm \in TM$
$cM_{p,tm}^{setup}$	Set-up cost average of product $p \in P$ in mid-term planning time-period $tm \in TM$
cM_p^{inv}	Inventory holding costs and capital commitment of a product stored $p \in P$ in one mid-term planning time-period
cM_p^{so}	Imputed stock-out costs for product $p \in P$
cM_p^{w}	Warehousing costs of a product for a mid-term time-period
cM_p^{yw}	Yearly warehousing costs of product $p \in P$
cM^{yir}	Yearly interest rate for capital commitment
$capaLT_{lt}$	Capacity of a loading equipment type $lt \in LE$
$c_{m,p,q,ts}^{setup}$	Sequence-dependent set-up costs at machine $m \in M$ from product $p \in P$ to product $q \in P$ in short-term period $ts \in TS$
$c_{m,p,ts}^{cc}$	Costs for coil changes at machine $m \in M$, product $p \in P$ in short-term period $ts \in TS$
$c_{m,p,ts}^{mtnc}$	Maintenance costs for one short-term period $ts \in TS$ related with a machine and product
$c_{m,p,ts}^{prod}$	Variable machine production costs of product $p \in P$ at machine $m \in M$ during short-term period $ts \in TS$
$cmM_{m,p,tm} \in [0,1]$	Percentage of die maintenance ready for machine $m \in M$, product $p \in P$ is maintained at the end of mid-term planning time-period $tm \in TM$
$cmS_{m,p,ts}^{mtnc} \in [0,1]$	Cumulated progress of maintenance in per cent of product $p \in P$ in short-term period $ts \in TS$ of the rolling horizon
c_p^{inv}	Inventory holding costs and capital commitment of $p \in P$ in one short-term period
$csS_{m,p,q,ts} \in [0,1]$	Set-up progress of a set-up from product $p \in P$ to product $q \in P$ at machine $m \in M$ in short-term period $ts \in TS$ in per cent
c_{ts}^{team}	Cost factor of a set-up team for one short-term period $ts \in TS$
$cwS_{m,p,ts} \in \{0,1\}$	=1, if a coil is currently changed at machine $m \in M$ for $p \in P$ in short-term period $ts \in TS$ (0, otherwise)
$dM_{p,tm}$	Announced demand of product $p \in P$ in mid-term planning time-period $tm \in TM$

$dS_{p,ts}$	Short-term planning demand of product $p \in P$ in short-term period $ts \in TS$
dfM_p	Monthly demand forecast of product $p \in P$
eiM_p	Ending inventory of product $p \in P$ at the end of mid-term planning time-period $n = TM_{max}$ of the rolling horizon
eiS_p	Ending inventory of product $p \in P$ at the end of short-term planning time-period $TM_{max} \in TS$ of the rolling horizon
$fmM_{m,p,tm} \in \{0,1\}$	=1, if die maintenance for machine $m \in M$, product $p \in P$ is finished during mid-term planning time-period $tm \in TM$ (0, otherwise)
$fmS^{mtnc}_{m,p,ts} \in \{0,1\}$	Binary state for a completed maintenance of product $p \in P$ in short-term period $ts \in TS$
$iM_{p,tm} \in \mathbb{N}^0$	Inventory of product $p \in P$ at the end of mid-term planning time-period $tm \in TM$
$iS_{p,ts} \in \mathbb{N}^0$	Inventory of product $p \in P$ in short-term period $ts \in TS$
$lotM_{m,p,tm} \in \mathbb{N}^0$	Lot variable to memorize produced amount of product $p \in P$ until the end of mid-term planning period $tm \in TM$ on machine $m \in M$
$lotS_{m,p,ts} \in \mathbb{N}^0$	Lot that is the cumulative production of product $p \in P$ in short-term period $ts \in TS$ of product $p \in P$ at machine $m \in M$
$maxlot_p$	Maximum lot size of product $p \in P$
$miM_{p,n} \in \mathbb{N}^0$	Missing ending inventory of product $p \in P$ at the end of mid-term planning time-period $n = TM_{max}$ of the rolling horizon
$minlot_p$	Minimum lot size of product $p \in P$
$mlS_{m,p,ts} \in \{0,1\}$	Variable for minimal lot size achievement. =1, if minimal lot size currently achieved at machine $m \in M$ is producing product $p \in P$ in the first short-term period $ts \in TS$ (0, otherwise)
$mpM_{m,p}$	Maintenance progress in per cent of die for machine $m \in M$ in one mid-term planning time-period $t \in TM$
$mstS_{m,p,q,ts} \in \{0,1\}$	Minimal set-up time variable. =1, if a set-up from product $p \in P$ to product $q \in P$ at machine $m \in M$ was finished in short-term period $ts \in TS$ (0, otherwise)
mtM_p	Maintenance time in mid-term periods
$mtnc_p$	Maintenance time in hours
$pptS_{p,m}$.	Products per short-term period for product $p \in P$ at machine $m \in M$
$price_p$	Selling price of product $p \in P$

$prodS_{m,p,ts} \in \{0,1\}$	=1, if machine $m \in M$ is producing product $p \in P$ in short-term period $ts \in TS$ (0, otherwise)
pt_p	Production time in minutes of product $p \in P$
$rS_{m,p,q,ts} \in \{0,1\}$	=1, if machine $m \in M$ is currently being set up from product $p \in P$ to product $q \in P$ in short-term period $ts \in TS$, whereas $p \neq q$ (0,otherwise)
$reS_{m,p,ts} \in \mathbb{N}^0$	Number of completely used steel coils of the actual lot relevant for machine $m \in M$, product $p \in P$ in short-term period $ts \in TS$
$reqLT_{lt} \in \mathbb{N}^0$	Number of required loading equipment entities of type $lt \in LT$
$sS_{m,p,ts} \in \{0,1\}$	=1, if machine $m \in M$ is set up for product $p \in P$ in short-term period $ts \in TS$ (0, otherwise)
$slS_{m,p,ts} \in \mathbb{N}^0$	Slack variable, representing the cumulative quantity of uncompleted batches relevant for machine $m \in M$, product $p \in P$ in the first short-term period $ts \in TS$
$stMin_{p,q}$	Set-up time of product $p \in P$ to $q \in P$ in minutes
stM_p	Average set-up time in hours for product $p \in P$
$st_{p,q}$	Number of short-term planning periods to represent set-up time of product $p \in P$ to $q \in P$
tM_{tm}	Available time-based capacity of mid-term planning time-period $tm \in TM$
$teamLimS_{ts}$	Limit of available set-up teams during short-term period $ts \in TS$
$teamsS_{ts} \in \mathbb{N}^0$	Number of required set-up teams during short-term period $ts \in TS$
udM_m	Maximum degree of utilization of machine $m \in M$
$verbPLT_{p,lt}$	Usage of loading equipment for a product $p \in P$ in loading equipment type $lt \in LE$
$xM_{m,p,tm} \in \mathbb{N}^0$	Production amount of $p \in P$ produced on machine $m \in M$ during in mid-term planning time-period $tm \in TM$
$xS_{m,p,ts} \in \mathbb{N}^0$	Production output of product $p \in P$ at machine $m \in M$ in short-term period $ts \in TS$
$\varpi ReS_{m,p}$	Initialization of the number of completely used steel coils of the actual lot relevant for machine $m \in M$, product $p \in P$ in the first short-term period $TS_{min} \in TS$
$\varpi SlS_{m,p}$	Initialization of the slack variable, representing the cumulative quantity of uncompleted batches relevant for machine $m \in M$, product $p \in P$ in the first short-term period $TS_{min} \in TS$
$\varpi binS_{m,p}^{mtnc}$	Initial maintenance binary state of product $p \in P$ in the first short-term period $TS_{min} \in TS$ of the rolling horizon

$\varpi binxM_{m,p}$	Initial production binary state of product $p \in P$ in the first mid-term planning time-period of the rolling horizon
$\varpi cmS^{mtnc}_{m,p}$	Initial cumulated progress of maintenance in per cent of product $p \in P$ in the first short-term period $TS_{min} \in TS$ of the rolling horizon
$\varpi csS_{m,p,q}$	Initialization of set-up progress of a set-up from product $p \in P$ to product $q \in P$ at machine $m \in M$ in the first short-term period $TS_{min} \in TS$ in per cent
$\varpi cwS_{m,p}$	Initialization of coil change status. =1, if a coil is currently changed at machine $m \in M$ for $p \in P$ in the first short-term period $TS_{min} \in TS$ (0, otherwise)
$\varpi fmS^{mtnc}_{m,p}$	Initial binary state for a completed maintenance of product $p \in P$ in the first short-term period $TS_{min} \in TS$ of the rolling horizon
ϖiM_{p}	Initial inventory of product $p \in P$ in the first mid-term planning time-period of the rolling horizon
ϖiS_{p}	Initial inventory of product $p \in P$ in the first short-term period $TS_{min} \in TS$ of the rolling horizon
$\varpi lotM_{m,p}$	Initial lot of product $p \in P$ in the first mid-term planning time-period of the rolling horizon
$\varpi lotS_{m,p}$	Initial lot of product $p \in P$ in the first short-term period $TS_{min} \in TS$ of the rolling horizon
$\varpi mbinM_{p}$	Initial maintenance binary state of product $p \in P$ in the first mid-term planning time-period of the rolling horizon
$\varpi mlS_{m,p}$	Initialization of minimal lot size achievement. =1, if minimal lot size was currently achieved at machine $m \in M$ is producing product $p \in P$ in the first short-term period $TS_{min} \in TS$ (0, otherwise)
ϖmpM_{p}	Initial maintenance percentage of product $p \in P$ in the first mid-term planning time-period of the rolling horizon
ϖmpS_{p}	Initial maintenance percentage of product $p \in P$ in the first short-term period $TS_{min} \in TS$ of the rolling horizon
$\varpi mstS_{m,p,q}$	Initialization of the minimal set-up time variable. =1, if a set-up from product $p \in P$ to product $q \in P$ at machine $m \in M$ was finished in the first short-term period $TS_{min} \in TS$ (0, otherwise)
$\varpi prodS_{m,p}$	Initialization of production. =1, if machine $m \in M$ is producing product $p \in P$ in the first short-term period $TS_{min} \in TS$ (0, otherwise)
$\varpi rS_{m,p,q}$	Initialization of machine set-up. =1, if machine $m \in M$ is currently being set up from product $p \in P$ to product $q \in P$ in the first short-term period $TS_{min} \in TS$ (0, otherwise)

$\varpi sS_{m,p}$	Initialization of machine status. =1, if machine $m \in M$ is set up for product $p \in P$ in the first short-term period $TS_{min} \in TS$ (0, otherwise)
$\varpi teamsS_{ts}$	Initialization of the number of set-up teams in the first short-term period $TS_{min} \in TS$
tsM	Mid-term period length in hours
tsS	Short-term period length in hours

1 Introduction

Customer satisfaction is of substantial interest for companies, which want to sustain their success.[1] This prioritization determines the targets of production planning and control, as it is a part of corporate planning.[2] Lot sizing and scheduling are related to production planning,[3] especially in multi-variant serial shop fabrication.[4] Due to the influence on lead times, on flexibility and on the adherence to promised delivery dates, lot sizing and scheduling has an impact on delivery serviceability. Despite its importance for productivity, lots and schedules are often planned without using mathematical methods that will guarantee the optimality of the plans.

The basic problem has already been formulated as a mixed-integer linear program known as the Discrete Lotsizing and Scheduling Problem (DLSP)[5]. This formulation cannot, however, be applied in practice[6] as important aspects are disregarded. Dynamically changing customer demands and unexpected events[7] complicate the basic problem. Inventory costs, sequence-dependent set-up costs, time-dependent production costs and so on are further examples of complicating factors. Personnel planning has to be focused as it influences overall costs significantly, especially selecting cheaper shifts for personnel-intensive tasks. Several technical and organizational restrictions in production, like the consideration of sequence-dependent set-up times, batched production, maximum lot sizes and maintenance of dies, make the calculation of feasible solutions more difficult. In this work, a lot sizing approach is presented, which considers all the mentioned as well as further aspects.

Due to the constantly changing environment, it is not useful to spend too much effort calculating detailed lot sizes and schedules for long planning horizons. Accordingly, the relevant operative and rolling planning horizon is split into two consecutive levels: On the first level, rough mid-term production plans are calculated, taking into consideration all the relevant costs and constraints using an extension of the basic Capacitated Lot-

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[1] See e.g. [LG09].

[2] See [Kur11], p.29, or [Paw07].

[3] See e.g. [KS01], pp.40–91.

[4] See [Tem06], p.1 and [AIKTF08], p.110.

[5] See e.g. [Fle90].

[6] The research project was executed in cooperation with a supplier to the automotive industry. Extensions are based on practical circumstances.

[7] In production practice, unexpected events can be machine or die malfunctions resulting in smaller production outputs and capacity reductions.

Sizing Problem (CLSP).[8] For the short-term, the resulting lots are detailed within the next planning level. An extension of the DLSP determines maintenance of the dies, personnel schedules, raw material and loading equipment, as well as procurement and detailed production scheduling, all of which minimize the overall costs.

[8] See e.g. [BY82].

2 Problem Statement / Problem Decomposition

The subject matter of this work is to give appropriate operative production plans which define lot sizes and schedules in capacitated production environments. The considered plant consists of different product stages:

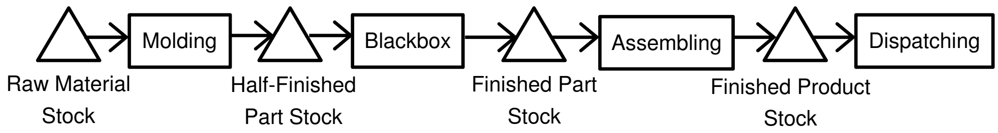

Figure 1: Product Stages

First, supplied raw material is stocked. The raw material is then processed in the molding presses stage. After that, half-finished parts are stocked before they are washed, polished and/or hardened. The need for passing parts through sub-processes as well as the material flow through sub-processes depends on the part. These steps, pooled in the black box (see figure 1), are neglected in this work, as the processing lead times are similar and because of high capacities. After that, finished parts are stocked and later assembled as final products, which are dispatched to the final customer. In this work, the focus is laid on the molding presses stage. The following sections describe the problem in further detail.

As competitiveness can only be sustained by satisfying customer needs, availability of supply is of great importance. The first section is dedicated to describing the obligatory guarantee of availability and characterized customer demands. In order to satisfy demands, several manufacturing resources are required. Being one of the major cost drivers, human resources have to be considered in production plans. Available machines as well as raw material and molding tools, from now on referred to as “dies”, must be used as efficiently as possible in order to produce at minimum cost. Lots and batches underlie constraints induced by production requirements which are described in the restrictions section. Lastly, the problem is broken down into smaller sub-problems that must be solved, and which are detailed in the last section. The goal and the necessities for each sub-problem are outlined. The broken-down problem and solution approaches for the sub-problems constitute the lot sizing concept.

2.1 The Necessity of Guaranteeing Availability to Customers

The long-term goal of manufacturing producing companies is to be successful. In particular, six strategic factors of success or competitive advantages[9] are named in the literature: costs, quality, flexibility, time, product variety and service.[10] An aspect of logistical service quality is the company's ability to deliver the correct amount of ordered products at the agreed time. This becomes more important as customers have higher exigencies towards supply availability due to the request of higher flexibility at low costs in a volatile and competitive environment.

The change from stock-oriented to more flexible just-in-time or even just-in-sequence production,[11] which is induced by the shift from a sellers' to a buyers' market, forces the necessity of coupling production systems[12] along the supply chain in order to fulfill changing customer demands as quickly as possible. An established communication between partners is a precondition for that. The basic interconnection between customers and their suppliers is the transfer of orders. Therefore, orders placed and the way in which they are placed have to be examined.

In particular, this work deals with the production and delivery of parts for the automotive industry. The sample company is a first and second tier supplier which produces seat parts and seat components for cars. The problem properties, which are described in the next sub-sections, can be found at other automotive suppliers and even in different industries. First, the customers' orders are characterized, and then the flexibility is explained and put into contrast with induced costs.

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[9] According to[Sim88], a competitive advantage is a performance which is better than the performance of a competitor if the following criteria are met:

1. The performance has to be an important feature for the customer
2. The performance has to be recognized and realized by the customer
3. It should not be possible for competitors to copy the performance quickly and the performance should be sustainable

[10] See [KB05] (p.6 et seqq.), [KG83] (p.27 et seqq.), [Eid91] or [BGG89].

[11] The main concept of just-in-time production is the initiation of goods and services by a customer order [Dan09] (p.1300). Just-in-sequence production is often considered as an evolution of just-in-time production for a production environment with a high number of variants [TDS9].

[12] The composition of a production system is described in [Dan09](translation): "A production system consists of (elementary) working systems, which represent the smallest unit of a combination of potential factors operating resources and workforce and which can execute one or more classes of transformations."

2.1.1 Characterization of Customer Orders

As the fulfillment of customer demands is a competitive advantage from the viewpoint of an automotive supplier, it is considered in this work and analyzed in the case in question in further detail in this sub-section. Customers of the selected company are Original Equipment Manufacturers (OEM) as well as first tier suppliers. The plant which is being examined delivers its products not only to external customers but also to other plants within the company, called internal customers.

Customer orders[13] are transmitted and updated electronically via the installed Enterprise Resource Planning (ERP) system. This enables the customer to be rather flexible and to change orders quickly. Although there exist long-term forecasts of sales for each product, which are necessary to dimension required capacities correctly, demands vary depending on the final consumer demand. Especially on the mid- and short-term horizon, seasonal reasons, marketing campaigns, stock increments or reductions along the supply chain or other accounts effect fluctuation of demands. This work concentrates on the operative level. A major problem to consider is therefore the satisfaction of altering customer orders with available but limited and fixed capacities at minimal costs on a short-term horizon.

An analysis of customer orders and order changes made some characteristics observable. Demand planning is carried out in a hierarchical way. As stated before, forecasts exist for about two years which serve as a basis for calculating required manufacturing capacities as well as required human resources. The results are input for shorter time-periods. Yearly demand forecasts are apportioned to each month. These calculations are adapted and corrected, applying the expert knowledge of production planners and using statistical methods, so that suitable monthly demand forecasts are available. More problematic are demand forecasts in shorter time-periods. As most customers apply just-in-time or even just-in-sequence principles in their production systems, orders are often modified regarding the amount or/and the exact delivery time due to changes in the customer environment. Relevant information about customer disruption concerning production or supply is not transmitted instantly. The differences between real and forecast orders depend on the time to the planned delivery.

[13] In this work, dependent demands as well as independent demands (see [OLL93] for a description of both terms) are available in the considered production. As the considered stage is at the beginning of the production process, the types do not have to be differentiated.

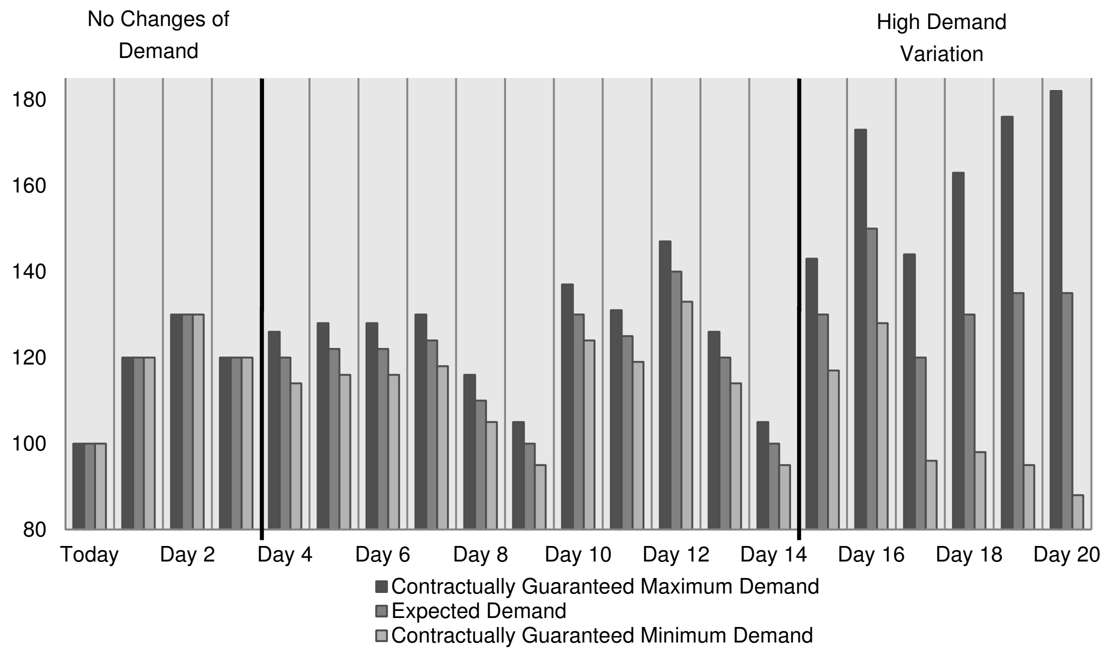

Figure 2: Customer Demand Characterization

The farther away the planned order date, the greater the variance of the exact delivery time and ordered amount. Experience has shown that starting from today orders from day one to three are not changed by the customer and can be considered as fixed. From day four to fourteen, orders change slightly. After that, order time and amount are no longer guaranteed and the production is confronted with high order variation.[14]

As the customer usually does not reveal information about process problems to the supplier but instead asks for just-in-time supply, the supplier has to adapt to this situation. The resulting questions are how the supplier can adapt to such volatile environments and how much the expected flexibility costs.

2.1.2 Flexibility vs. Costs

Due to the development from a sellers' market to a buyers' market, production principles have changed from push to pull. Today, material and products are no longer pushed into production (push principle) but available orders are realized (pull principle). This requires flexibility in production as the equalization of the order inflow with the production plan needs rapid reactions.[15] Automotive OEMs in particular exact accurate and on-

[14] See [Tha97] for a basic description of delivery request systems. See [VDa96], [VDA91] and [VDA96] for further details.

[15] See [Wan05].

time delivery of ordered goods at low costs. This sub-section is dedicated to the problem each supplier has to deal with: the balance between flexibility and costs.

The great number of different definitions[16] is a result of heterogeneous terms and diverse definitions about the dimensions of flexibility and the varied understandings of the delimitations of flexibility stretching to other terms like agility or adaptability.[17] Horváth and Mayer give a definition in the context of manufacturing. They consider flexibility as the ability to advance production in the short term and to keep freedom of action in the long term. As bordering areas like personnel management, finance or purchasing have a great impact on flexibility, they have to be reconciled with production.[18] Schmigalla defines flexibility as the capability of a production system, which is considered to be fixed during a defined time horizon, to adapt to changing requirements induced by the range of products and the technological process without changing the numbers of elements and without changing the structure.[19] Handrich combines two definitions and describes flexibility as the ability to adapt to changed environmental conditions which can occur in the future. Flexibility can generally be described as the ability to change within defined dimensions and scenarios.[20]

A standardized classification of flexibility types in entrepreneurial practice does not exist. Some authors make a classification on a time basis and others classify flexibility types according to system-dependent dimensions. A classification of flexibility types, which also groups the types according their time frame, is given by REFA.[21]

Flexibility Type	Quantitative Description	Time Frame
Flexibility of extension	Effort to make extensions	Long term
Flexibility of adaptations	Effort to make modifications	
Flexibility of products	Number of different component parts, degree of freedom at machine scheduling	Short term
Redundancy of production	Number of alternative means of production	
Flexibility of amount	Restrictions of additional shifts or reduced hours	

Figure 3: Flexibility Types According to REFA

[16] See [SM98].

[17] See [KK05],[KB05].

[18] See [HM86].

[19] See [Sch95].

[20] See [Han02].

[21] See [Rog09].

A classification of flexibility by Sethi and Sethi[22] is made according to system dependent dimensions. Eleven flexibility types are differentiated and scopes of flexibility are identified within group flexibility types.

Scope of Flexibility	Type of Flexibility	Description
Flexibility of component/basis	Flexibility of machine	Variety of operations at one machine without set-up
	Flexibility of material flow	Ability to produce various parts efficiently using different flow paths
	Flexibility of workflow	Possibility of different workflows
Flexibilities of the system	Flexibility of process	Ability to produce various parts without reconfiguration or rebuilding within the system
	Flexibility of process sequence	Possibility of producing a part in different sequences
	Flexibility of product range	Ease of introducing new products
	Flexibility of production quantities	Ability to work economically at different workloads
	Flexibility of extensions	Effort to adapt the flexibility and the ability to work
Aggregated Flexibilities	Flexibility of production program	Stability of the system to produce different variants without changing resources
	Flexibility of production	Variety of production of the system to produce parts without rebuilding but with set-ups
	Flexibility towards market	Ability of the system to react to market changes

Figure 4: Flexibility Types According to Sethi and Sethi

This way of classifying flexibility by means of system-dependent dimensions is also used in a similar classification carried out by Tempelmeier.[23]

Another classification is made by Wildemann,[24] which is based on a differentiation between quantitative, qualitative and time flexibility.

Group	Quantitative Flexibility	Qualitative Flexibility	Time Flexibility
Differentiation	Adaptation to varied quantities and structures	Adaptations to new manufacturing tasks	Time necessary to change production tasks
Characteristics	Ability to - Expand - Compensate - Store	- Versatility, ability to set up - Manufacturing redundancy - Ability to rebuild	- Permissive throughputs - Automated changes

Figure 5: Flexibility Types According to Wildemann

Essentially, most definitions refer to the availability of freedom of action, the availability of freedom for decisions, or the possibility of varying something in conjunction with

[22] See [SS90].

[23] See [TK93].

[24] See [Wil87].

changes.[25] Since uncertainty as well as unpredictable environmental changes overburden the technical and organizational adaptability, it is important to consider the changeability of production systems regarding structure and available resources. All in all, it can be said that flexibility of a production system, which is characterized by its adaptability and changeability to counteract environmental changes, creates and extends the technical and organizational scope for action.[26] The initial generation of flexibility and sometimes the sustainment of flexibility are related to time[27] and consequently to costs.[28] By considering only some aspects of Sethi and Sethi's classification, it is easy to find examples:

1. Flexibility of machine: A machine which can execute a variety of operations without set-up is more expensive than a simple machine designed to do only one task.
2. Flexibility of production quantities: In order to cope with different workloads, capacities of production requirements have to be adapted. Capacity extensions are often related to investments (i.e. machines) and take time. Capacity reductions are also limited as former invested capital is bound up in, amongst other things, buildings, machines or the specialized know-how of the personnel.
3. Flexibility of production program: Changes in the production program influence many entities of the production system. Overall flexibility costs are induced by the sum of the flexibility costs for all influenced entities. If considering, for example, only influenced machines, the sum of adaptation costs has to be calculated.

Flexibility enables adaption to market dynamics, in other words, changing customer demands. Investments in capacities to gain flexibility have to generate an adequate advantage. Instead of obtaining further entities to increase production capacity, the usage of the available ones should be analyzed and improved. A way to improve productivity quickly and with less financial investments is to automate and optimize planning. One goal of this work is to free capacity as a consequence of optimized planning resulting in larger flexibility to satisfy varying customer demands. Another goal is to make deci-

[25] See [Dor86].

[26] See [Rog09].

[27] [Hop89] identifies several types of period for an activity for improving flexibility to take effect. The time to perceive a change is taken into account, as well as the time to decide the activity, to realize the activity and finally the time the activity needs to take effect.

[28] See [Hal99].

sions faster and to reduce the delay time of activities executed as a reaction to changes.[29]

In the next section, requirements which are necessary for production in the considered production stage are described in detail. The flexibility of each requirement is analyzed in order to describe planning decisions' degrees of freedom.

2.2 Restrictions

In [Ame06], a restriction is defined as "Something that restricts; a regulation or limitation." A more precise and suitable definition is given in [Agn02]: "A condition that imposes a constraint on the possible values of a variable or in the domain of arguments of a function." This definition in the mathematical sense is useful for the purpose of this work.

In production there are many technological and organizational aspects which restrict decisions in many dimensions. Restrictions complicate decision making significantly. Without restrictions, it would be easy to satisfy all customer demands in the considered practical case. The required workforce, machines, dies, raw materials and loading equipment mentioned and described are necessary to produce and, consequently, they are also necessary to satisfy customer demands. These resources are not ubiquitous; they are only available in limited amounts. Different flexibility degrees pose a further challenge during decision making, as every requirement has to be considered individually and the interrelation between the requirements complicates the problem. Hence, the availability of resources has to be considered over time. As production does not run without production factors, the consideration of existing limitations of production factors[30] is essential during the preparation or planning[31] of production. Gutenberg[32] characterizes and groups production factors as follows:

[29] See [Hop89] for further details.

[30] Production factors are the inputs of a production [Dan09].

[31] According to [WVW00], "planning is a notional anticipation of future events" (translated). In [Lut], planning is defined as "basic management function involving formulation of one or more detailed plans to achieve optimum balance of needs or demands with the available resources." In [Hah96] (translated), production planning is defined as notional anticipation of future events through a systematic preparation of decisions and a systematic decision taking. It contains the decision process to search, evaluate and choose between solution alternatives to solve a problem in a target oriented way". He further states that planning as well as control are the most important leading and management tasks.

[32] See [Gut83].

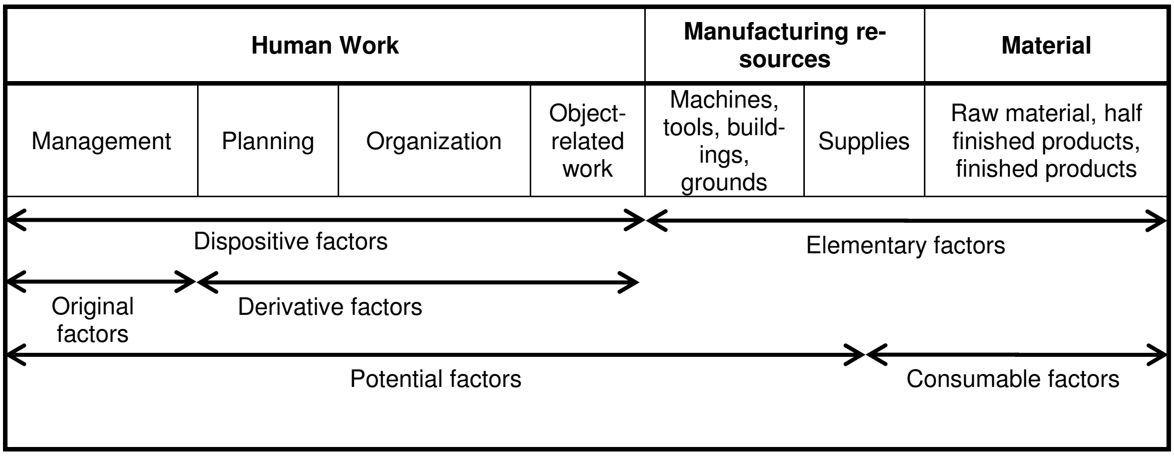

Figure 6: Classification of Production Factors according to Gutenberg

First, production factors can be subdivided into dispositive factors and elementary factors, which have direct influence on the production process. Object-related work directly influences the production process and manufacturing resources as well as raw material. Human work, which is dedicated to management and control of the companies' business processes, is further subdivided by Gutenberg into original factors and derivative factors. The following sub-sections describe those production factors which are relevant for the considered production stage. Starting with a detailed description of the human workforce, the most important manufacturing resources as well as needed materials are described.

2.2.1 Workforce

This section is dedicated to defining and describing relevant problem details about the workforce. Regarding Gutenberg's classification of production factors, planning and object related work is relevant. Beginning with a definition, human work and related processes in the actual practical case are described. Lastly, available flexibility and costs are mentioned and described.

A workforce is "the total number of workers employed by a company on a specific job, project, etc."[33] or "all the people working or available to work, as in a nation, company, industry, or on a project."[34] There exist several other words expressing the workforce in a company. Definitions for personnel are similar: "The body of persons employed by or active in an organization, business, or service"[35] or "persons employed in any work,

[33] See [Agn02].

[34] See [Ame06].

[35] See [Ame06].

enterprise, service, establishment, etc."[36] Another term often used to describe the production factor "Human work" is "Human Resource": the "scarcest and most crucial resource that creates the largest and longest lasting advantage for an organization. It resides in the knowledge, skills, and motivation of people, is the least mobile of the four factors of production, and (under right conditions) learns and grows better with age and experience which no other resource can."[37] For the purpose of this work, there can be found a suitable definition in [Beu96] (translation):"Human work is a potential factor with the inborn and trained ability to do corporal and mental work".

In the case study, different types of workers are necessary in order to keep production running. In this document, only those workforce types are mentioned and described which are relevant to keeping production running on an operative timescale. First, production planners will be described. Production planners are responsible for planning and scheduling production on a specified subset of machines.[38] As production planners possess detailed expert knowledge about products and processes, it is difficult to replace them. Machines are not necessarily compatible with each other. Commutability of planner–machine assignments is therefore impeded. Because of the emerging risk, the resulting dependency of the company on specialized workers is not desirable. In the case study, workers with specialized skills are required to change the dies of the machines. These workers, called machine operators, are assigned to a single machine. Despite comparably expensive working hours, machine operators are not explicitly considered during production planning and scheduling. If the assigned machine is already set up, the machine operator controls the production process, books the number of produced parts and replaces used and empty raw material units. Machine operators also help other machine operators during the die change at their machines. Although the time needed to change dies can be significantly reduced by having machine operators as set-up helpers, it does allow for the planning of parallel changes of dies at different machines. A set-up includes all tasks involved in the changing of one part for another. The used die has to be released and transported to the maintenance department. The new die has to be carried to and mounted on the machine. As a precondition before serial production can start, first a number of produced parts have to be quality checked. Dimensions are measured and compared with specifications. Depending on the part, this is sometimes done by machine operators and sometimes by specialized personnel. In both cases a limited number of measurement instruments are required to do this. Stackers, who are

[36] See [Agn02].

[37] See [Lut].

[38] In the case study, every production planner has to create production plan schedules for between two and six machines.

only needed for bigger or more delicate parts, are another type of worker. Stackers do not have to be highly skilled and their working hours are comparably cheap. They pick up formed parts and put them into boxes. The transport of finished parts to their next process destination is done by forklift operators, who are not studied in this work.

As in many processes where automation using machines instead of humans is not profitable, production often relies on the availability of a workforce. Human work is, compared to the machines and other intangible assets, flexible and tasks for workers can be changed to a certain extent. Nevertheless, human creativity cannot be replaced by machines, and human work is one of the major cost drivers in production. Therefore, induced costs have to be considered and minimized during production planning. Costs of workers basically depend on the workers' experience, responsibilities, and on the work that is carried out as well as on the time and day a worker is deployed. Hourly wages depend on the type of worker. The working hours of stackers, for example, are less costly than the hourly wages of machine operators. Another difference between working types is how costs are treated. Stackers have to be available at the machine for the whole production time. Some parts do not need stackers, as they simply fall into boxes. In the case study, costs for stackers are part of the manufacturing costs of the parts.[39] In contrast, planners, machine operators and measurement personnel are not calculated as direct manufacturing costs at the part level but rather as indirect manufacturing costs. In the long term, it is possible to change labor capacity by dismissing or employing people or by qualifying already available employees. Flexibility regarding labor capacity in the short term can be achieved by using more or less production shifts[40] within given constraints.[41] The day is divided into three shifts[42] and there exist three day types[43] with different cost factors for working hours.

[39] In the case study there exist four cost types for parts: direct material costs, indirect material costs, direct manufacturing costs per piece and indirect manufacturing costs.

[40] Short-term manpower planning on an individual level has to consider legal, organizational and personal aspects which are disregarded in this work.

[41] Labor capacity can be adapted only within defined limits. Long-term employment contracts limit reduction in labor capacity, and required technical schooling and limited availability of appropriate workers restricts an increase in labor capacity.

[42] A shift can be defined as follows: 1. A group of workers who work for a specific period 2. the period of time worked by such a group.[But03]

[43] Shifts in case study: morning shift: 06:00–14:00; late shift: 14:00–22:00; night shift: 22:00–06:00.

	Workday Cost Factor: 1	Sunday Cost Factor: 1.7	Bank Holiday Cost Factor: 2.5
Morning Shift Cost Factor: 1	1	1.7	2.5
Late Shift Cost Factor: 1.1	1.1	1.87	2.75
Night Shift Cost Factor: 1.2	1.2	2.04	3

Figure 7: Cost Factors of Different Day and Shift Types

Besides object-related work, other production factors are relevant. The next sub-sections describe consumable production factors.

2.2.2 Machines

According to Gutenberg,[44] machines are elementary production factors. This sub-section is dedicated to defining and describing relevant problem details about machines. First, a definition is formulated. Then, the elementary production factor itself and related processes in the case study are described. Lastly, the available flexibility and costs are mentioned and described.

> A device that applies force, changes the direction of a force, or changes the strength of a force, in order to perform a task, generally involving work done on a load. Machines are often designed to yield a high mechanical advantage to reduce the effort needed to do that work. A simple machine is a wheel, a lever, or an inclined plane. All other machines can be built using combinations of these simple machines; for example, a drill uses a combination of gears (wheels) to drive helical inclined planes (the drill-bit) to split a material and carve a hole in it.[45]

In this work, the focus is laid on the molding presses production stage. This first stage influences the rest of the production and can be seen as a bottleneck as all products have to be processed at this stage and the available machines are limited in production capacity. The analyzed production depends on the machines as only machines can apply appropriate pressures[46] on the molds to cut and form steel parts. Before production starts, steel coils[47] have to be fixed in the coiler. The machine pressure, production speed and diverse other adjustments have to be carried out by machine operators. Serial

[44] See [Gut83].

[45] See [The05].

[46] Depending on the machine, pressures between 500 tons and 1,500 tons can be applied.

[47] See sub-section 2.2.4 for further details on raw materials.

production can start after checking the quality and dimensions of the part. Every pass,[48] the machine pulls raw material by a defined infeed and applies pressure on the installed die,[49] which cuts and forms the parts. The produced half-finished parts fall onto a short conveyor belt. Bigger or more delicate parts can be picked from there by stacking personnel. Other parts fall directly into boxes. The pass counter is used to determine the number of produced parts. Filled boxes, provided with a control card,[50] are then placed by machine operators in a dedicated space, where they are collected and transported by forklift operators. On each machine, several dies,[51] which have to be compatible with the machine, can be installed. The initial installation of a die on a machine is very time intensive[52] as precision adjustments have to be made by machine operators and maintenance personnel. As the used stamping machines are relatively huge,[53] high investments leading to high capital commitment have to be made. Monetary aspects and limited space impede fast adaptations of available machine production capacity. In contrast to machine-related fixed costs, which are important for making strategic investment decisions but less relevant during operative production planning, variable costs, including amongst other things operating supplies, have to be considered in order to calculate time-dependent production costs.

The sample machine's cost center positions are grouped into four cost categories: primary or secondary variable costs, and primary or secondary fixed costs. The following table shows how these costs are defined in terms of the case study.

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[48] Depending on the machine, on the installed die and on the part which has to be produced, 15–30 passes per minute are possible.

[49] See sub-section 2.2.3 for detailed information about dies.

[50] The control card contains information on the content of a box as well as the next production steps.

[51] In the case study, there are about 10–20 dies assigned to each machine.

[52] As it is not very easy for the initial installation process to be standardized and it is difficult to estimate time for precision adjustments, between two and four shifts have to be reserved.

[53] Depending on the type, machines are about 14m x 4m x 5m in size.

	Variable Costs	Fixed Costs
Primary Costs	- Variable Wages - Variable Personal Extra Expenses - Tools and Dies - Basic and Maintenance Material - Consumable Material - Maintenance - External Labor	- Fixed Wages - Fixed Personal Extra Expenses - Depreciation - Debt service
Secondary Costs	- Energy - Maintenance - Overheads and Management - Maintenance	- Production Planning - Occupancy - Security - Cleaning - Overheads and Management - Further Internal Services - Maintenance

Figure 8: Classification of Cost Factors at Machines

The investments which have to be put into machines are high. It follows that depreciation and debt services are of high relevance in the sample cost center.[54] Consequently, adaptations to available machine capacity are only possible in the long term. Flexibility can only be gained by other means.

Because of the number of produced variants and because of changes to the products and the product portfolio, it is not possible to obtain one specialized machine for each product as this would generate high investment costs and small capacity utilizations. A way of obtaining flexibility in production, at the same time keeping investment costs at a low level, is to assign multiple products to a single machine[55] using different dies. Although there are machines which are constructed in the same way, they are not identical. Thus, time-intensive initial precision adjustments of dies are machine-specific. Consequently, machine-die assignments are set on a mid-term time horizon and considered as fixed for operative planning. The production speed, in this case expressed by passes per minute, is also set during the initial installation of a die on a machine. The production speed has an upper limit. Higher speeds result in lower quality of parts.

To sum it up, the capacity of a single machine can be flexibly shared so that multiple parts can be produced on one machine in a limited way. Considering flexibility types by Sethi and Sethi,[56] the described machines match with different ones. There is a certain

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[54] In the case study, primary and secondary costs are nearly equal. More than 50 % of the primary costs consist of depreciation and debt service of the machine. The next highest primary costs are maintenance costs and costs for basic and maintenance material. The sum of variable and fixed personal expenses is about 10 % of the total primary costs. The sum of overheads and management, maintenance and occupancy costs set 75 % of secondary costs. The sum of energy, production planning and further internal service costs are about 20 % of total secondary costs.

[55] Twenty to forty products are assigned to one machine in the case study.

[56] See [SS90].

flexibility of product range, as several products can be produced on one machine. Quantities can be adjusted to a limited extent (flexibility of production quantities). Extensions can be installed using new dies that are compatible with the machine (flexibility of extensions) and new parts can then be produced (flexibility of program / flexibility of production). Capacity adaptations are possible to a limited extent. These enable machines to adapt towards market changes (flexibility towards market). Other flexibility types, like machine, material flow and workflow, process or process sequence flexibility are not available from the considered machines. In order to be able to produce different products on a single machine, exchangeable dies are required. In the next sub-section, dies are defined and described in further detail.

2.2.3 Dies

Other elementary production factors are the dies. In this section, it is explained what dies are. Further, it is described which production processes require a die and it is clarified which restrictions exist.

In the [Ame06], a die is defined as “a device used for cutting out, forming, or stamping material.” The definition is specified by further explanations describing what a die is. A die is “an engraved metal piece used for impressing a design onto a softer metal, as in coining money”; “one of several component pieces that are fitted into a diestock to cut threads on screws or bolts”; “a part on a machine that punches shaped holes in, cuts, or forms sheet metal, cardboard, or other stock”; or “a metal block containing small conical holes through which plastic, metal, or other ductile material is extruded or drawn.” In [Agn02] a die is defined as “a shaped block of metal or other hard material used to cut or form metal in a drop forge, press, or similar device” or “a tool of metal, silicon carbide, or other hard material with a conical hole through which wires, rods, or tubes are drawn to reduce their diameter.” From the perspective of the case study, the first definition fits in particular. In this case, the die is a device for cutting out, forming and stamping metal.

For forming and shaping parts out of steel, exchangeable dies are used. As dies[57] allow the production of several parts by a single machine, and as they are as cost-intensive as a whole machine, usage provides the ability to cope with product variety. Nevertheless, investments have to be done to construct a new die with a mold to form and shape parts.

[57] The dies used in the case study are about 8.5m x 2.5m x 2m in size and can weigh up to 10 tons.

One die can produce either two or four identical parts, or two or four different parts.[58] The dies used are multi-stage dies which complete several process steps or stages[59] in succession without any buffers between each stage. The raw material is transformed into half-finished parts, which only need to be washed, polished, and/or hardened. Each sub-stage of a die is responsible for a part-specific transformation. Raw material is cut and formed according to part specifications. Oil is used during the cutting process in order to cool the material and the die, to improve the quality of the cuts and to reduce abrasion of the dies' molds and tools. Each stage has to be considered during initial precision adjustments when a die is firstly installed on a machine as well as during adjustments after setting up the die on its standard machine. That is the reason for the long set-up and adjustment times.[60] Initial precision adjustments have to be finished by people in the maintenance department together with machine operators. Regular set-ups of dies can be completed by machine operators. Two different types of set-ups can be differentiated: internal set-ups and external set-ups. Internal set-ups are completed in the machine. That means that both halves of the die remain installed in the machine during the changing of molds and/or tools of the die. Internal set-ups are only possible if the set-up's starting part and the target part use the same base and the set-up can be completed by simply changing some molds and/or tools. Alternatively, a set-up is completed externally. An external set-up is carried out by uninstalling the whole die from the machine. Molds and/or tools are changed outside the machine, which requires use of a set-up table whose availability is limited.[61] Whereas internal set-ups block the machine during the whole set-up time, production can continue during external set-ups. Nevertheless, internal set-ups applied to similar parts can reduce adjustment times. Besides the set-up table, further resources are needed during set-up like the crane for the dies and the measuring room as well as measuring personnel for first part checks. Set-up times are sequence-dependent, obeying the triangle inequality.[62] The sequence of production therefore has an influence on the loss of production capacity, personnel costs for set-ups and the usage of previously named shared set-up resources. The dies' cutting compo-

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[58] In the case study, if different parts are produced, they always have a certain relation to each other during the next production steps. Usually the left-hand part and the right-hand part are produced simultaneously with a single die, in the knowledge that both parts will later be needed simultaneously.

[59] According to the classification of manufacturing methods presented in [Dan09] (p.300), the process steps of the multi-stage dies in the case study are different types of metal forming and cutting. Surfacing, modification of material properties and assembling of parts is carried out in separate machines in further process steps as described at the beginning of chapter 2.

[60] Regular set-ups on the standard machine take 1.5–8 hours.

[61] A set-up table is a special piece of equipment which is used to prepare dies outside the machine.

[62] The triangle inequality for set-ups states that a set-up from a to b to c always takes more time than a direct set-up from a to c. For detailed geometrical explanations see [KK01] chapter 1.3.

nents and tools for foraminating steel become frayed,[63] so they have to be maintained. During maintenance, the components of the dies are replaced, polished or sharpened. Maintenance is carried out every time the die is dismounted from the machine.

The use of exchangeable dies enables the sequenced production of multiple products on a single machine and facilitates savings in machine investments. Nevertheless, dies also have to be designed, built and the initial sample inspection has to be done, which is related to costs.[64] The investment expenses impede the stocking up of a number of alternative dies for a product. Hence, operational flexibility is reduced due to the required maintenance of dies, which takes several days.[65] In some cases, dies can be adapted by changing only some tools or molds in the die in order to produce similar products. This is done to reduce initial investments for dies but reduces flexibility as one base die is used for more than one product and maintenance intervals have to be considered for all produced products. Although in this case only some components of the die have to be replaced, the machine is blocked for several hours if set-up is done internally.

2.2.4 Raw Material

Raw material is a consumable production factor. In this section, raw material is defined and described. Only relevant processes which are related to raw material are described. After that, costs and flexibility aspects of raw material are described.

There exist several definitions for raw material. “Basic substance in its natural, modified, or semi-processed state, used as an input to a production process for subsequent modification or transformation into a finished good.”[66] In [Agn02], raw material is defined by two alternatives: “material still in its natural or original state, before processing or manufacture” or “anything that is capable of being processed, converted, changed, etc. to produce something else.”[67] Another two different definitions are as follows: “an unprocessed natural product used in manufacture” or “unprocessed material of any kind.”[68] As the raw material in this case is already processed and the steel is not in its natural or original state, none but the first definition can be applied. In this case, raw material is a basic substance used as an input to a production process for subsequent transformation.

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[63] In the case study, dies have a durability of approximately 50,000 parts.

[64] In the case study, dies cost between €500,000 and €2,000,000.

[65] Maintenance of one die takes three days in the case study.

[66] See [Lut].

[67] See [Agn02].

[68] See [Ame06].

The most important raw material for the analyzed production is steel. In this case, it is delivered in coils of band steel.[69] Other operating supplies, like oil, energy or cleaning supplies are not considered in this work. Depending on the part, different steel types of different compositions and dimensions[70] are required for production. Raw material is ordered one year in advance, depending on demand forecasts. The supply of material is guaranteed within contractually defined increases or decreases of demands within a definite time horizon. The time between order and delivery on an operative timescale is one day. In the case study, a local inventory covering the next three days of production is sufficient to guarantee supply availability in the short term. The required steel has to be transported on a crane driven by a machine operator to the machine which is running out of raw material. Some machines have a dedicated space where the next steel coil can be placed some time before it is needed. If this is the case, the change can be executed fluently without the disruption of other machines running out of steel at the same time. The raw material unit is then put into the decoiler, and fixed and adjusted to the machine. During the fixing stage,[71] the production at the machine has to be stopped. Because of relatively small tolerances of the steel, production can usually continue as before. In exceptional cases, a die cannot be adapted to the used steel coil. Then, the coil has to be replaced, if possible. Removal of a steel coil from the decoiler is very dangerous as the high tension force of the furled band steel is difficult to control and can seriously injure workers. Another reason to avoid coil removal is that there is a possibility that removed raw material can no longer be used. Problems during the fixing stage of a previously used steel coil occur especially if the size of the coil falls below 50 % of the maximum diameter. The unusable raw material has to be scrapped. Very important for the stamping process is that the composition, thickness and width of the used band steel are always within defined tolerances. Variations in the length of the coiled band steel and variations of the coil weight are not important for product quality. But these variations influence the output of one coil regarding the amount of produced parts without changing the coil.

As the half-finished parts after the stamping presses are at the beginning of the value chain, raw material costs make up a major percentage of the value of the parts. In the present case study, between 60 % and 85 % and an average of 77 % of the half-finished part value consists of raw material costs. The cost structure of the parts cannot be changed due to lot size planning. In the considered case, only two of the 16 used raw material types are shared among six parts. Hence, the usage of alternative raw material

[69] About 10 steel suppliers deliver requested, specialized steel.

[70] In the case study, steel is between 0.8 cm and 1.5 cm thick and between 31.3 cm and 65.7 cm wide.

[71] The changing of the coil including required tasks takes about 15 minutes.

for the production of a part is constrained because of this technological restriction. Without flexibility in raw material sharing among different products, lot size planning has only a very small influence over improving the availability of half-finished parts whenever raw material is missing. The supply of raw material is a precondition for production. Although the costs for raw material and the proportion of raw material costs to the half-finished part costs cannot be reduced by lot size planning, scrap can be reduced if production batches and lots consider the coil size. The availability of raw material can also be improved by giving production plans in advance.

2.2.5 Loading Equipment

Loading equipment, that is, the boxes or cases used in production, is part of the supplies. As loading equipment is also relevant, this section is dedicated to describing the loading equipment used and to explain relevant related processes. Costs and flexibility of loading equipment are described as well.

There exist different types[72] of loading equipment. Depending on the stamped part and subsequent processes, a specific loading equipment type is chosen. Box types with different capacities can be classified into four major groups: small boxes, medium boxes, large boxes[73] and non-returnable cardboard boxes, whose size will not be distinguished any further. First, the selection of the box type depends on the size of the produced part. Stability of the parts restricts the amount of parts put into one box as well as the way boxes have to be filled. Small, stable parts can fall into boxes, whereas others have to be picked from the belt by stackers and put into cushioned boxes in separated layers. Other boxes are filled with parts by robots. The subsequent process steps of the parts also influence the type of loading equipment used. The most important example is parts which are transported to internal or external customers overseas. As the return of empty boxes takes too much time and is costly, only non-returnable cardboard boxes are used. Another example is that some parts have to be cleaned of the oil used to improve the stamping process. These parts often pass through the washing system inside the boxes, with the consequence that the varnish of the boxes is damaged. It is therefore preferred to use boxes without varnish for these parts.

The following table summarizes the main part-loading equipment type relations.

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[72] About six different types of relevant loading equipment are used.

[73] Depending on the used loading equipment, between 130 and 3,000 parts are bundled into one loading equipment unit.

Part Properties		Small Box	Medium Box	Large Box	Non-returnable cardboard box
Size	Stability				
Small	Damageable	X	(only with inlays)		All (Overseas Destinations)
	Stable		X	X	
Large	Damageable			X	
	Stable			X	

Figure 9: Loading Equipment Mapping according to Part Properties

Boxes become oily and dirty over time. Dirty loading equipment deteriorates the quality of the contained parts. Consequently, boxes have to be cleaned. As the cleaning process is outsourced in the case study, lead and transport times have to be considered when guaranteeing availability of the correct boxes at the desired time.

Because of part properties, it is not possible to use every loading equipment type for every part. Flexible substitution of loading equipment types is impeded. The flexible use of different loading equipment types is also reduced by successive processes. As described before, parts with overseas destinations have to be packed into non-returnable loading equipment and parts to be washed should be placed into boxes without varnish. Investments needed in loading equipment are much less than for dies or machines. Nevertheless, fixed capital has to be minimized. The limited available space required for loading equipment is also a problem, reducing the possibility of reserving large amounts of loading equipment of every type. Besides investment costs for loading equipment, other costs are relevant for loading equipment including loading equipment management costs, cleaning and loading equipment maintenance costs. These costs are not dependent on production planning. Therefore, they can be disregarded in this work.

2.2.6 Batches

According to [Ame06], a batch is “an amount produced at one baking” or “a quantity required for or produced as the result of one operation.” The most suitable definition, in [Agn02], states that a batch is a “group or set of usually similar objects or people, especially if sent off, handled, or arriving at the same time.”

The molding presses production stage considered has restrictions regarding batch sizes produced. As the changing of steel coils reduces the time available for production the changing of coils should be avoided when they are not completely used. Another reason is the danger posed to workers, due to the steel coils’ tension force, if they have to change a coil which has not been completely used. Consequently, the batch size is defined by the size of the coil currently used. The exact amount of parts which can be produced with one coil can only be estimated by dividing the coil weight by the charge weight of the part which has to be produced. In coupled production, the charge weight of all simultaneously produced parts has to be taken into account. Although inevitable small variations of the material fall within part production tolerance margins, they accumulate and influence the output amount of one coil. Consequently the exact production output and also the exact production time for one batch can only be estimated. In practice, the average coil size is calculated for planning production output and time and this is precise enough to estimate batch production ends. On the basis of the estimated production output and time, a batch-wise production can be planned, in which productivity reductions due to coil changes, the estimated time of a coil change, and required raw material units, can be planned.

2.2.7 Lots

Among other definitions, the [Ame06] defines a lot as “Miscellaneous articles sold as one unit.” This definition is not appropriate for the purpose of this work. A precise definition for a production lot, which is suitable for this work, can be found in [Dep01]. There, a lot is defined as “Specifically, a quantity of material all of which was manufactured under identical conditions and assigned an identifying lot number.”

Lot sizes at the considered molding presses production stage have to obey restrictions as well. The smallest lot size is defined by the smallest possible batch size which is in turn estimated using average coil sizes. As the production is executed batch-wise, lot sizes can only be integer multiples of raw material units, that is, the coils. The maximum lot size depends on the die’s lifespan. In order to keep the quality of the parts high and to prevent broken dies, the number of produced parts is limited. This number defines the maximum lot size. Since in some cases different parts use the same die, the sum of the cumulated production quantity for all these parts has to obey the maximum lot size. In other cases, different parts are produced simultaneously in coupled production. In this case, the cumulated production has to be considered separately, although both parts are using the same die. This is because the parts produced in coupled production use different cavities of the die. These cavities are frayed equally during production and not additionally. As the maintenance of the dies has great influence on the lot restrictions, different applicable maintenance trigger methods have to be taken into account. The first alternative would be to start maintenance just after dismounting a die from the machine after production. Another possibility is to carry out maintenance on the die before the defined maximum lot size is about to exceed. In this case, the cumulative production quantity has to be memorized between productions. The cumulative production quantity is in both cases reset during maintenance.

Apart from restrictions induced by raw material and die maintenance, set-ups have to be considered. Required times for set-ups are mainly influenced by the changing of the dies. A set-up consists of two main tasks: the changing of the die and the adjustment of the die. The changing of the die comprises the provision of required set-up material, including the new die, the dismounting of the installed die, the mounting of the new die and the removal of the old die and set-up material. The set-up and adjustment effort depend on the sequence of mounting the dies on the machine. As described in section 2.2.3, times depend on whether set-ups are executed internally or externally, too. As follows, set-up times are sequence dependent. In 2.2.1, it was described that skilled, specialized personnel are needed to carry out the set-ups. The limited availability of these personnel has to be taken into account during the definition of lots.

In summary, the lots' starting and ending times depend on the workforce and machine capacities, the sequence-dependent set-ups of dies, the dies' lifespans, and die maintenance, as well as the size of raw material units.

2.3 Two-Level Capacitated Lot Sizing in Production Control

Changes in the production environment on an operative timescale, especially changing customer demands,[74] make it senseless to define detailed production schedules for the long term. In order to cope with decision complexity and speed up planning, the calculation effort is reduced by splitting the planning horizon into time-based levels. Being a flexible but also costly resource, the production factor of human work is considered within both planning levels on a different level of detail. Depending on the planning level, requirements and related restrictions are considered in different ways. The following two sub-sections describe how the two planning levels are defined and separated in practice. It is also described which decisions on the basis of which data have to be taken at each level and which of the formerly described restrictions have to be considered.

2.3.1 Mid-Range Level

On an operative time-horizon, there are still many decisions to be taken which have a great impact on the success or failure of satisfying customer demands at minimal costs. Because of changing customer demands and other changes in the production system,

[74] See 2.1.1 for a detailed description of how customers make their orders.

like inventory differences due to rejections or refinishing operations, a planning horizon of two weeks is enough to guarantee the availability of required production factors.

Today, planners consider different input data to define production lots and schedules. First, monthly demand estimates, which are generated by program planners with yearly demand forecasts and customer contracts, are considered. The use of monthly demand estimates to plan production lots for the next two weeks guarantees that demand changes on a tactical time horizon are regarded during lot sizing. Product start-ups or run-offs or seasonal demand fluctuations can easily be managed. Although demand estimates do not meet short-term customer demands, they enable production planners to create plans which can satisfy customer demands with higher success. Secondly, production planners consider the declared customer orders of the next two weeks, which are fixed with small tolerance margins.[75] At the mid-range planning level it is decided which amount of which part is produced on which day during the next two weeks in order to fulfill customer demands. Production lots of parts which are personnel-intensive are ideally positioned in those days[76] which are cheaper in terms of workforce costs. The capacity of machines limits the production amount per day whereas different production speeds of different parts are taken into account. The availability of the dies, which is first and foremost determined by maintenance, is also planned. Maintenance intervals and maximum lot sizes restrict planners' decisions. Planned lots already have to be dimensioned in a way that enables complete coils to be used. Otherwise, the capacity utilization as well as the produced amounts would not be calculated correctly and the plans would not be suitable for practice. With determined production amounts for the whole mid-range planning horizon, it is possible to order the required amounts of raw material coils. The disposition of loading equipment depends on the information about production amounts and times defined by production planners, as loading equipment has to be cleaned of residual oil and dirt before usage, which takes time.[77]

The mid-range planning horizon slides forward every day by one day. This rolling planning horizon scheme guarantees that changes in the production environment are properly taken into account.[78] On the basis of the calculated mid-range planning results, a detailed short-range scheduling is carried out. Since the results of the mid-range planning, that is, the production lots, take capacity restrictions into account, it can be guaranteed

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[75] See 2.1.1 for a detailed description of customer demands and contracted change tolerances.

[76] See 2.2.1 for a chart of shifts' cost factors.

[77] As in the case study, cleaning is carried out by a specialized company, and loading equipment has to be transported, both of which take time. See chapter 2.2.5 for details.

[78] One alternative to a continuous rolling planning horizon scheme is a connected planning scheme. A description of both concepts can be found in [Ste07].

that short-range planning tasks are feasible. The next sub-section describes the decisions made for the short-range planning horizon and which data are used to determine production schedules.

2.3.2 Short-Range Level

As detailed lot sizing and scheduling is complex and takes time, it is not practicable to create plans far in advance, which then have to be recalculated every time something affecting the production changes. Hence, detailed planning is only used for a time horizon where as many parameters as possible are fixed. In this case, the contractual fixing of customer demands for the next three days is a suitable limitation for a detailed planning horizon.

A plan generated for this short range of three days has to take into account all the restrictions that the mid-range planning considers, plus those restrictions which are necessary to calculate feasible detailed schedules. First, there are the workforce restrictions and costs. In contrast to mid-range planning, where workforce distribution is done on a daily basis, short-range plans are able to allocate the workforce to smaller time units. Cost differences for shifts have to be taken into account. The usage of the limited machine production capacity is calculated for the short-range level to a higher level of detail, taking the same parameters into account as in mid-range planning. Sequence-dependent set-up times have to be regarded. The time used for set-ups of dies reduces production capacity at the machine which is currently set-up. Additionally, maintenance times and intervals are important in short-range planning. The calculation is made as in mid-range planning but to a shorter, more detailed timescale. The timing and the point of time for coil changes are planned in the short-range timescale. The reduction of production capacity is therefore automatically taken into account. Last but not least, loading equipment is planned depending on the planned production.

3 State of Art

After having described the problem in the previous chapter, the current approaches available in the literature are reviewed. First, available concepts and methods designed to improve service availability are presented. After that, available approaches to improve flexibility are presented. Then, several methods for planning the requirements are listed. Available decomposition approaches as well as lot sizing methods are described in the last sub-section.

3.1 Improvement of Delivery Service Availability

As the customers' purchasing decisions are influenced by the suppliers' delivery service availability, the importance of logistical service quality has increased during recent years.[79] According to Zibell,[80] the logistical service level can be evaluated by the following components:

- Delivery time: Time between the order and the delivery
- Willingness to supply: Proportion of orders which can be promised to be delivered
- Delivery reliability: Proportion of deliveries delivered on or before the promised date
- Delivery flexibility: Time-based scope for the customer to change orders
- Delivery quality: Quality and state (e.g. damage) of the delivered goods
- Willingness and readiness to provide information on the status of the customer order

[79] Compare [Paw07].

[80] See [Zib40].

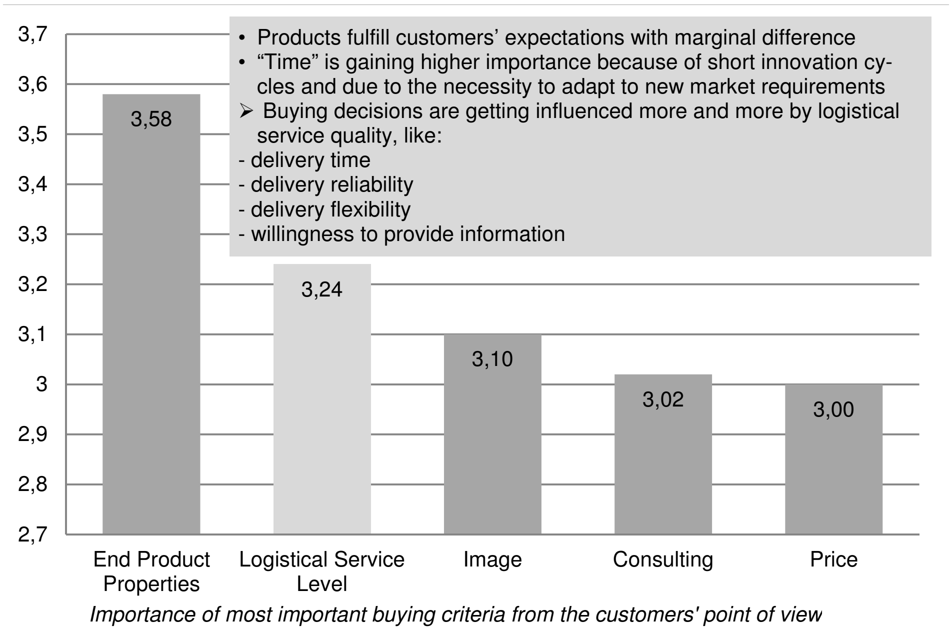

Figure 10: Buying Criteria according to Pawellek

In order to be able to improve service availability, evaluation methods for service availability, which are presented in the next sub-section, are needed. Depending on the situation, different methods for improving supply service availability can be applied. These are presented afterwards.

3.1.1 Evaluation of Delivery Service Level

In order to improve the service availability, the service level has to be evaluated. Pawellek[81] defines a basic performance indicator for the service level:

$$Service\ Level = \frac{Number\ of\ Deliveries\ within\ Agreed\ Time * 100}{Number\ of\ Orders}$$

The number of deliveries/orders can be replaced by the monetary value.

A more differentiated evaluation is presented in the VDA recommendation 5001.[82] With the presented method, it is possible to differentiate quantity variance as well as delivery schedule variance. A method for measuring flexibility and comparing it with completed deliveries is also presented.

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[81] See [Paw07].

[82] See [VDA94].

The next sub-section is dedicated to methods which can be used to improve supply availability.

3.1.2 Methods for Improving Supply Availability

There are several ways to improve supply availability. One way to improve supply availability is to plan demands using statistical methods. The first sub-section describes the methods used for demand planning. In the second sub-section, the methods used for fulfilling demands are described.

3.1.2.1 Demand Planning

On the one hand, there exists demand uncertainty, induced by the variation in planned or estimated demand and realized sales. On the other hand, the goal is to fulfill customer demand. Many decisions, including, for example, those on the procurement of raw material or components with long lead times, have to be made before the customer submits his order.[83] Therefore, demand planning is necessary in order to “improve decisions affecting demand accuracy and the calculation of buffer or safety stocks to reach a pre-defined service level.”[84] Depending on the planning horizon, different methods can be applied to obtain results for demand planning tasks, which can be structured in the same way as in the demand planning framework presented by Kilger and Wagner.[85]

Demand Planning Structures	⇨	- Structuring products, customers and time - Structuring input and output of demand planning - Aggregation and disaggregation
Demand Planning Process	⇨	- Phases of demand planning process - Participants in demand planning process - Statistical forecasting - Judgemental and consensus forecasting
Demand Planning Controlling	⇨	- Definition of basic metrics - Aggregation rules for forecast accuracy metrics - Dealing with exceptions - Technical implementation of KPIs - Incentives and responsibility

Figure 11: Demand Planning Framework by Kilger and Wagner

[83] See [SK08].

[84] See [SK05], p.139.

[85] See [SK08], p. 133.

In order to improve accuracy, demand planning data is structured, often on the basis of products or product families, customers or regions, and time. Demand planning is subdivided into a long-term aggregated demand prognosis level, in which demands for several periods are forecast and subdivided into a short-term prognosis level.[86] In order to plan demands, statistical forecasting techniques are used.[87] A problematic aspect of forecasting techniques, however, is that they are usually wrong.[88] Uncertainty about real demands has to be considered. Demand planning has to be controlled using defined basic metrics and key performance indicators.[89]

The next sub-section is dedicated to determining how the actual customer demand can be satisfied.

3.1.2.2 Demand Fulfillment

The planning process dedicated to determining how actual customer demands are satisfied is called demand fulfillment. "The demand fulfillment process determines the first promise date for customer orders."[90] Traditionally, the inventory is checked and orders are quoted against it. If there is not enough inventory available, production lead times are taken into account in order to provide achievable order promises. As constraints e.g. capacity limitations are not taken into account, infeasible quotes may be calculated. Nowadays, demand fulfillment solutions contain more sophisticated methods, which improve the generation of reliable quotes, the searching for feasible quotes and the increase of profitability. These methods[91] generate plans for future supplies from the suppliers on the basis of demand forecasts, even beyond the already existing scheduled orders.[92]

Depending on the product and the production environment, demands are satisfied from stock (make-to-stock) or produced after the receipt of the order (make-to-order). In make-to-stock environments, production is forecast driven. Customer orders can then be served with short lead times as only transport and order processing times arise. The

[86] See [GT09], p.148. Data warehouses and online analytical processing (OLAP) tools can be used for this purpose. See [SK05], p.142.

[87] Compare e.g. [GLM04], [SK05], [GT09].

[88] See [Nah97].

[89] In section 3.1.1 some metrics for logistical service quality were introduced.

[90] See [SK05], p.179.

[91] The newest approaches can be found under the available-to-promise concept. Examples of improved available-to-promise approaches can be found in [CZB02], [JSJK02], [XTKC03]; an overview is presented in [Pib05].

[92] See [SK05].

main restriction to fulfilling an order is the availability of stock. In make-to-order environments, procurement is driven by forecast; production is driven by customer orders. Consequently, order fulfillment depends on procurement time and capacities. Production time and capacities have to be considered as well.[93]

Planned demands and feasible order promises are preconditions to planning the procurement of resources as well as production.

3.2 Flexibility vs. Costs

Planning can be considered as the notional anticipation of future actions in order to achieve set objectives in an economically advantageous way[94]. Consequently, plans can reduce costs if actions are executed in compliance with the planned specifications. Production control, which is one of the most important leading and management tasks[95], is defined as the reaction on the actual events and the resulting plan deviations on a short-term[96]. But otherwise, adaptations, which may be necessary due to environmental changes, are limited and therefore decision flexibility is reduced. Demands are planned, and feasible order promises are given, on the basis of uncertain parameters. The main causes of uncertainty are:[97]

- Exact demand is not assured
- Actual times (e.g. replenishment) differ from planned times
- Real amounts (e.g. production or delivery quantities) differ from planned times
- Documentation is erroneous (e.g. available stock)

All uncertainties can be reduced by investments or contracts but they are never completely eliminated and are related to costs. Consequently, the flexibility required to be able to adapt to upcoming situations has to be obtained by other means. There exist different possibilities for improving flexibility through different planning approaches.

3.2.1 Total or Complete Planning

Ideally, complete, unchangeable information is used to plan cost-optimal activities for a long horizon. During total planning, it is assumed that the whole problem can be solved

[93] See [SK05].

[94] A definition of planning can be found in chapter 2.2.

[95] See [Hah96].

[96] Translated from [Krü96].

[97] Following [GT09].

in one planning step and this means that the planning horizon equates to the length of the total horizon T_{total}.[98] Therefore, all interdependencies have to be known in advance,[99] which is usually not the case in practice.

3.2.2 Cyclic Planning

If the cyclic planning approach is applied, the total horizon T_{total} is subdivided into smaller, consecutive, non-overlapping planning horizons T_c consisting of several periods. Planning for the next planning horizon $T_{c'}$ is carried out after $|T_c|$ periods. Actualized data as well as system state information gained from the previous planning horizons are used. Decisions made are fixed for all periods of the planning horizon $T_{c'}$.[100]

3.2.3 Rolling Planning

The rolling planning approach minimizes the problems of information dynamics and time-based interdependencies related to the previously described approaches. At each planning step, decisions for π periods are fixed. Decisions related to the other $|T_c|-\pi$ periods are revised and corrected depending on actualized data. Decisions for the π periods are implemented. Consequently, $|T_c|/\pi$ planning steps are executed and $|T_c|/\pi-1$ are fixed once. Comparable to the cyclic planning approach, several plans are generated considering the end state of the planned system. In contrast to cyclic planning, the rolling planning approach enables flexible reaction to environmental changes.

A result of applying the rolling horizon approach, when considering changes in information, is that less planning errors are made. Due to frequent changes in plans, high flexibility is expected from the planned resources. These adaptations, also known as planning nervousness, lead to organizational difficulties in fulfilling the changed plans and a consequence of this may be fewer acceptances of the planning procedure.[101]

An additional problem related to the rolling planning approach, whenever a planning horizon smaller than the relevant planning horizon is taken into account, [102] is that inventories at the end of the horizon are minimized in order to reduce inventory holding costs for the actual plan. This negatively influences adherence to delivery dates after the

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[98] See [SKH03].

[99] See [Bre04].

[100] See [SKH03], [KS01].

[101] See [SKH03].

[102] See [Heu03].

planning horizon and possibly leads to higher set-up and production costs. In order to improve planning quality and to reduce nervousness, ending inventories have to be set for each planning step.

There already exist methods for reducing the negative side effects of rolling planning approaches. Fisher et al. present a concept which calculates an ending inventory on the basis of the economic order quantity (EOQ).[103] Information about future average demands after the planning horizon has to be available. Heuvel extends the planning horizon so that amounts can be calculated using the Wagner–Whitin algorithm.[104] The *Periodic Order Quantity (POQ)* is the quotient of the average demand and the EOQ and determines the extension of the horizon. Another approach, which is also based on information available after the defined planning horizon, is presented by Stadtler.[105] Using the heuristic by Groff,[106] the *Time Between Orders (TBO)* value is calculated, in order to determine for how many periods the amount produced within one period can meet the demands. With an adapted Wagner–Whitin algorithm and the usage of the calculated TBO, an inventory level can be determined to reduce set-up costs which otherwise would occur.

So far, planning approaches with different flexibility and cost-optimality characteristics as well as methods to reduce negative side-effects of the rolling planning approach have been presented. Still missing are the methods for how workforce, production, set-ups, maintenance and coil changes are planned within the planning horizon. Alternatives for these factors will be described in the next sections.

3.3 Methods for Planning Requirements

3.3.1 Workforce Planning

Workforce or personnel planning can be defined as an ordered, information-processing process, whereas during its progress, the values of personnel variables are set anticipatorily, so that entrepreneurial targets are met.[107] Personnel variables can represent all aspects of availability and specificity problems on the individual or categorical level.[108]

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[103] See [FRZ01], for details about their presented *Ending Inventory Valuation* concept.

[104] See [WW58].

[105] See [Sta00].

[106] See [Gro79].

[107] Translated from [Kos93].

[108] See [Spe].

Depending on the focal point of personnel planning variables, nine categories of personnel planning can be differentiated, which are determined by combinations of variable characteristics. In this work, personnel planning characterized by variables determining the availability of personnel on a categorical level is relevant.[109] As follows, methods for the so-called collective personnel planning[110] are presented and evaluated. Categories can be differentiated into categories of activities and categories of qualifications.[111] Moreover, a goal is to integrate personnel planning into corporate planning including the calibration of all planning areas. For that reason the simultaneous planning approach has been introduced, in order to guarantee optimality. Depending on the case in question, theoretical simultaneous planning approaches may be able to be used in practice because of difficulties in obtaining relevant data and the high calculation effort required. Consequently, the traditional approaches of using successive planning still dominate planning procedures.

In the literature there exist several approaches and methods for workforce planning. The approaches can be distinguished by their area of application:[112]

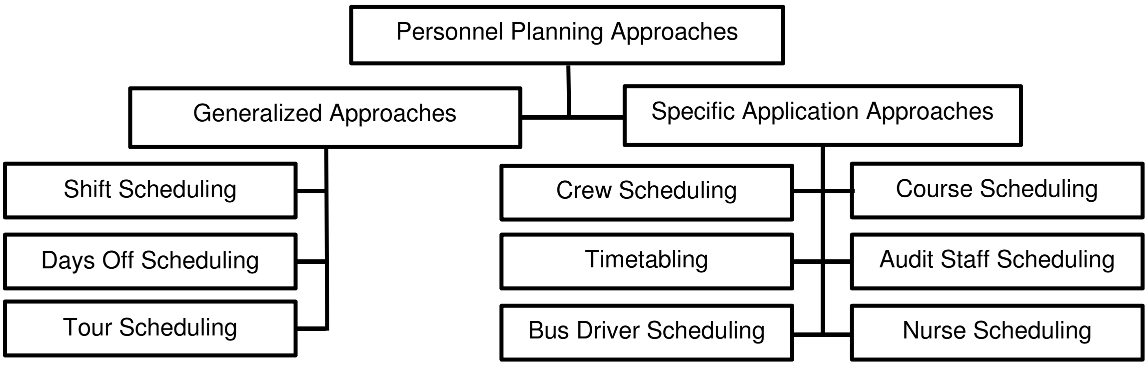


Figure 12: Differentiation of Personnel Planning Approaches according to Rossi

The three types of workforce planning approaches with general application areas can be distinguished by their time-based relationships. If the operating time is longer than the daily working time of employees, shift scheduling is necessary, and the working time is organized in shifts. In shift scheduling, it is decided which shifts are required to satisfy the necessary workforce. Decisions about working time and time points as well as breaks are made. If the operating time lasts longer than the average period of working

[109] Specificity problems, like skill enhancement planning or the design of incentives, are not considered here as they are not relevant for lot sizing. Availability planning on an individual level, that is, individual worker disposition, is omitted as well. Although it is relevant to dispose each worker in accordance to company agreements (e.g. maximum working hours, holidays etc.), this problem is disregarded, too.

[110] See [Kos75] and [Dru75].

[111] See [Kos75], [Str76] (S.28 ff), [Vie99] (S.18 ff).

[112] See [Ros07].

days of employees, days off have to be respected. Days off scheduling is dedicated to matching the off or working days of workers, taking into consideration days off during the week or at weekends over a period of several weeks. The combination of shift and days off scheduling is known as tour scheduling. In tour scheduling, shifts as well as days off are planned for each worker. Furthermore, there are models with specific application areas. Because of special characteristics and further restrictions, it is difficult to classify them into general approaches. Crew scheduling, bus driver scheduling, nurse scheduling, course scheduling, timetabling or audit-staff scheduling can be differentiated. In [EJKOS04], there is an overview of workforce planning approaches.

Crew scheduling examples can be found in [BMR04], where a new solution is presented to calculate multiple depot crew schedules which takes into consideration the time it takes for a crew to return to the starting depot, and limits of elapsed time and working time. Another crew scheduling approach is presented by [SFD98], in which the operational airline crew scheduling problem is described. The described problem consists of modifying personalized monthly assignments planned for airline crew members on an operative timescale in response to a given flight plan. Crew scheduling is a problem which is often analyzed from an airline perspective. Among other scheduling problems, especially for airlines, crew scheduling approaches are described in [Suh95].

Examples of methods for bus driver scheduling are [VH02], [BGL01], and [WW95], where schedules are calculated for bus drivers on an operational timescale. Different approaches to improving the performance of the solving of presented problems like heuristics or column generation methods are also presented.

An overview of nurse scheduling problems is given in [BCBv04]. The authors discuss the role of nurse scheduling in hospitals' personnel planning and review several nurse scheduling approaches in the literature.

Course scheduling, timetabling and audit staff methods and reviews are presented in [Bor00], [Sch99], [PVH03], [Hib01], [Wer97], [DE97], [Sal95] and [Fun02]. They will not be explained here as their restrictions and the practical background does not match the purpose of this work.

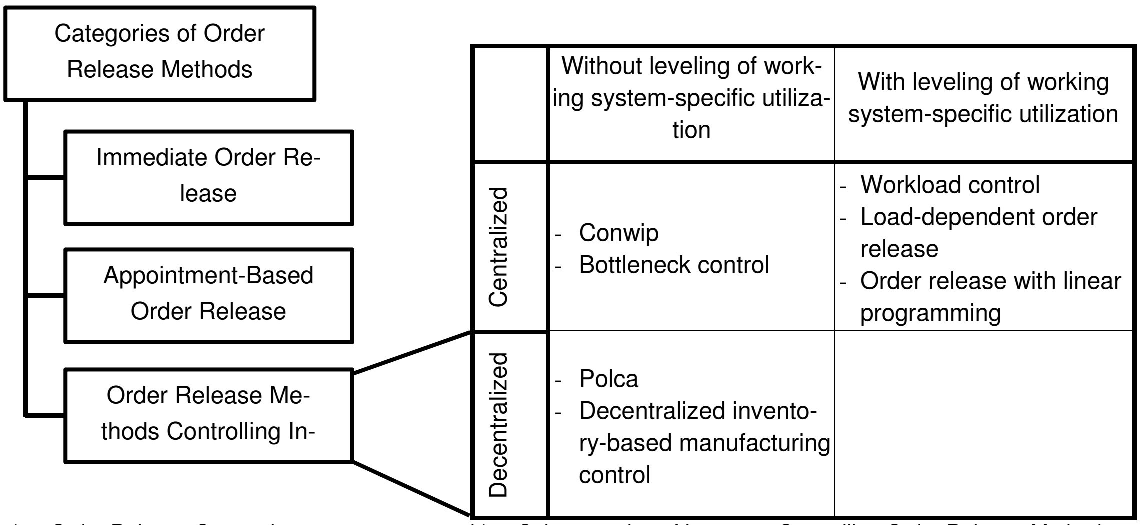
The available approaches concentrate on workforce scheduling. These generalized approaches do not consider any production restrictions. These methods have to be adapted in order to be usable for the presented problem. The methods with defined application backgrounds do not precisely match the problem described.

3.3.2 Machine Planning

In this section, machine planning approaches are subdivided into order release methods and scheduling methods. Relevant approaches are presented and discussed.

3.3.2.1 Order Release Methods

The order release determines the point in time at which the production can handle an order. An order release starts with material procurement and after this has happened the material usually cannot be used for other orders. The order release influences inventory and machine utilization. Order release methods can be classified as follows:[113]



a) Order Release Categories

b) Subcategories of Inventory Controlling Order Release Methods

Figure 13: Classification of Order Release Methods according to Lödding

As the immediate order release ignores utilization, lead times and inventory, they will not be analyzed in this work. The appointment-based order release is the basis of most production planning and control systems. A precondition is that superordinate planning, which determines a list of orders and starting appointments, is provided in advance. It is possible to describe the appointment-based order release by the following rule:[114]

In the appointment-based order release, an order is released when its planned start time has been reached or exceeded and the required material is available.

[113] See [LW05].

[114] Translated from [LW05] p. 313.

A centralized order release method controlling the inventory is the constant work in process approach (CONWIP).[115] This procedure is controlled by the following rule:

An order is released whenever the inventory of the considered production line falls below a defined threshold. The order with the highest priority is then selected from the order list. The order list contains unreleased orders with a planned start time, which is situated within a defined planning horizon.

Another centralized order release method is the bottleneck control. The basic rule of this approach is as follows:

Whenever an order has been finished by the bottleneck working system, a new order is released.

The bottleneck control approach subdivides the manufacturing into an inventory-controlled part which incorporates the bottleneck working system instead of being behind the bottleneck working system. A centralized order release approach supporting the leveling of the working system-specific utilization is called workload control.[116] The main parameters for this procedure are inventory limits of the working systems. Its basic idea can be described thus:

Detain orders which pass overloaded manufacturing entities. The load of the manufacturing entities is based on the analysis of inventory and already released orders.

The load-dependent order release[117] is centralized and considers system-specific utilization. Its basic rule can be summarized as follows:

An order is released whenever the utilization threshold or inventory threshold is not exceeded adding another order.

In its basic approach a periodic order release was proposed. An event-based order release is possible as well. A centralized order release considering the utilization of the working system is the order release using linear programming.[118] The basic rules are:

A list containing all unreleased orders is available. Release orders if the inventory differs from a previously planned level.

The workload is balanced using optimization software and requires a lot of parameters. The number of parameters complicates the method but an adaptation to a specific production system is possible. An example of a decentralized order release approach with-

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[115] See [SWH03], [SZ03], [HS96].

[116] [Jen78], [BW81], [KTH89].

[117] [Bec80], [Wie92].

[118] [ID74].

out leveling working system-specific utilization is the POLCA[119] control (Paired-Cell Overlapping Loops of Cards with Authorization). The production is subdivided into closed loops, where cards are used to control the inventory. A precondition of the POLCA control is the availability of an order list which has been generated in advance. A POLCA card, which provides the authorization of production, is assigned to a pair of manufacturing sections. A superordinate production planning and control system defines earliest order release dates using backward scheduling. The following rules are used in the POLCA concept:

1. *A manufacturing entity is allowed to execute an order, when the order release date is exceeded and a card is available. Otherwise, the order is blocked*
2. *The manufacturing entity checks whether other orders can be executed, if an order is blocked.*
3. *One card is added to the executed order at the first manufacturing stage and stays until the order reaches the last manufacturing stage. Then the card is freed and can be used for the next order.*

The decentralized inventory-based manufacturing control is another decentralized order release method without leveling of working system-specific utilization. On the basis of customer orders, a list of orders has to be generated in advance. The orders are stored in a list and released by decentralized inventory control cycles on the basis of the inventory from the next manufacturing stage. The exact rules used in this approach are available in [Löd01].

The following table summarizes the evaluation of the discussed approaches on the basis of the description presented in [Löd01]:

119 [Sur98].

Criteria of Manufacturing control methods	Order Release Method: Appointment based	Conwip	Bottleneck control	Polca	Decentralized inv. based man. cont.	Workload control	Load dependent	Linear programming
Inventory level should be controlled	-	o	o	+	+	+	+	+
Inventory deviations should be minimized	-	o	o	+	+	o	o	o
Blocked inventories should be minimized	+	+	+	-	-	-	-	-
Balancing of utilization and capacity	o	+	+	+	+	+	-	+
New sequencing should be minimized	+	+	+	-	o	-	o	-
Backlogs should be minimized and controlled	-	-	-	-	o	+	-	-
Bottleneck principle should be considered	-	-	+	o	o	+	o	o
Simplicity	+	+	+	o	-	o	-	-

Figure 14: Comparison of Order Release Methods

The presented approaches are suitable for planning production at machine level. The presented approaches are suitable for planning production at machine level, although many practical restrictions are not taken into consideration as they are outside the scope of this study.

3.3.2.2 Sequencing Methods

Sequencing methods determine which of the orders in the queue is processed next. Sequencing has a great influence on the logistical service quality, especially in situations where the order queue is long or inventory is high.[120]

The first sequencing approach is the First-In-First-Out (FIFO) rule. In this case, it is not possible to re-sequence the orders. Disadvantages are the interdiction of adaptations to planned schedules or the enforcement of standard lead times in every case. Although improvements responding to changes to orders cannot be achieved and flexibility is not available, several advantages can be obtained by using this method, like simplicity and calculability of lead times.

Further, there exist the earliest planned start date and the earliest planned end date rules. These rules change the order according to the planned execution date of an order and

[120] See [Löd01] p. 443–457 for more information on the described methods.

can improve e.g. serviceability towards the customer. It has to be assumed that the start and end dates of orders have been calculated in advance.

Another sequencing approach is the selection of an order by the minimal slack. The term “slack” is defined as the time until the planned end date of the order, which is not used for processing or minimal transition times. It is calculated as follows:

$$Slack\,time = ED_{plan} - T_0 - \sum_{\substack{i \in I \\ i \neq I_{max}}} PT_i - \sum_{i \in I} TT_{min,i}$$

ED_{plan}	=	Planned end date of an order
T_0	=	Planning date
PT_i	=	Processing time of process $i \in I$
$TT_{min,i}$	=	Minimal processing time of process $i \in I$
I	=	Set of processes

The basic idea is that delays are more probable for orders with a smaller slack time value than orders with a higher slack time value. On this basis, it is possible to consider future disturbances during order sequencing. One disadvantage is that the order sequence can be changed although there are no variations to the planned schedule.

In order to improve the performance, sequences can be improved using various simple methods. If set-up times are sequence dependent, the order with the lowest set-up costs is selected. The application of this approach risks orders related with high set-up times being delayed for a relatively long time.

The *Extended Work in Next Queue* (XWINQ)[121] is another approach. The basic order prioritization criterion is the inventory of the precedent and the subsequent working system. The lower the inventory, the higher the priority of an order. This method aims to reduce material flow breaks at consecutive manufacturing stages. Disadvantages are that the inventory is not a suitable criterion for reducing material flow breaks in an environment where numerous machines have to be controlled. The method does not differentiate between bottleneck systems and non-bottleneck systems. Moreover, planned order dates are ignored.

With the shortest operation time rule, the orders are sequenced according to their processing time. Orders with less processing time have a higher priority. Advantages are low inventories, short to medium lead times, a low medium order delay, and high ser-

[121] This concept is presented in [CMM03].

viceability. Disadvantages are that positive effects depend on inventory levels and that unimportant and important orders are equally prioritized.

3.3.3 Maintenance Planning of Dies

Maintenance takes time and restricts productive time but is necessary in order to guarantee error-free production. In this work, maintenance of the dies required for production has to be considered, as production is not possible during maintenance. Consequently, maintenance influences availability and productivity and the selection of an appropriate maintenance strategy is important.[122] According to [RF10] and [Mat02], maintenance strategies can be differentiated as follows:

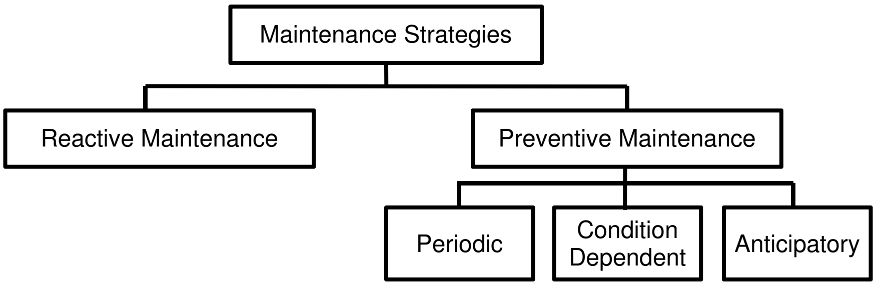

Figure 15: Classification of Maintenance Strategies

In [War09], maintenance strategies are differentiated as follows:

- Condition-Based Maintenance:
  It is possible for sensors or trained personnel to control and monitor the status of a component and to change the component in good time.
- Time-Based Maintenance:
  Inspection of component is done after prescribed time-periods, which is determined by experience.
- Damage-Based Maintenance:
  The maintenance of a component is executed after the component is damaged. Reduced availability is the consequence.

As it is not possible to monitor the status of all the components of a die during production in the analyzed case, condition-based maintenance planning is not applicable. Availability is the most important. This is the reason why damage-based maintenance is excluded. In this work, maintenance does not depend on time but on production lots and the number of produced parts, as the components of the dies are frayed during the

[122] See [Mat02] for practical relevance of the selection of the best maintenance strategy.

stamping process. As maintenance can be regarded as a logistical process,[123] planning improves the serviceability of maintained production factors.

There are already several reviews on maintenance planning approaches available. One example of such a review is [CP91], which deals with maintenance and replacement models for multi-unit systems. Approaches are partitioned into topical categories like machine interference/repair models or inspection/maintenance models. Other, newer reviews on maintenance planning approaches are presented by Dekker et al. who differentiate approaches by their stationary or dynamic character or by the type of their appliance in case studies or in decision support systems.[124]

[SK09] presents, in a generalized way, how modern information technologies can be applied to improve maintenance processes, especially planning. It is said that real benefits arise when maintenance planning tools become integrated communicatively with other planning systems. Therefore, concepts in which production planning as well as maintenance planning are executed simultaneously are relevant for the purpose of this work. In [AJA07], an integrated lot sizing and preventive maintenance strategy satisfying demands without the allowance of backlogging minimizing production and maintenance costs is presented. The authors make use of a mixed-integer linear program to solve experiments in order to obtain an optimal integrated production and maintenance strategy. Another approach is presented in [ST10]. The authors propose a method to determine simultaneously the period of preventive maintenance and the job sequence for two parallel machines in order to minimize the makespan with the result that a shop improves coordination between maintenance planning and production scheduling and improves shop efficiency.

Nevertheless, the consideration of relevant restrictions is not sufficiently integrated and therefore the presented approaches cannot be adapted to solve the problem described in this work.

3.3.4 Raw Material Procurement Planning

The purpose of raw material procurement planning is to satisfy the demands of production factors resulting from previously planned lots and generated schedules in a cost-effective way taking into consideration already existing suppliers.[125]

Corsten identifies the main goals of procurement planning in general:[126]

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[123] See [RF10].

[124] Examples of reviews on maintenance planning approaches are [Dek96], [DWv97], [DS98].

[125] See [Ste05].

- Guarantee of supply (assurance of material quality, flexibility and quantity; spreading risks of procurement, maintaining independence, etc.)
- Cost effectiveness (low capital commitment, reduction of costs, etc.)
- Safe disposal (ecologically acceptable materials)

There exist several approaches designed for cost-effective procurement planning. One of the first such approaches in systematic procurement planning was introduced by Andler,[127] in which the economic order quantity was defined. Many other research papers were published on the topic of purchase order sizing, but assumptions were made which do not reflect practice, like constant demand, unlimited capacities, constant prices and quantity discounts as well as multiple suppliers, none of which can be considered in the scope of this study.

Therefore, existing approaches were extended and can be found in the literature. Approaches to order sizing under quantity discounts are classified in [BP96] or [MR98]. A review on lot sizing models considering dynamic demands[128] is given in [BGv84].

In the Uncapacitated Multi-Supplier Order Quantity Problem with Time-Varying All-units Discounts[129] the sum of inventory costs and order costs, which consists of fixed and variable costs, is minimized. Besides other constraints, it is guaranteed that no delays can occur. Supplier-dependent discount levels are introduced. Last but not least, a heuristic is presented to solve the model. Besides constraints, which were already integrated in [T02], further aspects like supplier capacity limits, limited customer inventory capacities, limited period-dependent supplier capacities and supplier-dependent minimum purchase quantities are modeled in [Rei02]. With the approach presented in [Sta07], multiple products as well as different discount types are supported.

Although integrated procurement and production planning concepts are available,[130] it is not desirable in the analyzed case to influence the production plans since procurement as the raw material replenishment method can be disregarded for production in this case. Another more important argument against the available integrated approaches is that, according to the author's reviews, the literature is missing approaches which consider all relevant aspects of procurement and production planning simultaneously.[131]

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[126] See [CC95], p.573–586.

[127] See [And29].

[128] Examples are [Laf85], [Ben86], [HM02], [BS93], [CHK96], [Sil79], [CHK00], [KFW03a], [HS03].

[129] See [T02].

[130] Overview examples are [GD92].

[131] Examples of further integrated procurement production approaches are [Lee05], [Bal99], [San11], [BAS]. The latest developments of advanced planning systems (e.g. [Sta05]) do not consider practical restrictions in the required detail.

The reviewed approaches might be suitable for the cases described and provide concepts which are suitable for developing further procurement planning methods, but the integration into a planning method designed to solve the problem as was described in chapter 2 is not available. The consideration of immanent technical and organizational restrictions available is not supported by the presented approaches.

3.4 Two-Level Capacitated Lot Sizing in Production Planning

Minimizing the sum of set-up and inventory holding costs was already picked out as a central theme in [And29]. Since the assumptions made, such as endless production capacities and inventory capacities as well as static demands, are not practicable in most cases, further approaches have been developed. An extension of the economic order quantity considering dynamic demands was presented in [WW58]. According to the knowledge of the author, the first approach to solving the capacitated lot sizing problem with dynamic demands, which is considered as one of the most important and at the same time most difficult problems in production planning,[132] was presented in [Eis75]. Several adaptations added further aspects to the basic capacitated lot sizing problem in order to model further aspects, and planning results have become more practicable. But the consideration of further practical constraints is often related to higher model complexity. In order to reduce complexity, problem decomposition is often used as an accepted approach in practice. The first sub-section below is dedicated to decomposition and hierarchical production planning approaches. After that, mid-range lot sizing methods are depicted and their suitability for the previously described problem is analyzed. Short-term lot sizing methods, which have to define more detailed schedules, are described in the sub-section after that. Last but not least, available integrated short- and mid-term approaches are briefly explained and their usability for solving the problem is discussed.

3.4.1 Decomposition Approaches and Hierarchical Production Planning

A basic approach to solving complex planning problems is their division into partial models. Optimization problems can be obtained which are solvable with less effort.[133]

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[132] See for example [KFW03b]. See [BY82], [FLR80] for complexity analyses of the capacitated lot sizing problem in the single-item case, and [CT90] for a multi-item complexity analysis of the capacitated lot sizing problem. In [MMv91], it is shown that finding a feasible solution is NP-complete for problems with set-up times.

[133] See [Sta88].

According to [KS89], discrepancies between theoretical recommendations of operations research and practical requirements as well as practical limitations of production planning can be solved using hierarchical production planning by employing three devices:

1. Separation of distinct planning areas defined by organizational units and coordination by a few, controlled interfaces
2. Use of the natural time-structure of the planning process
3. Reduction of data by aggregation

The first approaches of hierarchical production planning and scheduling were presented in [HM73] and [Gab76]. In [HM73], the authors describe a hierarchical planning and scheduling system for a multiple plant and multiple products with a seasonal demand situation. Optimal decisions at an aggregate level, which are termed "planning", provide constraints for the detailed decision-making level at which schedules are defined. Although the described restrictions do not match the problem previously described, the presented concept of decomposing the problem in planning and scheduling decisions seems to be useful. Based on this work, a similar approach is presented in [Gab76]. Both references form the basis of later works on hierarchical production planning and scheduling.[134] First, developments on the provided basis were reviewed [HO85], including another proposition for a method for manufacturing control which subdivides medium-term and short-term decisions. Examples of newer approaches in hierarchical production planning are usually specific and designed to solve a particular problem. Examples are [Sta88], in which a method of hierarchical lot sizing is proposed, [KS89], which provides a review on problems and methods to solve production planning in hierarchies, [HG01], which deals with a hierarchical and product-based decomposition to plan production of a steel plant, and [WI07], which presents a hierarchical production planning method looking at uncertainty in demands. Another hierarchical production planning approach using Karmarkar's algorithm[135] is available in [YZJ04]. The hierarchical production planning approach in [ASv11] only considers production capacities on a weekly basis and does not define schedules. The most promising approach is presented in [OT07]. Many practical circumstances, like the multi-product environment or the batch processes, are similar to those available in the previously described problem. But most aspects are still missing. Examples are the consideration of lots, and maintenance- or sequence-dependent set-up times during the scheduling process. According to the knowledge of the author, there are no approaches available which simultaneously con-

[134] See [BT93] for further information on hierarchical production planning.

[135] See [ARVK89] for a detailed description of how Karmarkar's algorithm can be used to solve linear programs.

sider production and scheduling restrictions as well as personnel planning aspects in an integrated hierarchical method.

3.4.2 Mid-Term Lot Sizing

In the last sub-section, available hierarchical production planning and decomposition approaches were briefly described and their suitability to the problem in question analyzed. As the available approaches do not cover every requirement, it is necessary to analyze concepts which are used for lot sizing at a mid-term level only, without integration into a hierarchical planning approach.

In mid-range lot sizing, detailed schedules are not necessary, as dynamic input parameters in reality change very often.[136] But in the analyzed case, it is necessary, when planning production, to consider the available capacities, which are mainly reduced by set-ups and coil changes. Maintenance has to be considered as well as different cost factors. Capacitated lot sizing can therefore be modeled with big buckets.[137] The basic capacitated lot sizing model can be described thus:[138]

Assumptions:

- Several products J are produced on a single shared resource.
- The resource is limited in capacity.
- The planning horizon is finite and divided into T periods.
- The demand is dynamic but deterministic.
- Production depends on machine state, which can be changed by set-up.
- Resource capacity is reduced by set-ups. A set-up incurs set-up costs.
- The target is the minimization of the sum of holding and set-up costs

Sets:

J Set of products
T Set of periods

[136] Besides dynamic demands, production is related to uncertainties. The initial system state, that is, for example, initial inventories or initial machine states, can change over time and the longer the planning horizon the greater the difference from planned system state to real system state.

[137] The differentiation into small- and big-bucket models concerns the relative length of the time-periods with respect to the expected length of a production lot [Sue05]. "'Big' and 'small' bucket indicates how long a period of a calendar, which is used in a production system, a node or a point in a model, is in relation to the density of events set to the original production." (translated from [Dan99] p. 255).

[138] Compare the formulation and explanation available in [Sue05].

Data:

a_j	Consumption of capacity to produce one unit of item $j \in J$ (=production coefficient)
b_{jt}	Large number, not limiting feasible production quantities of product $j \in J$ in period $t \in T$
c_t	Available capacity in period $t \in T$
d_{jt}	Demand for $j \in J$ in period $t \in T$ (with d_{jT} including final inventory, if given for the planning horizon *T*)
h_{jt}	Inventory holding cost for one unit of $j \in J$ in period $t \in T$
sc_j	Set-up cost for product $j \in J$
st_j	Set-up time for product $j \in J$

Variables:

I_{jt}	Inventory of $j \in J$ at the end of $t \in T$
X_{jt}	Production quantity of item $j \in J$ in period $t \in T$ (lot size)
Y_{jt}	Set-up variable (=1, if a set-up operation for item $j \in J$ is performed in period t =0 otherwise)

$$Min \sum_{j \in J} \sum_{t \in T} h_{jt} * I_{jt} + \sum_{j \in J} \sum_{t \in T} sc_j * Y_{jt} \tag{1}$$

$$I_{jt-1} + X_{jt} = d_{jt} + I_{jt} \qquad \forall j \in J, t \in T \tag{2}$$

$$\sum_{j \in J} a_j * X_{jt} + \sum_{j \in J} st_j * Y_{jt} \le c_t \qquad \forall t \in T \tag{3}$$

$$X_{jt} \le b_{jt} * Y_{jt} \qquad \forall j \in J, t \in T \tag{4}$$

$$X_{jt} \ge 0, \quad I_{jt} \ge 0, \quad I_{j0} = 0 \qquad \forall j \in J, t \in T \tag{5}$$

$$Y_{jt} \in \{0;1\} \qquad \forall j \in J, t \in T \tag{6}$$

The sum of holding and set-up costs are minimized in the objective function (1). The inventory balance constraints (2) guarantee that all demands are met in time. Available capacity is shared by production (X_{jt}) and set-up operations (Y_{jt}) due to constraints (3). Production variables X_{jt} are coupled with set-up operations Y_{jt}, by constraint (4). Equations (5) and (6) define non-negativity as well as binary conditions.

Reviews of the capacitated lot sizing problem are presented.[139] In [BRG87], the authors present a classification of production planning problems differentiating between single-level and multiple-level problems which are then subdivided into problem groups with

[139] The author does not claim that the list of reviews is complete. The list is a small subset of available reviews.

unconstrained or constrained resources. They evaluate research work using computational effort, generalization, optimality, simplicity and testing as evaluation criteria. In [Mv88], the authors compare available heuristic approaches for solving the multi-item single-level capacitated lot sizing problem. They differentiate between single resource heuristics and methods based on mathematical programming. On the basis of computational results, suggestions are given for the appliance of the diverse heuristics in industry. In many review papers, extensions to the basic problem formulations were discussed in order to model practical aspects. In [TTM89], a review of capacitated lot sizing models is presented including set-up times. [KSv94] provide a structure for batching research and models on the basis of a distinction of batching issues and related decision levels. The authors define process design, activity planning and activity control to cluster research results. In [YL95] lot sizing models with random yields in production were reviewed and procurement costs were considered as well. [KFW03a] concentrate on single-level lot sizing problems and variations. Moreover, heuristic and exact solution approaches are discussed. Extensions to basic lot sizing models for industrial applications are collected and summarized in [JDZ05]. Examples of actual reviews formed on the basis of the latest research results are [QK08] and [UP10]. In [QK08], a literature review suitable for practitioners as well as scientists is presented, including formulations of capacitated lot sizing problems with back-orders, set-up carry-over, sequencing, parallel machines, multi-level product structures and overtime. A classification containing various approaches available in the literature and based on the characteristics of the planning horizon, the number of items, the order quantity, the frequency of review, lead times, capacities, demand properties, and stocking points is presented in [UP10].

According to the knowledge of the author, formulations which precisely match the problem are not available. Nevertheless, parts of other formulations can be used. There is only some literature available regarding simultaneous lot sizing and personnel planning. One example is [JMN05]. The target of the authors was to minimize the costs related to human resources needed in the process, linked with a lot sizing production plan. Another example of model extensions is the use of linked lot sizes in order to correctly represent capacity consumption due to set-ups. Basic models using linked lot sizes can be found in [DEWZ93], [Haa94] or [Tv85], in which a heuristic approach is presented to solve the previously presented problem. An example of a modeling framework which includes set-up carry-over is available in [GMS95]. In [SG99], multiple products are supported to be produced in one period. In the literature, capacitated lot sizing models and solution approaches considering batch-wise production are available. Examples are [AES93], [SWS06] and [van07]. Sample approaches, which are dedicated to maintenance and planning production lots simultaneously, are [CK05], [CRR08], [NFM10] and [BBH10].

All the presented approaches are well suited for the specifically analyzed and solved problems. But, according to the knowledge of the author, there is no approach available which integrates all required points into a single concept.

3.4.3 Short-Term Lot Sizing

In this section, available reviews and approaches for short-term lot sizing are described. Selected lot sizing approaches have to support scheduling and other aspects which are described in chapter 2. Therefore, small-bucket[140] problems in particular will be described in this section. Although it was stated[141] that the discrete lot sizing and scheduling problem has an edge over the continuous set-up lot sizing problem[142] regarding performance and practical relevance, other small-bucket problems and their extensions will be analyzed in order to find a solution to the problem.

One of the first contributions to the research on the discrete lot sizing and scheduling problem was presented in [LT71].[143] In [Sch82], the first extensions were formulated to model sequence-dependent set-up costs and a product-based decomposition approach was presented. In [vKKSv90], the complexity of the discrete lot sizing and scheduling problem was analyzed in further detail. A general formulation of the discrete lot sizing problem is available in [Fle90]:[144]

Assumptions:

- Products $j \in J$ are produced on a single shared resource.
- The resource is limited in its capacity.
- The finite planning horizon is divided into T periods.
- The demand is dynamic but deterministic.
- Only one product can be produced in a period.
- Full capacity is used if a product is produced within a given period (all-or-nothing assumption).
- The change of a set-up state of a resource incurs set-up costs.
- The minimization of the sum of holding costs and set-up costs is the target.

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[140] A differentiating definition is provided in [Dan99] p. 255.

[141] See [SKKW91].

[142] See [KS85].

[143] The application of the discrete lot sizing problem in practice has been important ever since the first contributions to research. The model formulated in [LT71], for example, was used in an automated production-scheduling system for a tire company. In another very early example, presented in [vV83], sequence-dependent set-up times are modeled.

[144] The model and its explanations are adaptations of the formulations presented in [Sue05] and [Fle90].

Sets:

J	Set of products
T	Set of periods

Data:

p_j	Production speed for $j \in J$
d_{jt}	Demand of $j \in J$ in period $t \in T$
h_j	Inventory holding cost for one unit of $j \in J$ per period
sc_j	Set-up cost for product $j \in J$
ss_{jt}	Safety stock of product $j \in J$ at the end of period $t \in T$

Variables:

I_{jt}	Inventory of $j \in J$ at the end of $t \in T$ (with I_{j0} for the initial inventory)
Z_{jt}	Set-up state variable (=1, if item j is set-up at the end of period t, = 0 otherwise) (with Z_{j0} representing the initial set-up state)

$$Min \sum_{j \in J} \sum_{t \in T} \left[sc_j \, max\left(0, Z_{jt} - Z_{j,t=1}\right) + h_j I_{jt} \right] \quad (1)$$

$$I_{jt} = I_{j,t-1} + p_j Z_{jt} - d_{jt} \qquad \forall j \in J, t \in T \quad (2)$$

$$\sum_{j \in J} Z_{jt} \leq 1 \qquad \forall t \in T \quad (3)$$

$$I_{jt} \geq ss_{jt,} Z_{jt} \in \{0,1\} \qquad \forall j \in J, t \in T \quad (4)$$

The target of the model is to minimize the sum of holding and set-up costs (1). As production has to be at full capacity or not at all in each period, the model formulation does not rely on production variables $X_{jt,}$ which are replaced by $p_j * Z_{jt}$ in the inventory balance constraints (1). Constraint (3) limits the number of simultaneous set-up states Z_{jt} in one period. Constraints (3) and (4) define non-negativity and binary conditions on the decision variables.

Reviews of the discrete lot sizing and scheduling problem are available in the literature. Examples are [DK97], which also contains reviews of big-bucket models, and [JD08], which contains a review of relevant extensions to lot sizing and scheduling models, especially for industrial applications.

Several extensions to the discrete lot sizing and scheduling model were formulated to cover practical constraints.[145] In [JD98], the discrete lot sizing and scheduling problem is solved with sequence-dependent set-up costs and times on a single machine. [JD04] provide an adaptation of the basic model supporting start-up times, which can be fractions of the time bucket, multiple alternative machines with different efficiencies, multiple capacitated resources and backlogging. Another approach, which supports set-up times as well as earliness and tardiness penalties, is presented in [SLM10]. One of the first approaches of batch-oriented scheduling can be found in [AADT92], in which the problem is stated, a complexity analysis given, and a heuristic solution approach is provided. Batch production and consequent complexity is considered in [BJH00], too. The paper [JD98] is another example of batch-oriented scheduling.

The papers [AGH99], [AGH98] and [LC00] are examples of scheduling problems which consider the maintenance of machines but not the maintenance of the required resources, which is the case with the dies in the current problem.

The most suitable approach implementing several relevant aspects of the discussed scheduling problem is presented by Suerie.[146] In his work, basic concepts for modeling period-overlapping actions are introduced. With the presented fundamental model, building blocks, batch production, and maximum lot sizes, as well as period-overlapping set-up times and maintenance, can be introduced in any formulation by adapting them to the specific situation.

Although all aspects required to solve the presented problem have already been discussed in the literature, there is no contribution available which combines all the required aspects into a single approach. Also, the most promising work by Suerie[147] has to be adapted in many directions. Sequence-dependent set-up times, and further activities like coil changes or the use of set-up personnel, are only a small excerpt of the characteristics it is necessary to add.

3.4.4 Integrated Mid- and Short-Term Lot Sizing

Another promising approach is the combination of mid-term and short-term planning, termed a general lot sizing and scheduling problem. A fundamental research contribution is formulated in [FM97]. In this approach, the schedules are independent of prede-

[145] The list of approaches is not complete. The depicted approaches are only a small subset of the approaches available in the literature.

[146] See [Sue05].

[147] See [Sue05].

fined time-periods and hence a generalization of known models using restricted time structures is provided.[148]

Assumptions:

- Products $j \in J$ are produced on a single shared resource.
- The resource is limited in its capacity in each big-bucket period t.
- Each big-bucket period consists of a set of small-bucket periods s.
- The finite planning horizon is divided into T big-bucket periods.
- The demand is dynamic but deterministic. Demand data is based on the big-bucket periods.
- In each small-bucket period s at most one product has to be produced.
- Set-up states are maintained across periods.
- The change of a set-up state of a resource incurs set-up costs and consumes resource capacity.
- The number of set-up operations per big-bucket periods is not limited by the number of products as the triangle inequality[149] does not have to hold.

Sets:

J	Set of products
S_t	Set of (small-bucket) periods forming a (big-bucket) period t
T	Set of periods

Data:

a_j	Consumption of capacity to produce one unit of item $j \in J$ (=production coefficient)
c_t	Available capacity in period $t \in T$
d_{jt}	Demand of $j \in J$ in period $t \in T$
h_j	Inventory holding cost for one unit of $j \in J$ per period
$minlot_j$	Minimal lot size for product $j \in J$
sc_{ij}^{sd}	Sequence-dependent set-up cost, if a set-up operation from product $i \in J$ to product $j \in J$ is performed
st_{ij}^{sd}	Sequence-dependent set-up time, if a set-up operation from product $i \in J$ to product $j \in J$ is performed

[148] See [Sue05].

[149] For detailed geometrical explanations of the triangle inequality see [KK01] chapter 1.3.

Variables:

I_{jt} Inventory of $j \in J$ at the end of $t \in T$ (with I_{j0} for the initial inventory)

Z_{jt} Set-up state variable (=1, if item $j \in J$ is set-up at the end of period $t \in T$, = 0 otherwise) (with Z_{j0} representing the initial set-up state)

Y_{ijt}^{sd} Sequence-dependent set-up variable (=1, if a set-up operation from $i \in J$ to $j \in J$ is performed in period $t \in T$, =0 otherwise)

$$Min \sum_{j \in J} \sum_{t \in T} h_{jt} * I_{jt} + \sum_{i \in J} \sum_{\substack{j \in J \\ j \neq i}} \sum_{t \in T} sc_{ij}^{sd} * Y_{ijt}^{sd} \quad (1)$$

$$I_{jt-1} + \sum_{s \in S_t} X_{js} = d_{jt} + I_{jt} \qquad \forall j \in J, t \in T \quad (2)$$

$$\sum_{s \in S_t} \sum_{j \in J} a_j * X_{js} * \sum_{s \in S_t} \sum_{i \in J} \sum_{\substack{j \in J \\ j \neq i}} st_j * Y_{ijt}^{sd} \leq c_t \qquad \forall t \in T \quad (3)$$

$$X_{js} \leq \frac{c_t}{a_j} * Z_{js} \qquad \forall j \in J, t \in T, s \in S_t \quad (4)$$

$$\sum_{j \in J} Z_{js} = 1 \qquad \forall j \in J, t \in T \quad (5)$$

$$Y_{ijt}^{sd} \geq Z_{is-1} + Z_{js} - 1 \qquad \forall j \in J, t \in T \quad (6)$$

$$X_{jt} \geq minlot_j * (Z_{is} + Z_{js-1}) \qquad \forall j \in J, t \in T, s \in S_t \quad (7)$$

$$X_{jt} \geq 0, \quad I_{jt} \geq 0, \quad I_{j0} = 0 \qquad \forall j \in J, t \in T \quad (8)$$

$$Y_{ijt}^{sd} \geq 0, Z_{is} \in \{0;1\}, Z_{i0} = 0 \qquad \forall i, j \in J, t \in T, s \in S_t \quad (9)$$

Minimizing the sum of the holding costs and sequence-dependent set-up costs is the objective, represented in (1). In (2) inventory balance constraints are formulated. The capacity limitation in (3) is based on big-bucket periods and guarantees that production as well as set-up activities do not exceed available limits. Production variables X_{jt} and set-up state variables Z_{is} are coupled in (4). Restriction (5) is introduced to guarantee that the set-up state at the end of each small-bucket period is well defined. Set-up operation Y_{ijt}^{sd} variables and set-up state variables Z_{is} are coupled in (6). Constraint (7) have to be introduced because of a missing triangle inequality.[150] A minimal production is enforced in order to avoid direct set-up changes ($i \rightarrow j \rightarrow k$, instead of $i \rightarrow k$) without production and without consuming capacity. Non-negativity and binary conditions are stated in (8) and (9).

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[150] The triangle inequality does not have to hold in every situation. Especially in the chemical industry, where cleaning processes are modeled by an additional “cleaning” product, the triangle inequality no longer holds [FM97].

In [KS05], it is shown that the basic general lot sizing and scheduling approach is limited to the case where the production state between two consecutive periods is conserved if the available capacity of the proceeding period exceeds the minimum batch quantity. Minimum batch sizes are modeled in [JZ08] but batch-oriented production is not supported.

In [Mey00], sequence-dependent set-up times were added to the basic general lot sizing and scheduling problem. The method was only tested with 18 products and other aspects like batch-oriented production are missing.

According to the author's research, further relevant model enhancements are not yet available, although the general lot sizing and scheduling approach seems to be a promising methodology for modeling production planning problems, especially regarding performance issues. Nevertheless, modeling of cross-machine constraints and aspects which require time continuity like set-up times, maintenance times or coil change times are supported in a better way by the fundaments of discrete lot sizing and scheduling.

4 Action Points

Although some ideas of the concepts and methods presented in the state of the art are useful and can be transferred, they are not satisfactory for solving the described problem. Even the combination of the approaches does not suffice to solve the problem in every detail. This section describes the action points—those things that still have to be done—in order to be able to plan lot sizes in production control, considering relevant restrictions and taking required resources sufficiently into account. As it is not useful to calculate detailed schedules for long-term situations in volatile environments with changing information, the planning horizon is split into two.

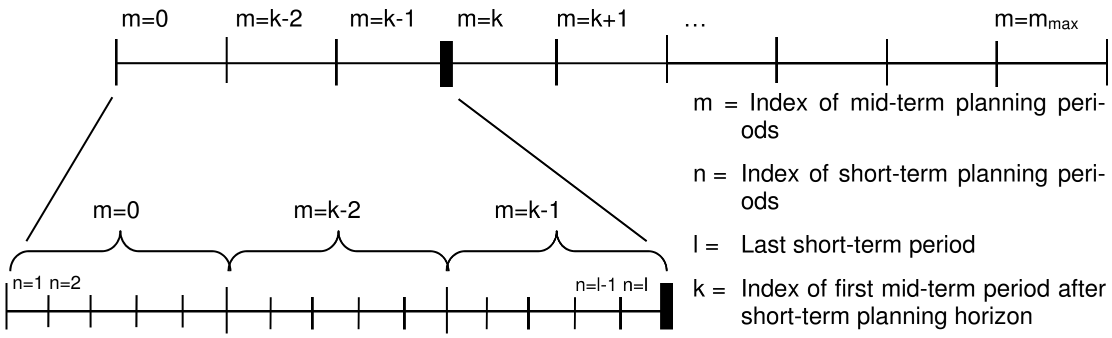

Figure 16: Split Planning Horizon

In the case study, detailed schedules are necessary for the first three days and information about demands can be assured for the next 14 days. Therefore, the short-term planning horizon starts today and ends with day three. The mid-term lot sizing starts at the end of day 3 and ends with day 14.

This partition can be adapted. It is important that both planning horizons are interconnected so that the information can be transferred. As shown in the state of the art, there exist many research contributions based on linear programs which aim to solve production planning tasks. The representation of practical problem instances can be realized in a relatively short time. Available commercial solver software, developed over a number of years, works efficiently with modern hardware, and implemented algorithms are tested. Therefore, the implementation of individual algorithms for the described problem is rejected and linear programming techniques are used.[151] The following chapters describe the aspects which have to be taken into account in each of the sub-problems, distinguished by their planning horizons. Last but not least, both approaches have to be coupled.

4.1 Mid-Term Lot Sizing

The mid-term lot sizing method has to generate valid, cost-effective production plans so that customer demands are satisfied. Cost factors influencing the results are all time-dependent. Production costs, set-up costs, maintenance costs and inventory holding costs have to be considered. Dynamics in demands and changes in the production system have to be factored into the planning procedure. Therefore, a rolling planning horizon is necessary, which takes updated information into account. In order to reduce negative side-effects of the rolling horizon scheme, like planning nervousness, simultaneous out-of-stock situations for more than one product, or the resulting risk of losing supply availability, a method is required which calculates expected ending inventories for each product. During planning, several practical conditions have to be taken into account. First, differences in production costs depending on the required personnel workload on the day have to be taken into account. Machines only have limited capacity, which has to be considered. Capacity is consumed by set-up or production activities and depends on the part produced or set-up. For production of the parts, dies are necessary, which have to be maintained after producing certain parts. Since during maintenance the dies are not available for production, maintenance has to be considered in mid-term lot sizing. Some dies provide two or more cavities for the same or different products which are then produced in coupled production. The provision of raw material has to be improved by calculating required steel coils. Production lots have to be integer multiples of raw material units. As the declared customer demands can be much smaller than the production output of one steel coil, production capacity consumption has to be calculated on the basis of the output of the steel coils.

[151] In [Kur11] (p. 49) it is said that the difficulties of solving optimization problems for practical instances have been reduced due to the development of efficient algorithms and improved hardware performance. In [Kal02] (p.36) it is stated that practical problem instances can usually be solved to optimality using linear programs as the resulting problem matrix is sparse.

4.2 Short-Term Lot Sizing and Scheduling

The short-term lot sizing and scheduling method has to generate valid, cost-effective operative production schedules. Set-up costs, inventory holding costs, production costs, and personnel costs for set-up teams, as well as maintenance costs, have to be considered. The results of the mid-term planning horizon, represented by expected ending inventories and declared customer demands, have to be used to calculate production lots and schedules which satisfy customer demands. The use of costly set-up teams during expensive shifts has to be minimized. As the set-up teams are available shift-wise, set-ups should be concentrated into a few shifts if total costs are to be reduced. Production of workforce-intensive parts should be carried out during cheaper shifts, but only if customer demands permit this and the sum of the costs does not increase. Generated short-term production plans have to consider the limited capacity of machines, which is reduced by production, set-ups or coil changes. Different production speeds depending on the product, sequence-dependent set-up times, and times for coil changes, need to be taken into account. In short-term lot sizing and scheduling, maintenance of the dies has to be considered. During maintenance, production of the related parts is not possible. Some dies have several cavities which produce different parts simultaneously. Hence, coupled production has to be taken into account as well. Coil changes have to be planned according to the coil size and the calculated production output.

4.3 Coupling of Mid-Term and Short-Term Planning

Another action point is to couple mid-term and short-term planning approaches. As the mid-term planning method has broader information about upcoming demands, planned production quantities have to be transferred to the short-term planning method. As the short-term planning method possesses information about the actual system state, it is necessary to communicate planning results from the short-term planning method to the mid-term planning method in order to guarantee that both procedures are based on up-to-date information and to be able to generate feasible and practicable planning results.

In summary, interfaces between both planning approaches and between the actual state of the production system and the planning procedure have to be defined by using the means available in linear programming.

5 Concept

After describing relevant action points, this chapter is dedicated to defining the concept for solving the previously described problem. The first sub-chapter describes and explains a prioritization of goals and requirements. Another topic is the decomposition of the problem. Then, mid-term lot size planning is explained. All required inputs and determined outputs are defined and clarified. After that, short-term schedule planning is explained using the same structure. Last but not least, coupling of both partial models as well as the integration into the real production is clarified in the following sub-section.

5.1 Goals, Requirement Prioritization and Decomposition of the Problem

As was said in section 2.1, it is essential for competitiveness that customer demands are satisfied as much as possible. The guarantee of supply availability is therefore the highest goal which has to be considered in the planning procedure. The requirements for achieving this goal are capacitated. The importance of each requirement depends on the flexibility to adapt capacity and its costs. The next priorities in the planning procedure are machine and workforce utilization. As the specialized machines entail high investments, the capacity of the machines, which cannot be adapted flexibly on a day-to-day basis, has to be used in the best possible way. The influence on the operative variable costs leads to the necessity of improving workforce capacity utilization, especially set-up time utilization. Both priorities are closely related to each other as the available workforce capacity influences the productivity of the machines and vice versa. Parallel set-ups at different machines have to be avoided, if only one single set-up team is available. As the production depends on dies which are individually designed and constructed for each product and are often only available in limited amounts, lot sizes are limited due to maximum die life. In combination with the coil sizes, which are the raw material units used, lot and batch sizes are restricted. These are the last two priorities which have to be regarded in the planning procedure. Due to the quick response to demands of raw material and loading equipment suppliers, availability does not affect planning and is therefore not regarded during lot sizing. As described by Domschke, Scholl and Voß in their textbook, the target is to minimize the overall costs. Other targets like the maximization of the service level or uniform capacity utilization are modeled using constraints.[152]

As stated before, the production system states as well as inputs like demand data can vary in reality and it is therefore not useful to spend a lot of effort in calculating detailed plans for a long horizon. Hence, it makes sense to subdivide the planning problem into sub-problems where the decision spectrum and decision detail of the sub-problems depend on the time and relevance for the actual production. Considering the mentioned priorities, two planning horizons are identified for operative production lot sizing. During mid-range planning, which starts on day 4 and ends with day 14 in the case study, production amounts to satisfy customer demands are defined on a daily basis considering given restrictions for lots and batches. Machine capacity limits and capacity utilization due to set-ups, coil changes and part production are calculated. As maintenance of dies takes time and can impede the production of parts, it is also considered during mid-range planning. Mid-range planning outputs serve as a planning basis for neighbored processes like raw material supply, the personnel planning department, loading equipment logistics, the die maintenance department etc. which then are responsible for providing requirements. The production cost, maintenance cost and personnel cost differences between days are considered, too. A more detailed differentiation of costs on the basis of shifts, for instance, is not possible in mid-term planning, but it is in short-term planning because of a higher planning granularity. In short-term planning, the same restrictions are taken into account but in a more detailed way. Other restrictions are added as well to generate a detailed production schedule for, in this case, the first three days. Besides customer demands, machine utilization and worker utilization - especially utilization of set-up teams - are considered. The avoidance of parallel set-ups at different machines reduces the loss of machine capacity due to missing set-up personnel and keeps set-up teams continuously working. Therefore, set-up-dependent set-up times are explicitly planned, as set-ups reduce production capacity. Maximum die life is never exceeded. Coil changes are explicitly planned as they reduce production capacity, too.

The next sections describe how the sub-problem is modeled. Which inputs are required to calculate the values of the desired output variables representing planning decisions is also discussed.

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[152] In [DSV97], 11 criteria for classifying lot sizing problems were identified: the level of information, time-based development of model parameters, the selection of the planning horizon, the number of products, the number of production stages, the consideration of capacities, characterization of relevant costs, the consideration of backlogs, production speeds, the transfer-type of the product and the targets are differentiated to classify lot sizing problems.

5.2 Mid-Term Lot Sizing Considering Multidimensional Restrictions

Within this section, the model for mid-term lot size planning is described and explained in detail. First, relevant inputs are defined and calculations to obtain specific parameters are explained. The following sub-chapter is dedicated to the outputs expected. After that, the model is elucidated in detail.

5.2.1 Input

This sub-section is dedicated to the inputs of the mid-term lot size planning. First, financial parameters are explained and some are calculated by given parameters. After that, parameters for variable initialization are determined. Then, production parameters are explained.

5.2.1.1 Financial Parameters

Calculation of lots and the distribution of calculated lots along the mid-term planning horizon require several input data. In order to generate optimal plans, relevant costs have to be considered during lot size planning. Inventory holding costs cM_p^{inv} are product dependent. They include capital commitment, which is calculated on the basis of the selling price $price_p$ of a product multiplied by a given interest rate cM^{ir}, as well as warehousing costs cM_p^{w} applying to a part.

$$cM_p^{w} + price_p * cM^{ir} = cM_p^{inv}$$

Next, set-up costs have to be taken into account. Sequence dependency of set-ups is not considered in mid-term planning. Consequently, it is enough to consider average estimates for set-up costs $cM_{p,tM}^{setup}$. Maintenance costs $cM_{d,tm}^{mtnc}$ have to be taken into account because otherwise, plans would be generated which provoke more maintenance, inducing too-high maintenance costs. In order to be able to guarantee availability, an ending inventory is set. Achieving this ending inventory has less priority than fulfilling announced, fixed customer demands. Consequently, it is desirable to use production capacity for announced demands instead of using it to fill the inventory. That means that it is possible to fall below the desired ending inventory and to lose the guarantee of availability. This risk is taken into account with the cost factor for imputed stock-outs cM_p^{so}, which consist of the selling price of a product $price_p$ multiplied by a defined factor representing the consequences cc of the inability to supply to customers:

$$price_p * cc = cM_p^{so}$$

Lastly, production costs $cM_{p,tm}^{prod}$ have to be taken into account. The costs are period and part dependent. They are based on given manufacturing costs and on the day-type factor.

$$pco_{p,t} * dtc = cM_{p,tm}^{prod}$$

5.2.1.2 Parameters for Variable Initialization

Besides costs, inventory, lot and maintenance parameters have to be considered. The available inventory level has to be transmitted to the model. This is done by initializing the parameter ϖiM_p, which defines the initial inventory level for each product. Planned lots have to obey several restrictions. Lots can overlap periods and, among other variables, die maintenance is controlled and triggered by the lot variable. Therefore, it is necessary to initialize the lot variable, too. The parameter $\varpi lotM_{m,p}$ is used to transmit the actual cumulative quantity of the lot. The initial production state is defined by $\varpi binxM_{m,p}$. Maintenance states and maintenance progress are considered in the model. That is the reason why the parameters $\varpi mbinM_p$ and ϖmpM_p are necessary to initialize whether maintenance is actually going on or not with respect to the maintenance progress.

Another parameter which has to be defined is the desired ending inventory used to guarantee availability. The parameter eiM_p has to be set for each product $p \in P$. Fixed values for ending inventories are not suitable because of missing adaptability and flexibility. Changes in customer demands or product run-outs are difficult to consider. Moreover, fixed-ending inventory levels are always either too small, resulting in supply shortfalls, or too large, resulting in high inventory holding costs and inventory risks. An algorithm for calculating flexible, self-adapting ending inventory levels has been designed. On the basis of the last production days and monthly demand forecasts dfM_p, the ending inventories are calculated easily, although information about capacities, exact demands and production times after the planning horizon are missing. As this situation fits the preconditions of the economic order quantity, the economic order quantity can be used as a basic component:

$$i^*(p) = \sqrt{\frac{2 * dfM_p * 12 * \frac{\sum_{t \in TM} cM_{p,tm}^{setup}}{|TM|}}{cM_p^{yw} + price_p * cM^{yir}}}$$

Then, a function has to be defined, which determines the last production day of a product:

Let φ:undefined mid-term period (F1)
$\{\varphi\} : \Phi$
Let $\lambda : (P, TM) \to TM \bigcup \Phi,\ (p, tm) \mapsto \lambda(p, tm) := tm$
A function that determines the last production mid-term period
$tm \in TM \bigcup \Phi$ of product $p \in P : \lambda(p, tm) = \tau$

Ending inventory of $p \in P$ is calculated depending on the value of $\lambda(p, tm) = \tau$.

If $\tau \equiv \varphi$ and $\varphi \in \Phi$ the last production mid-term period could not be defined.[153] Then, the ending inventory is set to the economic order quantity $eiM_p := i^*(p)$.

If $\tau \in TM$, the ending inventory is interpolated assuming that the last production lot of $p \in P$, ending in mid-term period τ, equates the economic order quantity $i^*(p)$ and assuming that the exit speed of a product[154] is constant with $\frac{dfM_p}{30}$:

$$eiM_p := i^*(p) - \frac{dfM_p}{30} * (\tau - TM_{\max})$$

This method has two main advantages: First, the ending inventory is dynamically calculated. Monthly demand variations are taken into account so that the planned inventory is always on an adequate level. The second advantage is the generation of stabilized production sequences by considering the last production period. The planning method for the mid-term horizon - the model on which the planning method is based is described in the next sub-section - guarantees that the production capacity of one mid-term period is never exceeded. The interpolation of every product's stock depending on the last day of production results in the avoidance of simultaneous stock-outs of too many products which could not be produced due to resulting missing daily production capacity. The consequence of avoiding simultaneous stock-outs of products is that the production se-

[153] This is especially the case at product start-ups.

[154] The exit speed of a product is calculated by dividing the monthly demand forecast by the length of a month. To ease calculation an average of 30 days is used.

quence calculated in the planning method, which takes practical constraints into account, is virtually continued after the end of the planning horizon. Demand fluctuations after the planning horizon are absorbed. Changes of the plans within the planning horizon, which result in lesser acceptance in practice, are minimized.

The following illustration visualizes the method. For simplification purposes, only one product is displayed and used to explain how the method works:

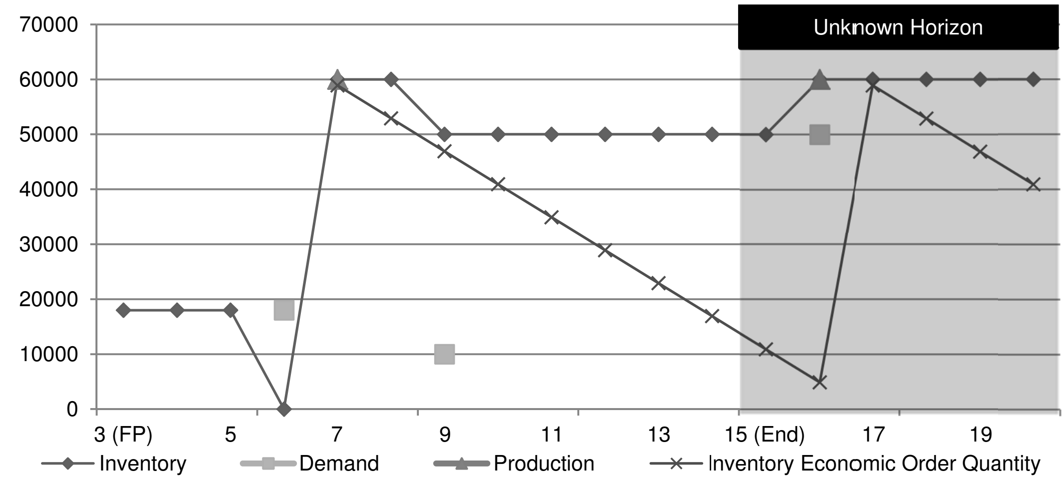

Figure 17: Visualization of Ending Inventory

In this example, the mid-term planning horizon ends on day 15. There is no detailed information available about the days after day 15. Consequently, the relatively high demand on day 16 would not be considered in the planning procedure and only capacity utilization for covering demands on days 6 and 9 would be planned. By setting an ending inventory at the end of day 15, that is, at the end of the planning horizon, this situation is avoided as monthly demand forecasts are used to calculate the economic order quantity. It is assumed that the economic order quantity is available on stock at the end of the last production day. The minimum inventory is interpolated for every day, assuming that the inventory is reduced every day by the average daily demand. The real inventory is then able to satisfy the demand on day 16.

5.2.1.3 Production Parameters

Besides financial parameters and parameters for variable initialization, production parameters are used as inputs to model the production. In order to calculate the capacity consumption of production, the production time for one part $pt_{p,m}$ has to be determined because the capacity limitation is defined by the available production time in one period. In this case, one mid-term period is one day. One period[155] consists of the time tM_{tm} less break time btM_{tm}. The remaining time cannot be used completely for production. There exist some tasks like cleaning or small maintenance tasks which cannot be planned in detail but estimated on the basis of experience. These tasks reduce the maximum utilization. Therefore, it has to be reduced by the maximum degree of utilization of the machine $m \in M$ factor udM_m. Monthly demand forecasts are available and represented by dfM_p. Exact demands announced by customers, which are contractually fixed with small tolerances, are stored in $dM_{p,tm}$. The average set-up time for a product is expressed in stM_p. Maintenance of dies takes more than one period. The average maintenance progress per mid-term time-period is defined by the parameter $mpM_{m,p}$. Production lots have to be designed as integer multiples of raw material units. The size of the steel coils is stored in the batch size parameter bs_p for each product $p \in P$. The size of steel coils varies. As the variance is not crucial, and a direct consideration of the individual coil size would increase complexity, average values are taken into account. First, a set C^p is defined. This set groups the coils $c \in C$ which can be used as raw material units for the production of a product $p \in P$. With this set, it is possible to calculate the average size, that is, the average weight of the coils $avgcs_p$, depending on their matching with a part $p \in P$:

$$avgcs_p := \sum_{c \in C^p} size(c) * \frac{1}{\left|C^p\right|} \quad \forall p \in P$$

The average weight of a coil is not suitable for defining lots directly. With the charge weight of a product, the number of parts which can be produced from one coil is calculated ($cout_p$). In this calculation, the number of parts produced simultaneously has to be taken into account. Any potential remainder has to be ignored.

$$cout_p := \left\lfloor \frac{avgcs_p}{chw_p} * \frac{1}{\left|CP_p\right|} \right\rfloor$$

The interrelation between the mid-term planning method and the short-term planning method prohibits the simple use of the average output of the coils $cout_p$ as batch-size. As explained in section 5.3, batches and lots have to fit to short-term periods. In order to avoid discrepancies, this has to be considered during mid-term planning. The batch-size

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[155] In the case study, one mid-term period is defined by a day containing 24 hours of time-based capacity, which is then further reduced by break time and machine utilization.

has to be defined in the same way as in short-term planning, where the size of short-term periods, that is, the time-based length, is considered:

$$bs_p := \left\lfloor \frac{cout_p}{tsS * pt_p * 60} \right\rfloor * tsS * pt_p * 60$$

Last but not least, maximum and minimum lot sizes $maxlot_p$ and $minlot_p$ have to be parameterized. The absolute minimum for a lot is the batch size bs_p. A higher minimum lot size can also be set, if necessary. The maintenance of a die overlaps several mid-term time-periods.[156] Therefore, the maintenance time has to be converted into a number of maintenance periods:

$$mtM_p := \left\lfloor \frac{mtnc_p}{tsM} \right\rfloor$$

Having defined and explained the calculation of all relevant inputs, the expected outputs have to be declared and explained in further detail. This is done in the next sub-section.

5.2.2 Output

The result of the planning model, which is described in the next sub-section, is represented by values of defined variables. First, there is the production variable $xM_{m,p,tm} \in \mathbb{N}^0$, which is used to store the amount of parts produced on machine $m \in M$ in a mid-term period $tm \in TM$. If production is running on, the binary variable $binxM_{m,p,tm}$ is activated. Then, the inventory variable $iM_{p,tm} \in \mathbb{N}^0$ is used to get the amount of parts available in the inventory. The variable $miM_{p,n} \in \mathbb{N}^0$ is used to evaluate the gap between the achievable inventory and the desired ending inventory level eiM_p at the end of the planning horizon. Another variable named $lotM_{m,p,tm} \in \mathbb{N}^0$ stores the cumulative quantity of the amount actually produced since the last die maintenance. Set-ups are managed by binary variables $binsM_{m,p,tm}$ and $binsrM_{m,p,tm}$. The former is activated if a product change is necessary. On this basis, capacity reductions and set-up costs are planned. The latter represents the case where a set-up requiring only low effort is executed. This is the case whenever products with different identifications but which

[156] In the case study, maintenance takes about 70 hours. That corresponds to three mid-term periods in the model.

are very similar or even identical are produced consecutively.[157] The variables $bcM_{m,p,tm} \in \mathbb{N}^0$ serve as counting variables for complete batches. Die maintenance is managed by three other variables: the binary variable $binmM_{m,p,tm}$, indicating whether maintenance is actually going on; a progress variable $cmM_{m,p,tm}$, storing the percentage of the maintenance progress; and, last but not least, the binary variable $fmM_{m,p,tm}$, representing the completion of maintenance.

5.2.3 Model

The mid-term horizon, which is in this case a planning period between day 4 and day 14, is modeled using a big-bucket linear programming model. In one time-period, it is possible that multiple actions like production of several parts, set-ups or coil changes are planned.

In order to define whether two products are produced in coupled production, whether two products have to use the same die, or whether a product can be produced with a machine, the following functions are used.

Let $\mathcal{B} = \{0,1\}$ and (F2)
$\gamma : (P,P) \to \mathcal{B}, \quad (p,q) \mapsto \gamma(p,q) := b$
A function that determines whether two products $p, q \in P$ are produced in coupled production:
$\gamma(p,q) = 1$, if p,q are produced in coupled production.

Let $\mathcal{B} = \{0,1\}$ and (F3)
$\delta : (P,P) \to \mathcal{B}, \quad (p,q) \mapsto \delta(p,q) := b$
A function that determines whether two products $p, q \in P$ are produced with the same die:
$\delta(p,q) = 1$, if p,q are produced with the same die.

[157] In the case study, there are several products which are identical but which have different identification numbers. The reason for that is to ease the differentiation between different subsequent processes.

Let $\mathcal{B} = \{0,1\}$ and (F4)

$\rho : (P, M) \rightarrow \mathcal{B},\ \ (p,m) \mapsto \rho(p,m) := b$

A function that determines whether a product $p \in P$ can be produced with machine $m \in M$:

$\rho(p,m) = 1$, if p can be produced with m .

As products which are produced in coupled production use the same die, it is clear that the following expression applies:

$$\gamma(p,q) \rightarrow \delta(p,q)$$

Target function:

$$\begin{aligned} \min Z = & \sum_{m \in M} \sum_{p \in P} \sum_{tm \in TM} \left(binsM_{m,p,tm} - binsrM_{m,p,tm} \right) * cM^{setup}_{p,tm} \\ & + \sum_{m \in M} \sum_{p \in P} \sum_{tm \in TM} xM_{m,p,tm} * cM^{prod}_{p,tm} \\ & + \sum_{m \in M} \sum_{p \in P} \sum_{tm \in TM} binmM_{m,p,tm} * cM^{mtnc}_{d,tm} \\ & + \sum_{p \in P} \sum_{tm \in TM} iM_{p,tm} * cM^{inv}_{p} \\ & + \sum_{\substack{p \in P \\ n = TM_{max}}} miM_{p,n} * cM^{so}_{p} \end{aligned}$$

The target function of the mid-term lot sizing consists of several main components: First, estimated set-up costs are calculated. The sequence dependency of set-up costs is ignored, except in the case where no set-up is needed for two parts.[158] In addition, production costs, which vary depending on the day,[159] are another component of the target function. Being only an aggregated model, shift-based costs are ignored. Then, maintenance costs are also considered and calculated. Then, inventory holding costs are considered. Last but not least, imputed stock-out costs for each product for the last period of the rolling planning horizon are calculated and inserted into the target function. Whenever $miM_{p,n}$ is greater than 0, the availability of product p cannot be guaranteed.

[158] In the case study, there are parts which are identical but have different part numbers in order to differentiate them from ones needed in subsequent production processes. These parts are produced sequentially but do not induce set-ups at the machines.

[159] Differentiation of production costs depending on the days can be read in 2.2.1.3.

The estimated sum of the costs for the consequences[160] is calculated by multiplying cM_p^{so} for every product.

The linear programming model consists of several restrictions describing practical conditions. A basic condition for all lot sizing models is a constraint which sets all inputs equal to outputs. In this case, this is done by the inventory balance equation.

$$iM_{p,tm-1} + \sum_{m \in M} xM_{m,p,tm} = dM_{p,tm} + iM_{p,tm} \qquad \forall p \in P; \forall tm \in TM \tag{1}$$

The inventory balance equation (1) guarantees that announced demands are covered either by the inventory available until $t \in TM$ and/or by manufactured products during the mid-term period $t \in TM$. Hence, production is necessary to cover demands. But, production capacity is limited and has to be restricted.

$$\begin{aligned} &\sum_{p \in P} xM_{m,p,tm} * pt_p * \frac{1}{|CP_p|} \\ &+ \sum_{p \in P} \left(binsM_{m,p,tm} + binsM_{m,p,tm} \right) * stM_p * \frac{1}{|CP_p|} \\ &\leq \left(tM_{tm} - btM_{tm} \right) * udM_m \\ &\forall m \in M; \forall tm \in TM \end{aligned} \tag{2}$$

Available production capacity, which is calculated on the basis of times, cannot be exceeded. The upper limit is calculated by the available day production time multiplied by the maximum degree of utilization experienced which represents capacity losses due to coil changes, cleaning, and other minor works on the machine which are not explicitly planned. The rest of the available capacity is then shared by production and set-up times, in both cases considering coupled production (2).

$$xM_{m,p,tm} - maxlot_p * binxM_{m,p,tm} \leq 0 \qquad \forall m \in M; \forall p \in P; \forall tm \in TM \tag{3}$$

$$xM_{m,p,tm} - binxM_{m,p,tm} \geq 0 \qquad \forall m \in M; \forall p \in P; \forall tm \in TM \tag{4}$$

Binary variables $binxM_{m,p,tm}$, which indicate the production of a product in a mid-term period, are activated by restrictions (3) and (4). The maximum lot size parameter for

[160] High contract penalties are the consequence in the short term. In the long term, competitive advantage is endangered.

product p is taken as Big-M. The indication variables for production are necessary to model further practical aspects and are used in other restrictions described later.

$$\begin{gathered} lotM_{m,p,tm} - lotM_{m,q,tm} = 0 \\ \forall m \in M; \forall tm \in TM; \\ \forall p,q \in P \wedge \gamma(p,q) = 1 \wedge p \neq q \end{gathered} \tag{5}$$

$$\begin{gathered} binmM_{m,p,tm} - binmM_{m,q,tm} = 0 \\ \forall m \in M; \forall tm \in TM; \\ \forall p,q \in P \wedge \gamma(p,q) = 1 \wedge p \neq q \end{gathered} \tag{6}$$

$$\begin{gathered} fmM_{m,p,tm} - fmM_{m,q,tm} = 0 \\ \forall m \in M; \forall tm \in TM; \\ \forall p,q \in P \wedge \gamma(p,q) = 1 \wedge p \neq q \end{gathered} \tag{7}$$

$$\begin{gathered} cmM_{m,p,tm} - cmM_{m,q,tm} = 0 \\ \forall m \in M; \forall tm \in TM; \\ \forall p,q \in P \wedge \gamma(p,q) = 1 \wedge p \neq q \end{gathered} \tag{8}$$

$$\begin{gathered} xM_{m,p,tm} - xM_{m,q,tm} = 0 \\ \forall m \in M; \forall tm \in TM; \\ \forall p,q \in P \wedge \gamma(p,q) = 1 \wedge p \neq q \end{gathered} \tag{9}$$

Constraint (9) models coupled production. The solution space is reduced by valid inequalities (5) to (8), which are based on the same function $\gamma(p,q)$ calculating whether two products are manufactured in coupled production.

$$\begin{gathered} lotM_{m,p,tm} \leq xM_{m,p,tm} + lotM_{m,p,tm-1} \\ \forall m \in M; \forall p \in P; \forall tm \in TM \end{gathered} \tag{10}$$

$$\begin{gathered} lotM_{m,p,tm} \geq xM_{m,p,tm} + lotM_{m,p,tm-1} - maxlot_p * (1 - binmM_{m,p,tm}) \\ \forall m \in M; \forall p \in P; \forall tm \in TM \end{gathered} \tag{11}$$

$$\begin{gathered} lotM_{m,p,tm} + \sum_{\substack{q \in P \\ p \neq q \\ \delta(p,q)=1 \\ \gamma(p,q)=0}} \frac{1}{|CP_q|} lotM_{m,q,tm} \leq maxlot_p \\ \forall m \in M; \forall tm \in TM; \forall p \in P \end{gathered} \tag{12}$$

Constraints (10) and (11) define lot variables $lotM_{m,p,t}$. If $binmM_{m,p,tm}$ is not active, that means that no maintenance is planned in period tm; the combination of (10) and (11) constrain $lotM_{m,p,tm} = xM_{m,p,tm} + lotM_{m,p,tm-1}$. Restriction (12) guarantees that the abrasion of a die is correctly taken into account. As a die can be used for multiple products, the lot size, that is, the cumulative production amount, has to be calculated for all related parts.

$$binmM_{m,p,tm} + binxM_{m,p,tm} \leq 1 \quad \forall m \in M; \forall p \in P; \forall tm \in TM \tag{13}$$

In (13), it is guaranteed that no production is planned simultaneously with die maintenance.

$$binmM_{m,p,tm} - cmM_{m,p,tm} \leq 0 \quad \forall m \in M; \forall p \in P; \forall tm \in TM \tag{14}$$

$$mpM_{m,p} * binmM_{m,p,tm} + cmM_{m,p,tm-1} = cmM_{m,p,tm} + fmM_{m,p,tm} \quad \forall m \in M; \forall p \in P; \forall tm \in TM : t > 0 \tag{15}$$

Constraints (14) and (15) manage the die maintenance progress, whereas (14) guarantees that the progress variable $cmM_{m,p,tm}$ is greater than 0 whenever die maintenance $binmM_{m,p,tm}$ is active; (15) guarantees that the defined daily maintenance progress factor $mpM_{m,p}$ is correctly added to $cmM_{m,p,tm}$ until die maintenance is finished, indicated by $fmM_{m,p,tm}$.

$$binmM_{m,p,tm} - binmM_{m,q,tm} = 0 \quad \forall m \in M; \forall tm \in TM; \forall p,q \in P \wedge \delta(p,q) = 1 \wedge p \neq q \tag{16}$$

Maintenance variables for all other parts produced with the same die are connected and activated or deactivated by (16).

Maintenance can be triggered in two different ways: The first way is to start die maintenance directly after a die change. Another possibility is to start die maintenance after a defined maximum cumulative quantity. The first two restrictions describe the first option. The latter option is modeled by the following restriction.

$$binmM_{m,p,tm} + binxM_{mp,tm} + \sum_{\substack{q \in P \\ \wedge \delta(p,q)}} \frac{1}{|CP_q|} * binxM_{m,q,tm} \geq binxM_{m,p,tm-1} \quad \forall m \in M; \forall p,q \in P; \forall tm \in TM : tm > 0 \tag{17}$$

Depending on the maintenance rule used, restriction (17) is either inserted into the model or not. Restriction (17) is necessary to represent the case where maintenance is started after changing production to another product which is not being produced with the same die. If maintenance in a previous period $binxM_{m,p,tm-1}$ is active, production is either continued or finished, indicated by $binmM_{m,p,tm}$, in the actual mid-term period $tm \in TM$ (17). If finished, maintenance is activated in the following mid-term period $tm \in TM$, indicated by $binmM_{m,p,tm}$.

$$\begin{gathered} binmM_{m,p,tm+1} - binxM_{m,p,tm} - binxM_{m,p,tm-1} - binxM_{m,q,tm} \geq -2 \\ \forall tm \in TM : tm > 0; \forall m \in M \\ \forall p,q \in P \wedge \delta(p,q) = 1 \wedge p \neq q \end{gathered} \tag{18}$$

$$\begin{gathered} binmM_{m,p,tm+1} - binxM_{m,p,tm} - binxM_{m,p,tm-1} - binxM_{m,q,tm+1} \geq -2 \\ \forall tm \in TM : tm > 0; \forall m \in M \\ \forall p,q \in P \wedge \delta(p,q) = 1 \wedge p \neq q \end{gathered} \tag{19}$$

Maintenance of the die used to produce $p \in P$ is started in a mid-term period $(tm+1) \in TM$, when production of product $p \in P$, which has been started in at least two mid-term periods before, is changed to product $q \in P$ in a mid-term period $tm \in TM$. In propositional logic, this can be represented like this:

$$\begin{gathered} binxM_{m,p,tm} \wedge binxM_{m,p,tm-1} \wedge \left(binxM_{m,q,tm} \vee binxM_{m,q,tm+1} \right) \rightarrow binmM_{m,p,tm+1} \\ \forall tm \in TM : tm > 0; \forall m \in M \\ \forall p,q \in P \wedge \delta(p,q) = 1 \wedge p \neq q \end{gathered}$$

The algebraic formulation can be found in (18) and (19).

$$\begin{gathered} binxM_{m,p,tm-1} - binsrM_{m,p,tm} \geq 0 \\ \forall m \in M; \forall p \in P; \forall tm \in TM : tm > 0 \end{gathered} \tag{20}$$

$$\begin{gathered} binxM_{m,p,tm} - binsrM_{m,p,tm} \geq 0 \\ \forall m \in M; \forall p \in P; \forall tm \in TM : tm > 0 \end{gathered} \tag{21}$$

$$\begin{gathered} -binxM_{m,p,tm-1} - binsrM_{m,q,tm} \geq -1 \\ \forall m \in M \\ \forall p,q \in P \wedge \delta(p,q) = 0 \wedge p \neq q \\ \forall tm \in TM : tm > 0 \end{gathered} \tag{22}$$

$$-binxM_{m,p,tm} - binsrM_{m,q,tm} \geq -1$$
$$\forall m \in M$$
$$\forall p,q \in P \wedge \delta(p,q) = 0 \wedge p \neq q \qquad (23)$$
$$\forall tm \in TM : tm > 0$$

Period-overlapping lots are represented by restrictions (20) to (23). As no set-up is necessary, no capacity reduction has to be calculated for the actual mid-term period if production is continued from previous periods (20), (21). Restrictions (22) and (23) are the algebraic formulation of the expression

$$binsrM_{m,p,tm} \rightarrow (binxM_{m,p,tm-1} \wedge binxM_{m,p,tm})$$
$$\forall tm \in TM : tm > 0; \forall m \in M$$
$$\forall p,q \in P \wedge \delta(p,q) = 0 \wedge p \neq q$$

This expression activates the set-up reduction whenever a product is produced in two consecutive mid-term time-periods.

$$lotM_{m,p,tm} = bs_p * bcM_{m,p,t}m$$
$$\forall m \in M; \forall p \in P; \forall tm \in TM \qquad (24)$$

As real capacity usage for production has to be calculated correctly,[161] batch-wise production dependent on steel coil sizes has to be considered in mid-term lot sizing already, constraint (24) is inserted. It constrains planned lots to integer multiples of raw material units.

$$iM_{p,TM_{min}} = \varpi iM_p$$
$$\forall p \in P; TM_{min} \in TM \qquad (25)$$

$$miM_{p,TM_{max}} + iM_{p,TM_{max}} \geq eiM_p$$
$$\forall p \in P; TM_{max} \in TM \qquad (26)$$

Restrictions (25) and (26) define starting and ending inventories. Missing amounts at the end of the planning horizon are saved in $miM_{p,n}$ and inserted into the target function in order to consider the loss of guarantee of availability towards the customer.

[161] Customer demands vary within the product portfolio. High runners' demands are usually higher than the output of a steel coil. In contrast, there exist some low runners, whose demands within the considered time horizon are smaller than the output of a steel coil. As it is a practical constraint to produce in batches of raw material units, that is, in integer multiples of steel coil outputs, capacity utilization has to be calculated on the basis of the production time for a whole coil instead of the production time for a relatively small customer demand.

$$lotM_{m,p,TM_{min}} = \varpi lotM_{m,p}$$
$$\forall\, p \in P; m \in M; TM_{min} \in TM \tag{27}$$

$$binxM_{m,p,TM_{min}} = \varpi binxM_{m,p}$$
$$\forall\, p \in P; m \in M; TM_{min} \in TM \tag{28}$$

Equations (27) and (28) set the initial values for the lot variable or the state of the binary production variable.

$$mbinM_{p,TM_{min}} = \varpi mbinM_{p}$$
$$\forall\, p \in P; TM_{min} \in TM \tag{29}$$

$$mbinM_{p,TM_{min}} = \varpi mbinM_{p}$$
$$\forall\, p \in P; TM_{min} \in TM \tag{30}$$

$$mpM_{p,TM_{min}} = \varpi mpM_{p}$$
$$\forall\, p \in P; TM_{min} \in TM \tag{31}$$

Last but not least, restrictions (29) to (31) initialize the variables which are relevant for maintenance regarding the first mid-term period of the rolling horizon.

5.3 Short-Term Scheduling Considering Multidimensional Restrictions

This section contains the description and explanations necessary for understanding the model for short-term schedule planning. Parameters are elucidated in the first sub-section. Then, the outputs are explained. Lastly, the model is explained in detail containing all the restrictions required to consider practical conditions.

5.3.1 Input

In this sub-section, inputs of the short-term lot size planning are determined. First, financial parameters are described and some are calculated by other parameters. After that, parameters for variable initialization are determined. Lastly, production parameters are explained.

5.3.1.1 Financial Parameters

During short-term schedule planning, diverse costs have to be taken into account in order to achieve cost-optimal plans. First, c_p^{inv} $p \in P_{ST}$, inventory holding and capital commitment costs of a product for a single short-term period are parameterized. Sequence-dependent set-up costs $c_{m,p,q,ts}^{setup}$ $p \in P_{ST}$ have to be regarded as well. Set-up costs depend on the time-period in which they are executed. This is similar with production costs $c_{m,p,ts}^{prod}$ $p \in P_{ST}$ and maintenance costs $c_{m,p,ts}^{mtnc}$ $p \in P_{ST}$, which are machine-, product- and period-dependent. In order to calculate the costs of the plans correctly, coil change costs $c_{m,p,ts}^{cc}$ $p \in P_{ST}$ are parameterized. Set-up team costs are calculated and stored separately in c_{ts}^{team} $p \in P_{ST}$ for each short-term period.

5.3.1.2 Parameters for Variable Initialization

In order to be able to link the system state in reality with planning, the relevant data has to be transmitted to the planning method. This is done by parameter settings for variable initialization. The following parameters have to be set with updated values determined in real production.

First, there is the initial inventory ϖiS_p representing the actual inventory of products $p \in P_{ST}$. In order to couple short-term and mid-term lot size planning, eiS_p is set. The coupling of the partial models is explained in further detail in section 5.4. The current real world production is initialized using $\varpi prodS_{m,p,t}$ $p \in P_{ST}$. Parameter $\varpi lotS_{m,p}$ $p \in P_{ST}$ is used to define the initial cumulative quantity of a production lot. If the minimal lot size is exceeded in the initialization short-term period, the parameter $\varpi mlS_{m,p}$ $p \in P_{ST}$ is set to 1. Maintenance has to be considered in mid-term planning as well as in short-term planning. Maintenance state and maintenance progress are initialized with $\varpi mbinS_p$ $p \in P_{ST}$ and ϖmpS_p $p \in P_{ST}$. The actual set-up state of a machine is important for the planning method. The machine status is initialized with binary variable $\varpi sS_{m,p}$ $p \in P_{ST}$. It is possible that a machine is in the process of being set up when planning starts. This is done by setting the value of the binary variable $\varpi rS_{m,p,q}$ $p,q \in P_{ST}$. In combination with the binary parameter $\varpi mstS_{m,p,q,ts}$ $p,q \in P_{ST}$, which is set to 1 if the set-up was finished in the short-term period $ts \in TS$, and the parameter $\varpi csS_{m,p,q}$ $p,q \in P_{ST}$, representing the set-up progress, the set-up of a machine $m \in M$

from product $p \in P_{ST}$ to product $q \in P_{ST}$ during the first planning period for short-term planning can be transmitted completely from the real production world to the model. The number of available set-up teams is initialized with parameter $\varpi teamsS$ and limited by $teamLimS_{ts}$. Last but not least, real production statuses of coil changes have to be transmitted to the model. The parameter $\varpi ReS_{m,p}$ $p \in P_{ST}$ initializes the number of completely used steel coils of the actual lot. The initialization of the slack variable $\varpi SlS_{m,p}$ $p \in P_{ST}$ guarantees that the coil usage is modeled correctly, and then the parameter $\varpi cwS_{m,p}$ $p \in P_{ST}$ sets the value of the corresponding variable for the coil change.

5.3.1.3 Production Parameters

Production parameters are necessary for describing the relevant production. Basically, all parameters define capacity limits and capacity usages for different actions or entities. The production speed parameter $pptS_{p,m}$ $p \in P_{ST}$ defines how many products of $p \in P_{ST}$ can be produced on a machine $m \in M$ in one short-term period. The demand of one product $p \in P_{ST}$ in the short-term period $ts \in TS$ is set. As in the actual practical case, demands are available on a daily basis. As the periods of the short-term planning are shorter, available demand data has to be transformed beforehand. In this case, demands announced for the mid-term period $tm \in TM$ are transformed into demands of the final short-term period of the mid-term period $(tm-1) \in TM$. Consequently, it is guaranteed that ordered products are available on time. Maximum and minimum lot sizes are parameterized, defining values for $maxlot_p$ and $minlot_p$ $p \in P_{ST}$, as in mid-term planning. The calculation of the batch size parameter was already explained in 5.2.1.3. As the model, which is described in further detail in section 5.3.3, underlies the all-or-nothing assumption, set-up times, which are given in minutes, have to be converted to a number of corresponding short-term planning periods using the parameter tsS, which represents the length of a short-term period:

$$st_{p,q} = \left\lceil \frac{stMin_{p,q}}{tsS * 60} \right\rceil p,q \in P_{ST}$$

As the parts' usage of loading equipment differ from each other, $verbPLT_{p,lt}$ $p \in P_{ST}$ is determined. The parameter $kapaLT_{lt}$ limits the capacity of a loading equipment type.

5.3.2 Output

The result of the planning method is represented by values of variables used in the model. In this sub-section, variables for short-term planning are described.

First, there are the variables $prodS_{m,p,ts}$ $p \in P_{ST}$ and $xS_{m,p,ts}$ $p \in P_{ST}$. The values of these variables determine whether production of a product $p \in P_{ST}$ is taking place at machine $m \in M$ in the short-term planning period $ts \in TS$ accordingly the production amount. The set-up status is stored in variable $sS_{m,p,ts}$ $p \in P_{ST}$. The calculated inventory is stored for every product in each short-term period in $iS_{p,ts}$ $p \in P_{ST}$. The cumulative quantity of produced products of the current lot can be obtained by reading variable $lotS_{m,p,ts}$. $p \in P_{ST}$. The auxiliary variable $mlS_{m,p,ts}$ $p \in P_{ST}$ determines whether the minimal lot size was already exceeded. A product change is then possible. The number of completed batches, that is, completely used coils, is stored in $reS_{m,p,ts}$ $p \in P_{ST}$. In order to be able to model coil usage on the basis of a cumulative production quantity, a slack variable $rlS_{m,p,ts}$ $p \in P_{ST}$ is introduced. The binary variable $cwS_{m,p,ts}$ $p \in P_{ST}$ is set true when a coil is changed. Sequence-dependent set-ups are represented by $rS_{m,p,q,ts}$ $p,q \in P_{ST}$. The corresponding binary variable is set true when a machine is being set up from product $p \in P_{ST}$ to product $q \in P_{ST}$ during the short-term period $ts \in TS$ whereas $p \neq q$ and $\gamma(p,q)=0$. With binary variables $mstS_{m,p,q,t}$ and real variables $cs_{m,p,q,ts}$, the end or the progress of a set-up are managed. The variable $teams_t$ defines how many set-up teams are required within a short-term period $ts \in TS$. Binary indicator variables $binS^{r}_{m,ts}$, $binS^{prod}_{m,ts}$, and $binS^{cw}_{m,ts}$ enable the identification and separation of activities on machines during a short-term period. Another binary variable $binS^{mtnc}_{m,p,ts}$ $p \in P_{ST}$ represents the maintenance activity.

5.3.3 Model

The short-term horizon, which is in this case a planning period between day 1 and day 3, is modeled using a small-bucket linear programming model. The all-or-nothing assumption applies. Consequently, it is not possible that different actions like production, set-up or coil changes are planned in one single time-period.

Target function:

$$\min Z = \sum_{ts\in TS} teams_{ts} * c_{ts}^{team}$$
$$+\sum_{m\in M}\sum_{p\in P}\sum_{\substack{q\in P_{ST}\\ \gamma(p,q)=0\\ p\neq q}}\sum_{ts\in TS} rS_{m,p,q,ts} * c_{m,p,q,ts}^{ruest}$$
$$+\sum_{m\in M}\sum_{p\in P_{ST}}\sum_{ts\in TS} cwS_{m,p,ts} * c_{m,p,ts}^{cw}$$
$$+\sum_{m\in M}\sum_{p\in P_{ST}}\sum_{ts\in TS} xS_{m,p,ts} * c_{m,p,ts}^{prod}$$
$$+\sum_{m\in M}\sum_{p\in P_{ST}}\sum_{ts\in TS} binS_{m,p,ts}^{mtnc} * c_{m,p,ts}^{mtnc}$$
$$+\sum_{p\in P_{ST}}\sum_{ts\in TS} iS_{p,ts} * kl_{p}$$

The model's target function consists of several components. The first component is the sum of set-up team costs. Then, the sum of sequence-dependent set-up costs is added. The costs are activated depending on the value of the binary variables $rS_{m,p,q,ts}$ $p,q\in P_{ST}$. The sum of the coil changing costs is added as well as the sum of the production costs and maintenance costs. These costs depend on the time-period in which they are created. The sum of inventory holding costs is finally added.

Let $\mathcal{B}=\{0,1\}$ and (F5)

$\sigma:(\text{TS},\text{TS})\to\mathcal{B},\quad (u,v)\mapsto\sigma(u,v):=b$

The above is a function which determines whether two short-term periods $u,v\in TS$ belong to the same shift $s\in S$.
$\sigma(u,v)=1$, if u,v are part of the same shift.

$$iS_{p,t-1}+\sum_{m\in M} xS_{m,p,t} = dS_{p,ts} + iS_{p,ts} \qquad \forall\, p\in P_{ST};\forall ts\in TS: ts > TS_{min} \tag{1}$$

An inventory balance equation (1) guarantees that the input equals all outputs and that the inventory is always correctly filled.

$$pptS_{p,m} * prodS_{m,p,ts} = xS_{m,p,ts} \qquad \forall m\in M;\forall ts\in TS;\forall p\in P_{ST} \tag{2}$$

The production output $x_{m,p,ts}$ is calculated by constraint (2), multiplying the production amount per period with the corresponding binary production variable.

$$\sum_{p\in P_{ST}} sS_{m,p,ts}\frac{1}{|CP_p|}=1 \qquad (3)$$
$$\forall m\in M;\forall ts\in TS$$

Restriction (3) guarantees that during one short-term period, a machine is always set to produce only one product, or one product with all other coupled products. Therefore, set-up states are always well defined and it is not possible that a machine has no set-up state.

$$sS_{m,p,ts} - sS_{m,q,ts} = 0$$
$$\forall m\in M;\forall ts\in TS; \qquad (4)$$
$$\forall\, p,q\in P_{ST} \wedge \gamma(p,q)=1\wedge p\neq q$$

$$prodS_{m,p,ts} - prodS_{m,q,ts} = 0$$
$$\forall m\in M;\forall ts\in TS; \qquad (5)$$
$$\forall\, p,q\in P_{ST} \wedge \gamma(p,q)=1\wedge p\neq q$$

$$prodS_{m,p,ts} - sS_{m,p,ts} \leq 0 \qquad (6)$$
$$\forall m\in M\ ;\forall p\in P_{ST};\forall ts\in TS$$

The interconnection of set-up state variables and the interconnection of production variables in the case of coupled production are modeled with restrictions (4) and (5). As production of a certain part requires the machine to be in the corresponding set-up state, it is necessary to introduce (6), which ensures this.

$$sS_{m,p,ts-1} + sS_{m,q,ts} - rS_{m,p,q,ts} \leq 1$$
$$\forall p,q\in P_{ST} \wedge \gamma(p,q)=0\wedge p\neq q; \qquad (7)$$
$$\forall m\in M;\forall ts\in TS: ts>TS_{min}$$

A set-up state change requires a set-up which is modeled with the variables $rS_{m,p,q,ts}$. In order to represent the coherence of set-up state variables and set-up variables, (7) is essential.

$$rS_{m,p,q,ts} \leq binS^{r}_{m,ts}$$
$$\forall p,q\in P_{ST} \wedge \gamma(p,q)=0\wedge p\neq q; \qquad (8)$$
$$\forall m\in M;\forall ts\in TS$$

$$\sum_{\substack{q \in P_{ST} \\ q \neq p \wedge \gamma(p,q)=0}} \sum_{p \in P_{ST}} rS_{m,p,q,ts} \leq binS^{r}_{m,ts} * \max\left(\sum_{p \in P_{ST}} \sum_{\substack{q \in P_{ST} \\ q \neq p \wedge \gamma(p,q)=0}} \left|CP_p\right| * \left|CP_q\right| \right) \quad (9)$$
$$\forall m \in M; ts \in TS$$

$$\sum_{p \in P_{ST}} \sum_{\substack{q \in P_{ST} \\ q \neq p \wedge \gamma(p,q)=0}} rS_{m,p,q,ts} \geq binS^{r}_{m,ts} \quad (10)$$
$$\forall m \in M; ts \in TS$$

Restrictions (8) to (10) control the activation of the binary indication variable for set-ups $binS^{r}_{m,ts}$. In restriction (9), the maximum number of all possible $p, q \in P_{ST} : q \neq p \text{ and } \gamma(p,q) = 0$ combinations is taken as Big-M.

$$cwS_{m,p,ts} \leq binS^{cw}_{m,ts} \quad (11)$$
$$\forall p, q \in P_{ST}; \forall m \in M; \forall ts \in TS$$

$$\sum_{p \in P_{ST}} cwS_{m,p,ts} \leq binS^{cw}_{m,ts} * \left|P_{ST}\right| \quad (12)$$
$$\forall m \in M; ts \in TS$$

$$\sum_{p \in P_{ST}} cwS_{m,p,ts} \geq binS^{cw}_{m,ts} \quad (13)$$
$$\forall m \in M; ts \in TS$$

Restrictions (11) to (13) are necessary to control the activation/deactivation of the binary indication variable for coil changes $binS^{cw}_{m,ts}$. As Big-M, the cardinality of the product set $\left|P_{ST}\right|$ is considered.

$$prodS_{m,p,ts} \leq binS^{prod}_{m,ts} \quad (14)$$
$$\forall p \in P_{ST}; \forall m \in M; \forall ts \in TS$$

$$\sum_{p \in P_{ST}} prodS_{m,p,ts} \leq binS^{prod}_{m,ts} * \left|P_{ST}\right| \quad (15)$$
$$\forall m \in M; ts \in TS$$

$$\sum_{p \in P_{ST}} prodS_{m,p,ts} \geq binS^{prod}_{m,ts} \quad (16)$$
$$\forall m \in M; ts \in TS$$

Similar to the previously defined control of the binary indication variables, $binS^{prod}_{m,ts}$ is activated/deactivated. Restrictions (10), (13) and (16) are redundant but improve model performance by reducing solution space.

$$binS^{prod}_{m,ts} + binS^{r}_{m,ts} + binS^{cw}_{m,ts} \leq 1 \quad \forall m \in M; ts \in TS \tag{17}$$

Restriction (17) guarantees that the exclusive activities of production, set-up and coil changes are never done simultaneously at one single machine. Modeling of sequence-dependent set-up times in combination with coupled production has to be correctly achieved. Erroneous set-up state changes, shown in the following illustration, in which machine states are no longer well defined, have to be eliminated.

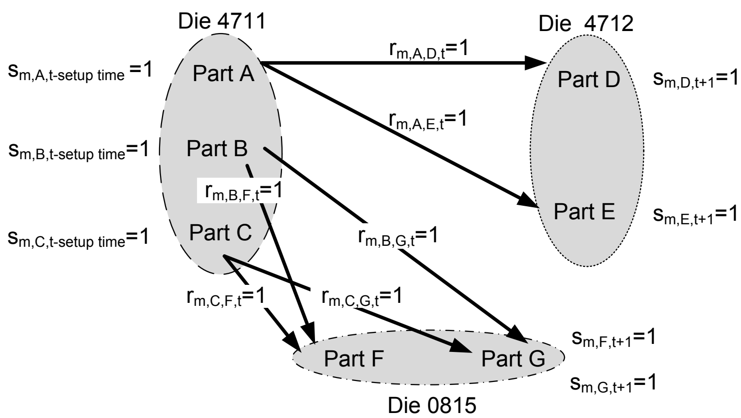

Figure 18: Erroneous Modeling of Set-up State Changes at Coupled Products

$$rS_{m,p,q,ts} \leq sS_{m,p,ts-st_{p,q}} \quad \forall m \in M; \forall p,q \in P_{ST} : \delta(p,q) = 0; \quad \forall ts \in TS : ts > TS_{min} + st_{p,q} \tag{18}$$

$$rS_{m,p,q,ts} \leq sS_{m,q,ts+st_{p,q}} \quad \forall m \in M; \forall p,q \in P_{ST} : \delta(p,q) = 0; \quad \forall ts \in TS : ts < TS_{max} - st_{p,q} \tag{19}$$

$$sS_{m,q',ts} \leq 1 - \sum_{\substack{p \in P_{ST} \\ p \neq q' \\ p \neq q"}} \sum_{\substack{q" \in P_{ST} \\ q" \neq q' \\ \gamma(q',q")=0 \\ \gamma(p,q")=0}} \frac{1}{|CP_p| * |CP_{q"}|} mstS_{m,p,q",ts}$$
$$\forall m \in M; \forall ts \in TS; \forall q' \in P_{ST} \tag{20}$$

Restrictions (18) to (20) prevent the set-up state variable from taking incorrect values after set-up. With (18), a set-up from product p to q ($p,q \in P_{ST}$) is avoided whenever the set-up state that exists before set-up $sS_{m,p,t-st_{p,q}}$ is not set correctly to p. Restriction (19) works in a similar way: a set-up from product p to q ($p,q \in P_{ST}$) is avoided whenever the set-up state that exists after set-up $sS_{m,q,t+st_{p,q}}$ is not correctly set to q. These restrictions are only valid for a subset of TS as $sS_{m,q,TS_{max}+st_{p,q}}$ is not defined. Additionally, (20) guarantees that the set-up state $sS_{m,q',ts}$ is never set true when another set-up is completed, indicated by $mstS_{m,p,q",ts}$.

$$csS_{m,p,q,ts} \leq rS_{m,p,q,ts+1}$$
$$\forall m \in M; \forall ts \in TS : ts < TS_{max};$$
$$\forall p,q \in P_{ST} \wedge \gamma(p,q) = 0 \wedge p \neq q \tag{21}$$

$$csS_{m,p,q,ts-1} + rS_{m,p,q,ts} \frac{1}{st_{p,q}} = mstS_{m,p,q,ts} + csS_{m,p,q,ts}$$
$$\forall m \in M; \forall ts \in TS;$$
$$\forall p,q \in P_{ST} \wedge \gamma(p,q) = 0 \wedge p \neq q \tag{22}$$

Inequality (21) sets the cumulative set-up time $csS_{m,p,q,ts}$, which represents the progress of a set-up in per cent, to 0 whenever the set-up, managed by binary variable $rS_{m,p,q,ts}$, is deactivated. Equality (22) saves the cumulative set-up time and sets the variable $mstS_{m,p,q,ts}$ true, when a set-up was finished. For every period in which a set-up is taking place, the progress percentage per set-up period $\frac{1}{st_{p,q}} = \frac{tsS * 60}{stMin_{p,q}}$ is added to $csS_{m,p,q,ts}$.

$$rS_{m,p',q,ts} = rS_{m,p",q,ts}$$
$$\forall m \in M; \forall ts \in TS;$$
$$\forall p', p", q \in P_{ST} \wedge \gamma(p', p") = 1 \wedge \gamma(p', q) = 0 \wedge \gamma(p", q) = 0 \wedge$$
$$p' \neq p" \wedge p' \neq q \wedge p" \neq q \tag{23}$$

$$rS_{m,p,q',ts} = rS_{m,p,q'',ts}$$
$$\forall m \in M; \forall ts \in TS;$$
$$\forall q', q'', p \in P_{ST} : \gamma(q', q'') = 1 \wedge \gamma(p, q') = 0 \wedge$$
$$\gamma(p, q'') = 0 \wedge q' \neq q'' \wedge q' \neq p \wedge q'' \neq p \tag{24}$$

The set-up of coupled products is managed by (23) and (24). These restrictions are necessary to activate all set-up variables correctly in order to be able to model the practical situation in which products are produced simultaneously with one single die. The following figure illustrates how the set-up and set-up state variables are set, so that product changes of coupled products are correctly modeled.

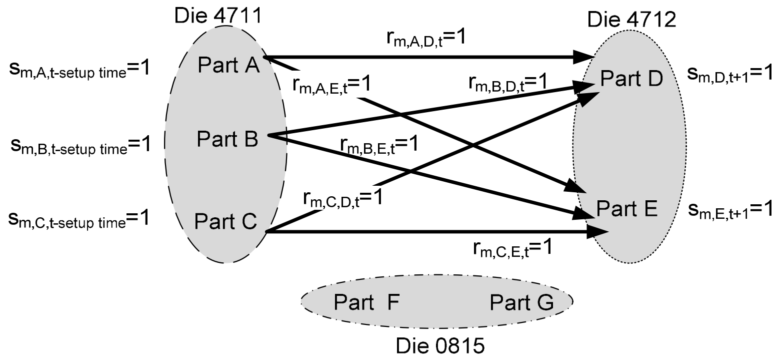

Figure 19: Correct Modeling of Set-up State Changes for Coupled Products

$$mstS_{m,p',q,ts} = mstS_{m,p'',q,ts}$$
$$\forall m \in M; \forall ts \in TS;$$
$$\forall p', p'', q \in P_{ST} \wedge \gamma(p', p'') = 1 \wedge \gamma(p', q) = 0 \wedge \gamma(p'', q) = 0 \wedge$$
$$p' \neq p'' \wedge p' \neq q \wedge p'' \neq q \tag{25}$$

$$mstS_{m,p,q',ts} = mstS_{m,p,q'',ts}$$
$$\forall m \in M; \forall ts \in TS;$$
$$\forall q', q'', p \in P : \gamma(q', q'') = 1 \wedge \gamma(p, q') = 0 \wedge$$
$$\gamma(p, q'') = 0 \wedge q' \neq q'' \wedge q' \neq p \wedge q'' \neq p \tag{26}$$

$$csS_{m,p',q,ts} = csS_{m,p'',q,ts}$$
$$\forall m \in M; \forall ts \in TS;$$
$$\forall p', p'', q \in p \in P_{ST} \wedge \gamma(p', p'') = 1 \wedge \gamma(p', q) = 0 \wedge \gamma(p'', q) = 0 \wedge$$
$$p' \neq p'' \wedge p' \neq q \wedge p'' \neq q \tag{27}$$

$$csS_{m,p,q',ts} = csS_{m,p,q'',ts}$$
$$\forall m \in M; \forall ts \in TS;$$
$$\forall q', q'', p \in p \in P_{ST} : \gamma(q', q'') = 1 \wedge \gamma(p, q') = 0 \wedge$$
$$\gamma(p, q'') = 0 \wedge q' \neq q'' \wedge q' \neq p \wedge q'' \neq p \quad (28)$$

Although restrictions (25) and (26) are sufficient to model the described case, further redundant equalities (27) to (28) are introduced in order to make the solution space smaller.

$$binS_{m,p,ts}^{mtnc} = binS_{m,q,ts}^{mtnc}$$
$$\forall m \in M; \forall ts \in TS; \forall p, q \in p \in P_{ST} : p \neq q, \delta(p, q) = 1 \quad (29)$$

$$binS_{m,p,ts+1}^{mtnc} \geq mstS_{m,p,q,ts}$$
$$\forall m \in M; \forall ts \in TS; \forall p, q \in p \in P_{ST} : p \neq q, \delta(p, q) = 0 \wedge \gamma(p, q) = 0 \quad (30)$$

Restrictions (29) and (30) activate maintenance. Equation (29) activates maintenance of all products whose production is based on the same die. Inequality (30) activates the maintenance variable after having terminated a set-up. This is the first way that maintenance is triggered. This inequality is not introduced into the model, if the maintenance is triggered by cumulative production.

$$cmS_{m,p,ts-1}^{mtnc} + binS_{m,p,ts+1}^{mtnc} * \frac{tsS}{tsM} * mpM_{m,p} = fmS_{m,p,ts}^{mtnc} + cmS_{m,p,ts}^{mtnc}$$
$$\forall m \in M; \forall ts \in TS; p \in p \in P_{ST} \quad (31)$$

$$fmS_{m,p,ts}^{mtnc} \leq binS_{m,p,ts}^{mtnc}$$
$$\forall m \in M; \forall ts \in TS; p \in p \in P_{ST} \quad (32)$$

Maintenance progress is modeled with restrictions (31) and (32). Every maintenance period, $\frac{tsS}{tsM} * mpM_{m,p}$ is added to the cumulated maintenance progress variables $cmS_{m,p,ts}^{mtnc}$. When maintenance is finished, indicated by $fmS_{m,p,ts}^{mtnc}$ set true, the progress variable is reset to 0.

$$lotS_{m,p,ts} \leq lotS_{m,p,ts-1} + xS_{m,p,ts}$$
$$\forall m \in M; \forall ts \in TS : ts > TS_{min}; \forall p \in p \in P_{ST} \quad (33)$$

$$lotS_{m,p,ts} \geq lotS_{m,p,ts-1} + xS_{m,p,ts} - maxlot_p * binS^{mtnc}_{m,p,ts} \quad \forall m \in M; \forall ts \in TS; \forall p \in p \in P_{ST} \tag{34}$$

Restrictions (33) and (34) allow $lotS_{m,p,ts}$ to be the cumulative production quantity until the next maintenance takes place, which resets the lot variable.

$$lotS_{m,p,ts-1} + xS_{m,p,t} \geq \sum_{\substack{q \in P_{ST} \\ p \neq q \\ \delta(p,q)=0}} \frac{minlot_p}{|CP_q|} rS_{m,p,q,ts}$$

$$\text{if } minlot_p > bs_p \text{, otherwise}$$

$$lotS_{m,p,ts-1} + xS_{m,p,ts} \geq \sum_{\substack{q \in P_{ST} \\ p \neq q \\ \delta(p,q)=0}} \frac{bs_p}{|CP_q|} rS_{m,p,q,ts} \tag{35}$$

$$\forall m \in M; \forall ts \in TS : ts > TS_{min}; \forall p \in P_{ST}$$

$$lotS_{m,p,ts} + \sum_{\substack{q \in P_{ST} \\ p \neq q \\ \delta(p,q)=1 \\ \gamma(p,q)=0}} \frac{1}{|CP_q|} lotS_{m,q,ts} \leq maxlot_p \quad \forall m \in M; \forall ts \in TS; \forall p \in P_{ST} \tag{36}$$

Inequalities (35) and (36) set the lot variables correctly and guarantee that available practical constraints regarding lots are considered. Depending on the relation between the set minimal lot size and the batch size, a different restriction for the minimal lot size is relevant for model (35). In (36) the lot size is constrained to the maximum lot size defined by the die. As other products are produced by using and fretting the same die, the cumulative production quantity of all products has to be considered.

$$lotS_{m,p,ts} = bs_p * reS_{m,p,ts} + slS_{m,p,ts} \quad \forall m \in M; \forall ts \in TS; \forall p \in P_{ST} \tag{37}$$

$$rlS_{m,p,ts} \leq bs_p * prodS_{m,p,ts} \quad \forall m \in M; ts \in TS; p \in P_{ST} \tag{38}$$

$$bs_p * cwS_{m,p,ts} \geq slS_{m,p,ts-1} - slS_{m,p,ts} \quad \forall m \in M; \forall ts \in TS : ts > TS_{min}; \forall p \in P_{ST} \tag{39}$$

$$bs_p * \left(prodS_{m,p,ts} - prodS_{m,p,ts+1} \right) \leq slS_{m,p,ts}$$
$$\forall m \in M; \forall ts \in TS : ts < TS_{max}; \forall p \in P_{ST} \tag{40}$$

$$binS^{mntc}_{m,p,ts+1} * \frac{maxlot_p}{bs_p} + cwS_{m,p,ts} + reS_{m,p,ts-1} = reS_{m,p,ts}$$
$$\forall m \in M; \forall ts \in TS : ts > TS_{min} \wedge ts < TS_{max}; \forall p \in P_{ST} \tag{41}$$

Restrictions (37) to (38) model the coil-oriented production depending on the determined batch size bs_p. Equality (37) is used to model the relation between lots and batches. The slack is introduced to be able to model period-overlapping batches. It can be seen as a cumulative quantity of the actual batch. The variable $slS_{m,p,ts} > 0$ can only apply when production is going on, which is also modeled by valid inequality (39). Inequalities (40) and (41) activate the coil change variable. For the activation of $binS^{mntc}_{m,p,ts+1}$, $\frac{maxlot_p}{bs_p}$ is calculated as Big-M. The reason for introducing the binary maintenance variable into this equation is that the restriction has to be deactivated in the case of maintenance, as otherwise, the model would be infeasible. This is because of the relation between the cumulative quantity of used coils and the variable for the cumulative quantity of the lot $lotS_{m,p,ts}$, which is reset at the beginning of the die maintenance process.

$$\sum_{m \in M} binS^{r}_{m,ts} \leq teams_{ts}$$
$$\forall ts \in TS \tag{42}$$

$$teams_{ts} \leq teamLimS_{ts}$$
$$\forall ts \in TS \tag{43}$$

$$teams_u = teams_v$$
$$u, v \in TS \wedge \sigma(u,v) = 1 \tag{44}$$

The number of required set-up teams is determined by (42). A limitation of available teams is modeled with inequality (43). Actually, the number of parallel set-ups at different machines is limited by the number of available set-up teams, because set-up teams are the most cost-intensive requirement. The upper limit could also be determined by other requirements. Equality (44) is dedicated to activating the set-up team variables for a whole shift. This is because in practice set-up personnel are only available shift-wise.

Depending on the capacity situation and on the cost benefit, set-ups are bundled into cheaper shifts as a consequence of restriction (44).

$$-reqLT_{m,p,lt} + \frac{verbPLT_{p,lt}}{kapaLT_{lt}} \sum_{ts \in TS} xS_{m,p,ts} \leq 0 \qquad (45)$$
$$\forall lt \in LT; \forall p \in P_{ST}; \forall m \in M$$

The department responsible for the disposition of loading equipment has to take care that the correct type of loading equipment is available on time and in the correct amounts. Required loading equipment is calculated in (45), taking into consideration the capacity of the boxes. Consequently, management of loading equipment is simplified and can be improved.

$$iS_{p,TS_{min}} = \varpi iS_p \qquad (46)$$
$$\forall p \in P_{ST}$$

$$iS_{p,TS_{max}} \geq eiS_p \qquad (47)$$
$$\forall p \in P_{ST}$$

Variables have to be initialized with practical values in order to link the real production with the model for planned production. First, initialization equations (46) and (47) determine the inventory at the beginning and the ending inventory of the short-term planning horizon. The latter one is important for the linkage of the mid-term and short-term planning methods. Details about the interconnection can be read in the next sub-section.

$$lotS_{m,p,TS_{min}} = \varpi lotS_{m,p} \qquad (48)$$
$$\forall m \in M; p \in P_{ST}$$

$$mlS_{m,p,TS_{min}} = \varpi mlS_{m,p} \qquad (49)$$
$$\forall m \in M; p \in P_{ST}$$

$$ReS_{m,p,TS_{min}} = \varpi ReS_{m,p} \qquad (50)$$
$$\forall m \in M; p \in P_{ST}$$

$$slS_{m,p,TS_{min}} = \varpi SlS_{m,p} \qquad (51)$$
$$\forall m \in M; p \in P_{ST}$$

$$cwS_{m,p,TS_{min}} = \varpi cwS_{m,p} \qquad (52)$$
$$\forall m \in M; p \in P_{ST}$$

Equations (48) to (52) initialize the values for lots and batches. Numerical as well as binary variables are set to the values corresponding to the system state in reality.

$$sS_{m,p,TS_{min}} = \varpi sS_{m,p} \qquad \forall m \in M; p \in P_{ST} \tag{53}$$

$$prodS_{m,p,TS_{min}} = \varpi\, prodS_{m,p} \qquad \forall m \in M; p \in P_{ST} \tag{54}$$

Binary set-up state and production variables are set in (53) and (54).

$$\varpi rS_{m,p,q,TS_{min}} = \varpi rS_{m,p,q} \qquad \forall m \in M; p,q \in p \in P_{ST} : \delta(p,q) = 0 \tag{55}$$

$$mstS_{m,p,q,TS_{min}} = \varpi mstS_{m,p,q} \qquad \forall m \in M; p,q \in p \in P_{ST} : \delta(p,q) = 0 \tag{56}$$

$$csS_{m,p,q,TS_{min}} = \varpi csS_{m,p,q} \qquad \forall m \in M; p,q \in p \in P_{ST} : \delta(p,q) = 0 \tag{57}$$

$$teamsS_{TS_{min}} = \varpi teamsS \tag{58}$$

Variables representing set-up state and the progress and finish of set-up as well as team variables are initialized in equations (55) to (58).

$$binS^{mtnc}_{m,p,TS_{min}} = \varpi binS^{mtnc}_{m,p} \qquad \forall m \in M; p \in p \in P_{ST} \tag{59}$$

$$cmS^{mtnc}_{m,p,TS_{min}} = \varpi cmS^{mtnc}_{m,p} \qquad \forall m \in M; p \in p \in P_{ST} \tag{60}$$

$$fmS^{mtnc}_{m,p,TS_{min}} = \varpi\, fmS^{mtnc}_{m,p} \qquad \forall m \in M; p \in p \in P_{ST} \tag{61}$$

The maintenance state and progress is transferred to the model initializing the corresponding variables (59) to (61).

In this section, the short-term schedule planning model was described in detail. First, required inputs and calculated outputs were explained. As this model has several interrelations with the mid-term lot size planning model as well as with the actual production system state, the coupling of the partial models as well as the integration into real-world production will be explained in the next section.

5.4 Coupling of Partial Models and Integration into Real Production

The last part of the concept contains two topics: First, there is the coupling of the previously described and explained planning models. The coupling is important as both models are interdependent. The interdependencies are clarified in order to give an understanding of how both models work together. The second topic is the integration or, in technical terms, the interface of the planning models with production in the real world. This is an important aspect in order to be able to transfer the developed theoretical models into practical production planning.

5.4.1 Coupling of Partial Models

The previously described partial models influence each other reciprocally by using their output to constrain or even define the variable values of the other model. A data interchange is provided by the models' input parameters for variables, which were described in the input sections 5.2.1.2 and 5.3.1.2 for mid-term lot size planning and short-term schedule planning respectively. Beginning with the mid-term lot size model, there are the parameters ϖiM_p, $\varpi lotM_{m,p}$, which define the initial inventory or the initial lot, $\varpi binxM_{m,p}$, which sets the production status of a product, and $\varpi mbinM_p$ and ϖmpM_p which define relevant maintenance variable values. The values for these parameters are obtained by calculating the results of the short-term schedule planning. The other interface direction from the mid-term planning results to short-term planning method is done by setting a single parameter value eiS_p. The precondition is that the end of the short-term planning horizon equals the beginning of the mid-term horizon:

$$TS_{max} = TM_{min}$$

First, the starting inventory for the mid-term planning is set:

$$iS_{p,ts} \rightarrow \varpi iM_p$$
$$\forall p \in P; ts \in TS : ts = TS_{max}$$

Second, the production activity is transmitted, in order to be able to consider the set-ups in the mid-term planning horizon correctly:

$$prodS_{m,p,ts} \rightarrow \varpi binxM_{m,p}$$
$$\forall m \in M; p \in P; ts \in TS : ts = TS_{max}$$

As maintenance can be controlled by the cumulative production quantity stored in the $lotS_{m,p,ts}$ variables, it is important to transfer the values to the corresponding mid-term parameters:

$$lotS_{m,p,ts} \rightarrow \varpi lotM_{m,p}$$
$$\forall m \in M; p \in P; ts \in TS : ts = TS_{max}$$

After that, maintenance has to be transferred correctly, otherwise it may be overlooked in mid-term planning that dies might not be available, and part production might be planned in an infeasible way. The binary indicator variables as well as the maintenance progress variables have to be transferred from the short-term to the mid-term planning parameters. The transfer of the progress is more complicated than the other transfers as the maintenance progress in the short-term planning depends on short-term planning periods and the maintenance progress in the mid-term planning depends on larger mid-term periods; a recalculation therefore has to be made before the values are transferred.

$$\frac{cmS^{mtnc}_{m,p,ts}}{mtM_p} * \frac{1}{mtM_p} \rightarrow \varpi cmS^{mtnc}_{m,p}$$
$$\varpi cmS^{mtnc}_{m,p} \rightarrow \varpi mbinM_{m,p}$$
$$\forall m \in M; p \in P; ts \in TS : ts = TS_{max}$$

This calculation is rather pessimistic. The maintenance progress during the first maintenance mid-term planning period is ignored. The following figure illustrates the values and the linkage with an example:

M-T Period	M1					M2				
M-T Mntnc	0					1				
M-T Prog.	0					>0				
S-T Period	S01	S02	S03	S04	S05	S06	S07	S08	S09	S10
S-T Mntnc	0	0	1	1	1	1	1	1	1	1
S-T Prog.	0	0	>0	>0	>0	>0	>0	>0	>0	>0

M-T Period	M3					M4					M5				
M-T Mntnc	1					1					0				
M-T Prog.	>0					>0					1				
S-T Period	S11	S12	S13	S14	S15	S16	S17	S18	S19	S20	S21	S22	S23	S24	S25
S-T Mntnc	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0
S-T Prog.	>0	>0	>0	>0	>0	>0	>0	1	1	1	1	1	1	1	1

Figure 20: Illustration of Maintenance Interconnection of Partial Models

Although maintenance was started within mid-term period M1 in short-term period S03 and the progress value at the end of M1 stored in S05 is higher than 0, the mid-term maintenance progress of M1 is still set to 0. This is because it is not possible to guarantee in practice that maintenance starts exactly when it is purported to by the results of the short-term planning. Consequently, maintenance time is reserved until the end of the mid-term planning period M4 and production can restart with the maintained die in M5 instead of in the middle of M4 in short-term period S18.

The parameter settings discussed so far are all dedicated to transferring information from the short-term planning results to the mid-term planning method. The setting for an ending inventory of the short-term planning horizon is dedicated to covering the other direction. The value is obtained from previously calculated mid-term planning results. As the planning horizon moves on, the inventory levels calculated in the mid-term planning can later be used in short-term planning.

$$iS_{p,TS_{max}} \geq eiS_p$$
$$\forall p \in P$$

This restriction, which was described in section 5.3.3, guarantees that production lots, brought forward by mid-term planning, are correctly considered during short-term planning. After describing the interconnection of both partial models, the next sub-section is dedicated to describing the integration of both models into real production.

5.4.2 Integration into Real Production

In the last section, it was described how the models are interconnected. In order to be able to turn planning results into reality, it is necessary that changes in the production reality are transmitted to the planning methods. Examples of changes can be inventory changes due to scrap or retouching work, or demand changes generated by customers. This section describes which parameters are changed in order to adapt the planning results to the production in reality.

The actual situation in production can be modeled in a summarized way by obtaining and transferring only some relevant values. These parameters were described in 5.3.1.2. Besides the initialization of the variables, the demand has to be taken into account. Slight demand changes can be considered in the short-term planning. Therefore, the demand $dM_{p,tm}$ is transferred to a short-term demand $dS_{p,ts}$ by mapping small and mid-term time-periods.

$$\theta:(TM)\rightarrow TS,\quad (tm)\mapsto\theta(tm):=ts \qquad \text{(F6)}$$

A function that determines the last short-term period $ts \in TS$ of a mid-term period $tm \in TM$

A function is defined which determines the last short-term period of a mid-term period. This function is then used to map the time-periods of the demands.

$$dM_{p,tm} = dS_{p,ts}$$
$$ts = \theta(tm), ts \in TS, tm \in TM$$

No mapping is necessary when demands which are situated in the mid-term planning horizon are changed. Besides the adaptation of the plans in the case study, plans have to consider that production does not end with the planning horizon. Therefore, the parameter eiM_p was defined[162] and set.

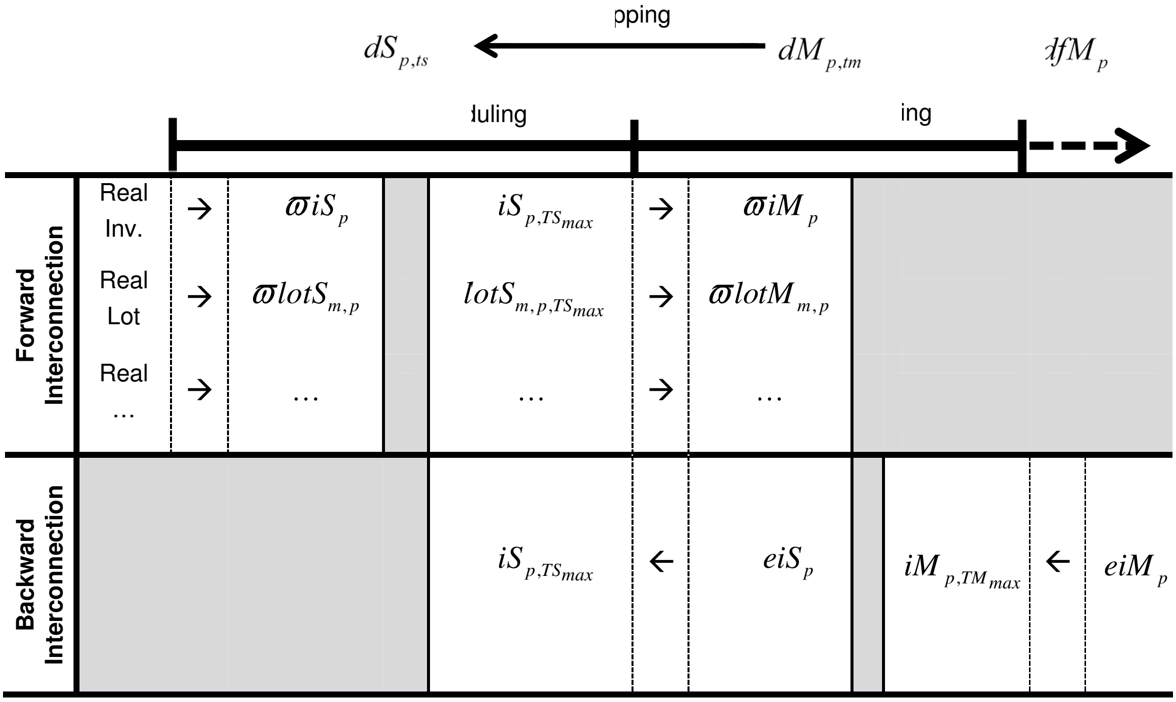

Figure 21: Summary of Partial Model Interconnection

This illustration shows how forward and backward interconnection of parameters and variables work. The integration of the planning models into the real world as well as the coupling of the models is visualized.

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[162] The calculation of the ending inventory is explained in 5.2.1.2.

5.4.3 Determination of Relevant Short-Term Planning Subsets

The lots calculated in the mid-term planning define which products are produced in which mid-term period $tm \in TM$. The short-term planning horizon only ranges over a subset of *TM*. Because of practical restrictions regarding lots and batches and because of the limitation of production capacity, only a subset of products $P_{ST} \subseteq P$ can be produced within the entire short-term planning horizon. Consequently, the short-term model size is significantly reduced in practical problem instances. This first sub-section describes how product subsets, which are relevant for short-term schedule planning, are determined. The following sub-section explains how data excluded during short-term schedule planning is extrapolated.

5.4.3.1 Determination of Short-Term Relevant Product Subset

Because of practical restrictions and limited production capacities, it is not possible in practice to produce the whole product portfolio during the limited short-term schedule planning horizon. The relevant subset of products has to be determined.

$$\begin{gathered} P_{ST} := \left\{ p \mid p \in P : iS_{p,TS_{min}} < eiS_p \right\} \cup \\ \left\{ p \mid p \in P : \varpi sS_{m,p} = 1, \forall m \in M \right\} \cup \\ \left\{ p \mid p, q \in P_{ST} : \gamma(p,q) = 1 \right\} \end{gathered}$$

The set is defined by all products which have to be produced by the end of the short-term planning horizon, determined by calculating the difference of the existing inventory at the initialization period TS_{min} and the desired production amount at the end of the short-term planning horizon eiS_p, and then adding to all coupled products all the products which are actually set up in the initialization period of the short-term planning horizon TS_{min}, represented by $\varpi sS_{m,p}$.

5.4.3.2 Extrapolation of Short-Term Irrelevant Data Sets

Inventories, lots, batches, maintenance data, and so on are only calculated and updated within the short-term model for those products $p \in P_{ST}$ which are relevant for short-term scheduling, in order to reduce model size and consequently improve performance. To guarantee data consistency and to be able to start planning at every point in time, data for other products, $p \notin P_{ST}$, has to be extrapolated. The extrapolation of most data is simple, as it is a simple copy process for all short-term periods:

$$iS_{p,ts} = \varpi iS_p \quad \forall p \in P, p \notin P_{ST}; ts \in TS \tag{1}$$

$$lotS_{m,p,ts} = \varpi lotS_{m,p} \quad \forall m \in M; p \in P, p \notin P_{ST}; ts \in TS \tag{2}$$

$$mlS_{m,p,ts} = \varpi mlS_{m,p} \quad \forall m \in M; p \in P, p \notin P_{ST}; ts \in TS \tag{3}$$

$$reS_{m,p,ts} = \varpi ReS_{m,p} \quad \forall m \in M; p \in P, p \notin P_{ST}; ts \in TS \tag{4}$$

$$slS_{m,p,ts} = \varpi SlS_{m,p} \quad \forall m \in M; p \in P, p \notin P_{ST}; ts \in TS \tag{5}$$

$$cwS_{m,p,ts} = \varpi cwS_{m,p} \quad \forall m \in M; p \in P, p \notin P_{ST}; ts \in TS \tag{6}$$

The extrapolation of the maintenance variables is more sophisticated. Maintenance is still going on in the background and the maintenance progress values have to be adapted correspondingly. Therefore, the following algorithm is necessary:

Do $\forall m \in M; \forall ts \in TS; p \in P, p \notin P_{ST}$
Do
$cmS^{mtnc}_{m,p,ts-1} + \frac{tsS}{tsM} * mpM_{m,p} \rightarrow cmS^{mtnc}_{m,p,ts}$ $1 \rightarrow binS^{mtnc}_{m,p,ts}$
While $cmS^{mtnc}_{m,p,ts-1} + \frac{tsS}{tsM} * mpM_{m,p} < 1$
If $cmS^{mtnc}_{m,p,ts-1} + \frac{tsS}{tsM} * mpM_{m,p} == 1$ then
$1 \rightarrow fmS^{mtnc}_{m,p,ts}$

5.5 Techniques to Improve Solution Time

The linear programming models described in sub-sections 5.2.2 and 5.3.3 consider lots of sets and many elements. Many relations between elements of the sets complicate the model further. Moreover, lots of constraints are taken into account. Changes of the model structure, decomposition techniques and relaxations are possible ways to improve solution time. The next two sub-sections are dedicated to describing the methods used for that purpose for mid-term lot size planning and short-term schedule planning.

5.5.1 Mid-Term Lot Size Planning

One way to improve the solution time of mid-term lot size planning models is to first solve a precedent model of relaxation and use the found solutions as possible starting solutions for the original modeled problem. The mid-term lot size planning can easily be relaxed by ignoring the constraint for the guarantee of availability. The guarantee of availability is modeled using the following constraint:

$$miM_{p,TM_{max}} + iM_{p,TM_{max}} \geq eiM_p$$
$$\forall p \in P; TM_{max} \in TM$$

Ignoring this inequality, valid solutions, which consider real announced demands and inventory within the mid-term planning horizon, can be generated quickly. Although the generated solution is a bad solution with no availability guarantee, it is useful for reducing the search space of the original problem.

Another way to improve solution performance is by introducing further inequalities, known a priori after analyzing the problem. An inequality can be calculated by carrying out a backward scheduling of the inventory.

$$iM_{p,tm-1} \geq dM_{p,tm} - tsM * \sum_{m \in M} udM_m * \frac{1}{pt_p * |CP_p|}$$
$$\forall p \in P; tm \in TM$$

The restriction states that the inventory $iM_{p,tm-1}$ has to be greater than the difference of the demand $dM_{p,tm}$ and the maximum production amount in period $tm \in TM$. This inequality is also applicable to improve short-term schedule planning.

5.5.2 Short-Term Schedule Planning

The short-term schedule planning model is very complex. Therefore, several approaches are necessary to guarantee processing times suitable for practice. First, two decomposition approaches will be described. After that, valid inequalities, as well as the modeling techniques used, are explained.

5.5.2.1 Using Past Solutions

One way to improve solution performance is to use past planning solutions. Not all parameters and system states are changed from one planning run to the next. The starting solution has to be adapted by considering the new planning horizon. Although the values for variables relevant to the new part of the planning horizon are not set, heuristics implemented in optimization software are able to find feasible solutions. Especially when the time between two planning runs is short, this is a suitable method for generating a starting solution from past planning runs.

5.5.2.2 Decomposition by Time Axis

The first decomposition approach described is the decomposition by time axis. The short-term planning horizon represented by the set of short-term periods TS can be subdivided according to their belonging to mid-term periods TM, which is determined by the following function.

$$\Theta : (TS) \rightarrow TM, \quad (ts) \mapsto \Theta(ts) := tm \qquad \text{(F6)}$$

Is a function that determines the mid-term period $tm \in TM$ of a short-term period $ts \in TS$

With this function, the set of short-term periods can be partitioned into subsets

$$TS_{tm} := \{\forall tm \in TM \mid tm = \Theta(ts) : \forall ts \in TS\}$$

The short-term model can then be processed for each partition separately, as relevant parameters regarding demands and minimum inventories at the end of each period are obtained from the mid-term lot sizing solutions. After that, all solutions are merged, so that a solution is obtained which corresponds to the whole set of short-term periods. The merged solution is not optimal for the entire short-term planning horizon but suits as a good starting solution.

5.5.2.3 Decomposition by Machines

Another decomposition approach is the decomposition of the problem by machines. The optimization procedure is sequentially started considering only one element of the machine set M. The result is a schedule, valid for each machine. If this decomposition is applied, restrictions of shared resources upon machines are ignored. In the case study, this is the limitation of set-up teams. The fusion of the decomposed sub-solutions considers this, and calculates the amount of required set-up teams. Although a very costly starting solution is generated, it enables the reduction of the search space of the original problem.

5.5.2.4 Valid Inequalities and Modeling Techniques

Besides decomposition approaches, further inequalities and modeling techniques can be applied to improve the performance to solve the model. The Constantino[163] inequality, for example, can be adapted to the current model. It models the logical conditions that production can be active in period t-1, or that a set-up is going on in period t, or that either production or set-up of another product is going on in period *ts*.

$$prodS_{m,p,ts-1} + \sum_{\substack{q \in P \\ \gamma(p,q) \neq 1}} rS_{m,p,q,ts} + \sum_{\substack{q' \neq q \\ q' \neq p}} \sum_{\substack{q \in P \\ q \neq p}} (prodS_{m,q',ts} - rS_{m,q',q,ts}) \leq 1$$
$$\forall p,q,q' \in P, ts \in TS$$

Another way to improve the solution is to use double variables instead of integer or Boolean variables. This depends on the variable selection and has to be tested as no general rule is applicable. In the case of the actual short-term model, the change of set-up and production variables from Boolean to fractional variables with 0 and 1 as lower and upper limits improved performance.

$$rS_{m,p,q,ts}, prodS_{m,p,ts} \in \{0,1\} \rightarrow rS_{m,p,q,ts}, prodS_{m,p,ts} \in [0,1]$$

Another improvement method is the disaggregation of restrictions. This was already mentioned in the model description. In this case only the restriction which guarantees that excluding actions cannot be executed simultaneously is disaggregated.[164]

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[163] See [Con00].

[164] See section 5.3.3 for more details.

6 Realization

In order to transfer the previously described theoretical concept into production reality, it has to be implemented and tested in realistic scenarios. In this chapter, the system design is described and explained. The integration into SAP is described in the following section; and then, calculated results are evaluated and compared with manual planning results.

6.1 System Description

In order to improve acceptance of the realized planning method, integration into the existing ERP System is helpful. Users do not have to switch from one software tool to another and this way redundant data management is avoided. The first sub-section describes the system architecture and explains the overall structure of the implemented system. Although data redundancy is minimized, some data has to be stored in a system database in order to improve data connection speed. Another argument for separate data management is that data can easily be added, merged and obtained in a beneficial way and calculated results can be stored quickly. The used database and its data structure are described in the following sub-section. Finally, the software structure is described.

6.1.1 Overall Architecture

In order to understand how the system is used and how it is integrated into the business environment, the overall system architecture is explained in this sub-section. The following figure illustrates the principle of operation of the system:

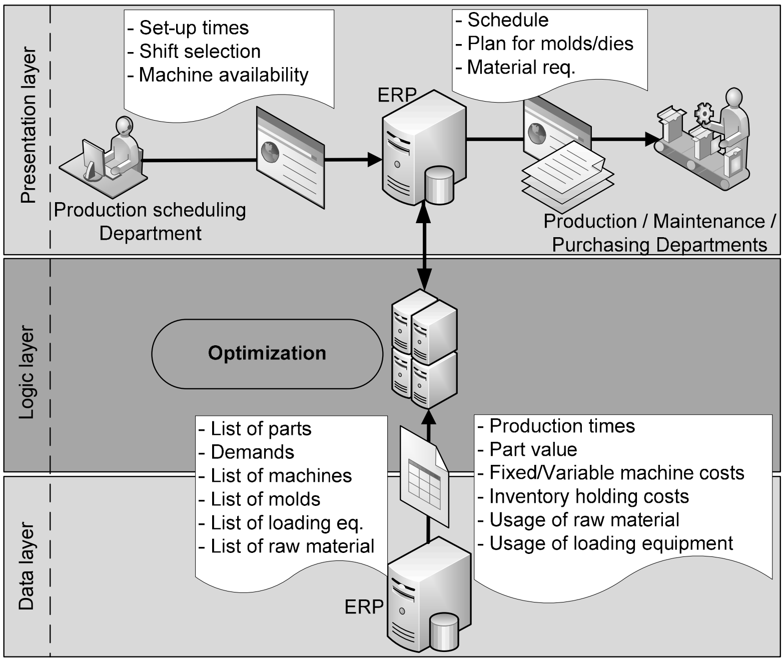


Figure 22: Overall System Architecture

The system can be subdivided into three main layers, as each layer works rather independently of the others. The interconnection is achieved by interfaces which have to be adapted to the systems used within the affected layers. The data layer is responsible for supplying the system with up-to-date data. In order to facilitate the actualization, the active ERP system should be used as a data source, as the actuality of the data stored there has to be guaranteed due to other processes within the company. Only a small selection of data is necessary for the lot sizing and scheduling optimization. First, the defined sets of the models have to be filled with entities. A list of the parts, demands, machines, dies and molds, loading equipment, and raw material, as well as data about available coils, have to be transmitted. Relations between the elements of the sets are also important in order to be able to consider them in the planning. Besides sets, parameters have to be obtained from the ERP system used. Production times, part prices, and machine costs, as well as inventory holding costs, have to be communicated. Parts' utilization of raw material and loading equipment are also saved in the ERP and can therefore be used. More details about the obtained input data transmitted from the used ERP system can be read in the concept chapter.

The logical layer consists of the optimization method, which was implemented in Java using IBM® ILOG CPLEX 12.1 optimization software. Both the mid-term lot sizing method and the short-term scheduling method are part of this layer. The sets and parameters of both models are set by the interface connecting with the subjacent layer. Some obtained data sets require calculations and set operations in order to transform them into a suitable form. Some parameters, especially those which control the optimization process, cannot be obtained directly or via calculations from the existent ERP data. These have to be input at an individually designed user interface.

Individually designed user interfaces are part of the presentation layer. Although it would be possible to present these as a web interface or in an individual application, the acceptance of the lot sizing and scheduling tool is higher when it is directly integrated into the ERP software, which is used daily. Parameters can be set by production planners who possess a great deal of process knowledge. Set-up times, machine availability or the selection of shifts is done in specialized graphical user interfaces which are integrated into the ERP system. The set parameters have to be communicated to the logical layer. After executing the lot sizing and scheduling methods, the results have to be presented to the end users. Depending on the department, a different presentation of the results is necessary. The production department gets schedules and lot plans. The maintenance department receives maintenance plans for the dies and plans for required raw material are transmitted to the purchasing department. There is also a view for required loading equipment in order to be able to better plan cleaning and transport.

6.1.2 Database and Data Structure

In this sub-section, the structure of the database is described, which works as fast background data storage. Although the database does not influence planning methods' principles of operation directly, it is useful for telling us how specific data from the ERP system is abstracted, stored and used. The presented database structure is an example of a way to manage sets, parameters and variables of a mathematical model in a relational database, as a match to the models' components is given. The following illustration shows the database structure in detail. Explanations of contained entities are provided afterwards.

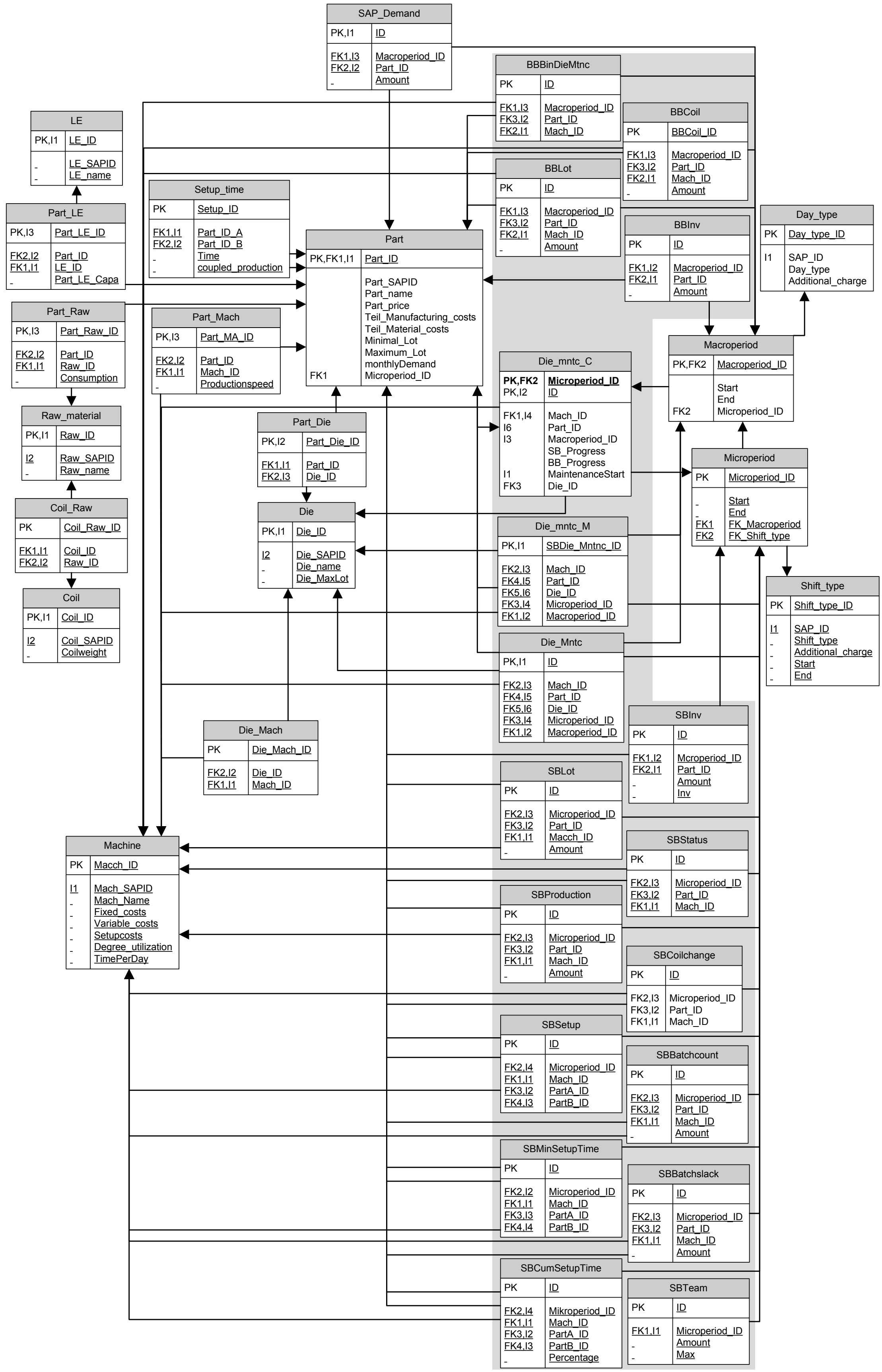


Figure 23: Database Diagram

First, the database can be subdivided into two main components: input and output tables for data storage. Visually, output tables can be distinguished from input tables by their grey background. Looking at input tables first, different types of input tables can be distinguished. There exist tables representing the sets, like parts, machines, dies, raw materials, coils, mid-term periods and short-term periods; and then there are tables representing relations between these sets. The machine and the parts tables occupy a central position. Element-dependent properties like material costs or manufacturing costs, or the degree of utilization and the time that a machine can be used for per day, are saved in the parts table. The production speed is saved in the table representing the relation between parts and machine, named *Part_Machine*. The relations of dies with machines or dies with parts are defined in the similarly named tables. Parts cannot be directly related with coils because some parts consist of the same raw material. Therefore, a raw material table has to be introduced. The *Part_Raw* relation, represented by another table, contains data about the consumption of raw material of one part that is the charge weight of a part. The relation to loading equipment, stored in table *LE*, is structured in a similar way. Sequence-dependent set-up times are saved in the *Setup_Time* table. Technically realizable part-part set-up sequences, including set-up times, are stored in this table. A Boolean value determines whether two parts are produced in coupled production. Mid-term periods and short-term periods are saved in the tables titled *Macroperiod* and *Microperiod* respectively. Both tables contain entries about the starting and ending times of the periods. Additionally, every macro-period is linked to a day-type and every micro-period is linked to a shift-type. In these tables, additional charges are saved. Demands transferred from the ERP system are stored in the *SAP_Demand* table. The output tables are highlighted with a grey background. Only a selection of the models' variables is stored as the rest can be calculated automatically. The variable tables, which are relevant for mid-term planning, start with a *BB* in their name; tables relevant for short-term planning are named starting with an *SB*. The die maintenance tables are hybrid tables used for both models. Basically, all tables store the values in a similar way: If a binary output variable is active in the method results, an entry is made in the corresponding table. In the case of integer or fractional variables, entries are made in the corresponding table including the value in specified columns.

6.1.3 Software Structure

In this section, the overall structure of the software is briefly described. The following figure illustrates the overall software structure.

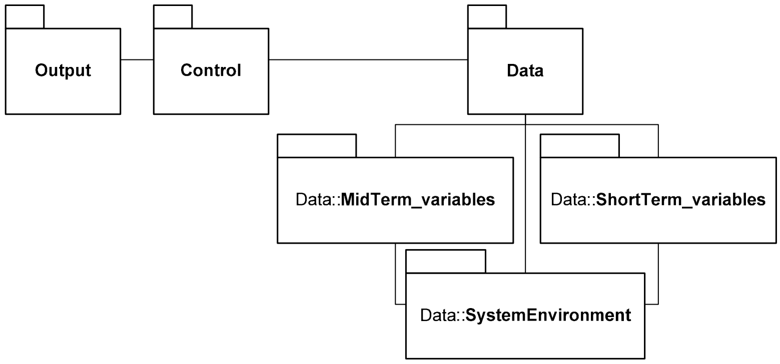


Figure 24: Software Structure

The data package is dedicated to making data available for other packages. The sub-package *SystemEnvironment* contains the classes representing production-relevant objects and relations. Properties and methods are saved in these objects. The packages *MidTerm_variables* and *ShortTerm_variables* contain all classes representing the model variables. This enables the transfer of the variables, calculations of calculated variable values as well as an appropriate output of the results. In the *Data* package, classes are defined, some of which control the data access to the ERP system, and some of which manage the data storage. The models for short-term and mid-term planning are defined in classes which are part of the control package. Interaction between the models and control of communication between the top-level packages is managed by another class. The *output* package contains the classes which manage the visualization of the calculated results. In this package, variable values are interpreted and transformed into appropriate, understandable charts. These charts can be presented in an integrated ERP, in typical office suite-compatible spreadsheet formats or in an individually programmed graphical user interface. The first two alternatives are already implemented in subordinated classes.

6.1.4 Application Flow

Several steps have to be passed before planning results can be obtained. The following activity chart represents the application flow:

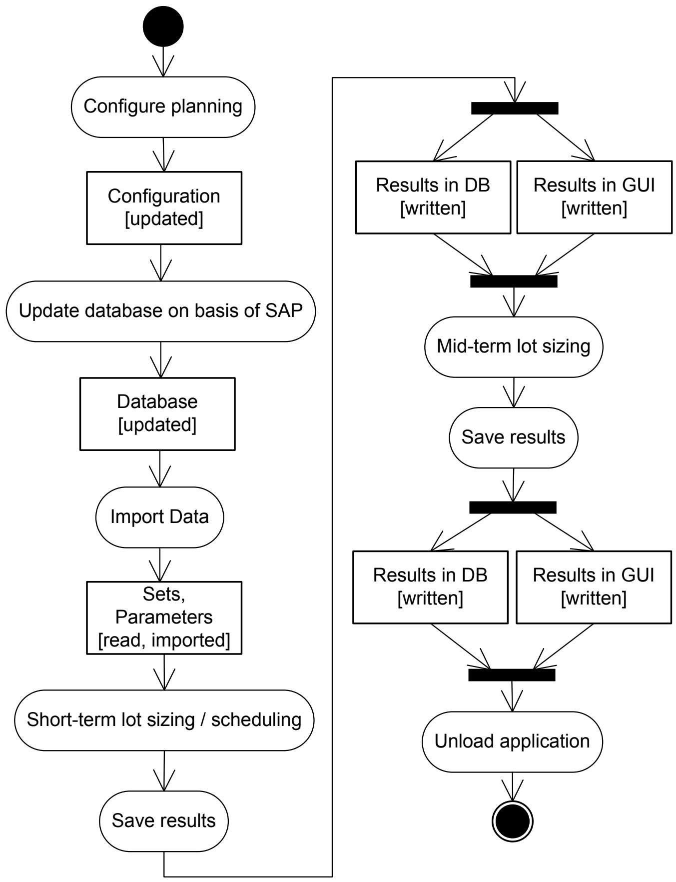


Figure 25: Overall Application Flow Diagram

After starting the application, the planning has to be configured. The selection of the planning horizon, the selection of relevant product groups, and the configuration of the times for short-term and mid-term optimization, as well as the activation/deactivation of preceding heuristics, are set. After that, the internal database has to be updated on the basis of ERP data.

The following activity chart illustrates the steps which have to be completed:

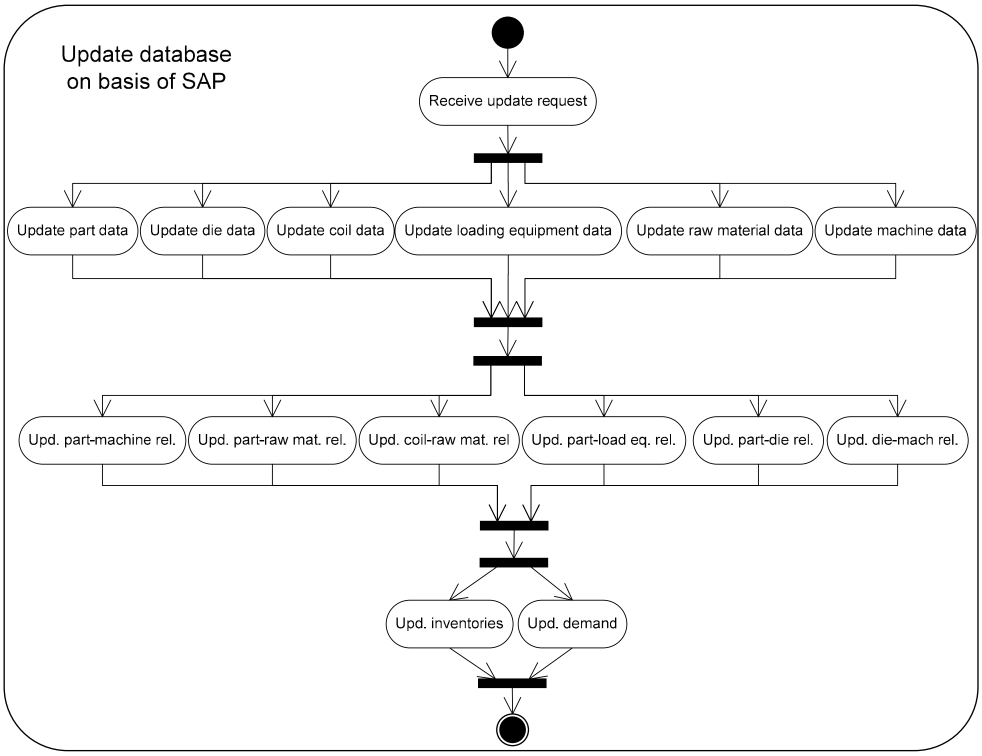


Figure 26: Sub-process: Database Update Application Flow Diagram

After receiving the update request from the main application, the database update process starts to update, write or remove data from the used ERP system into the application database. First, the sets of relevant system objects are imported, which can be processed parallel to one another as no interdependencies have to be considered when importing these basic sets. The relations between these objects have to be updated in a subsequent step, as the relations depend on the previously imported data. Last but not least, inventories and demands are updated.[165]

After updating the data of the application database, only relevant datasets have to be read from the application database in order to present objects which are then much faster to access. As there are interdependencies, not all import tasks can be executed in parallel. In particular those data sets representing relations need the linked objects in advance. The following flow diagram roughly visualizes the import and instantiation process:

[165] The interface required for obtaining the data from the SAP system was provided as a dynamic link library by application developers of the case study partner.

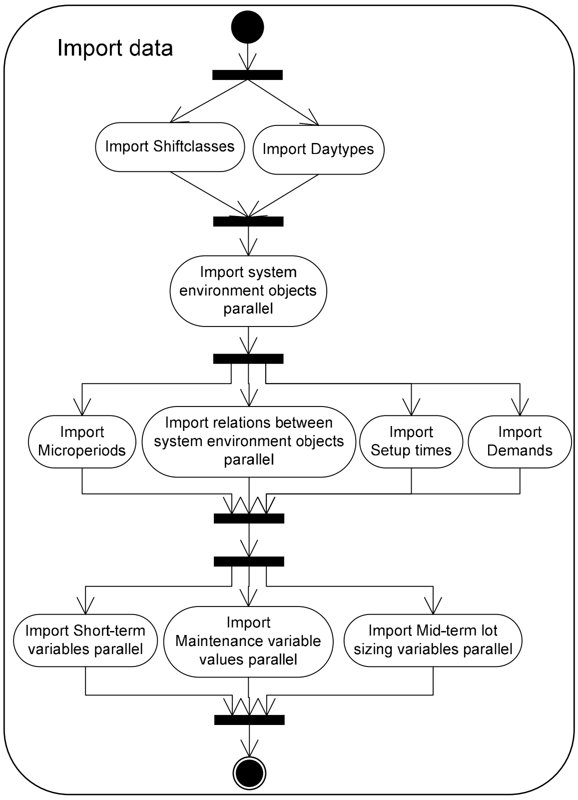


Figure 27: Sub-process: Instantiation and Import Flow Diagram

The obtained data sets and parameters are stored in an object which encapsulates and manages the data access. On the basis of imported data sets, the lot sizing and scheduling procedures are started. The procedures of both the short-term lot sizing and scheduling and the mid-term lot sizing are basically the same and differ merely in details of the data and parameters required, variables built and restrictions modeled.

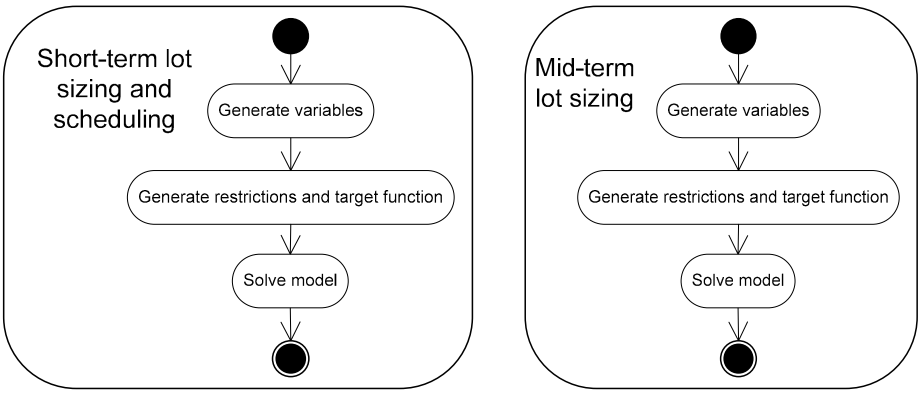


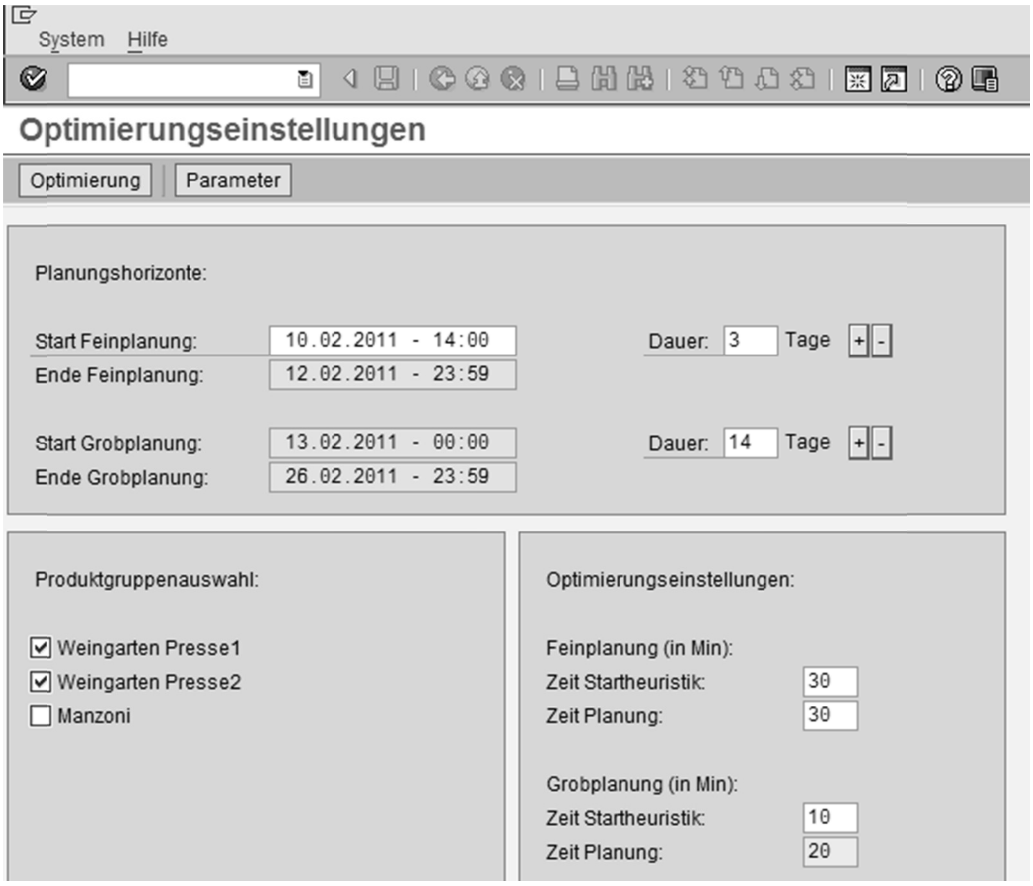
Figure 28: Sub-process: Lot Sizing and Scheduling Flow Diagrams

Results of both procedures are saved in the database and output. The mid-term lot sizing method makes use of the short-term lot sizing procedure's results in order to correctly initialize, for example, inventory, lot or maintenance variables in the model.

6.2 SAP Integration and User Interface

The acceptance of a planning system can be improved by integrating it into the system which is already being used for manual planning on a daily basis.[166] Redundancy and double data inputs are minimized. In the considered practical case, most parameters and data sets can be obtained from SAP.

The configuration screen in SAP,[167] designed to define short- and mid-term planning horizons, to select relevant product groups and to set optimization parameters, looks like this:



As production data acquisition is not available, many parameters have to be set in order to transfer the up-to-date system state. Accordingly, further screens are required in which required parameters like set-up states, die-relevant maintenance parameters and the number of set-up teams can be set and configured. The following illustrations are two examples of the integrated configuration screens.

---

[166] See [HGH03].

[167] The presented SAP screens were created in student projects by Thomas Seebothe and Benedict Blomen based on the SAP Graphics library BC_FES_GRA and the SAP Java Connector (JCo).

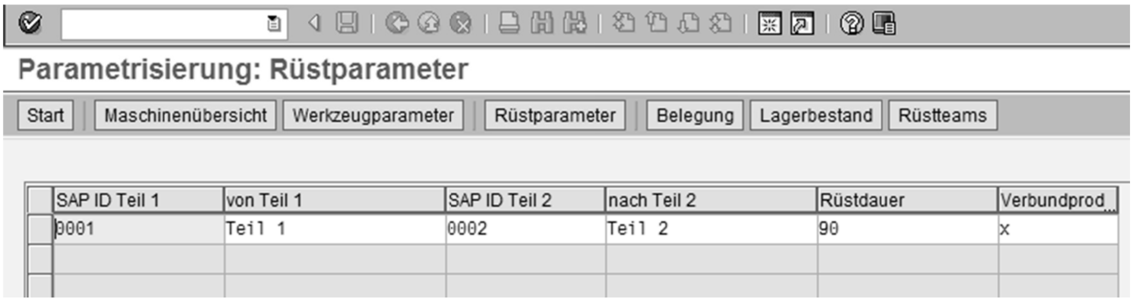


Figure 29: Set-up Parameter Screen

The set-up parameter screen is necessary because the set-up times from one part to another are not yet stored. Consequently, the sequence-dependent set-up times have to be obtained and entered into this screen. Apart from set-up time, coupled production has to be input.[168]

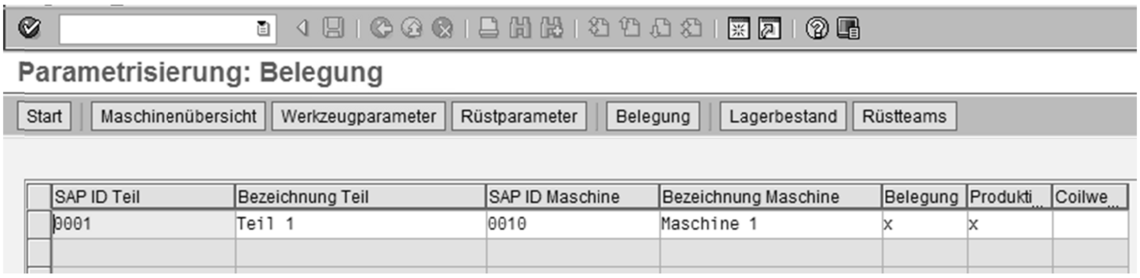


Figure 30: Set-up State Parameterization

The second screen defines the set-up and activity state of the machines. These settings are used to initialize the short-term planning procedure. All the presented screens and their background logic are programmed using SAP ABAP.

The optimization process is visualized in a further screen:

[168] The set-up time table is large as the power set of the product set has to be displayed. The coupled production flag has to be defined for the same product combination set. In order to reduce the required storage space and configuration effort for production planners, parameters, set-up time and coupled production are bundled in one screen.

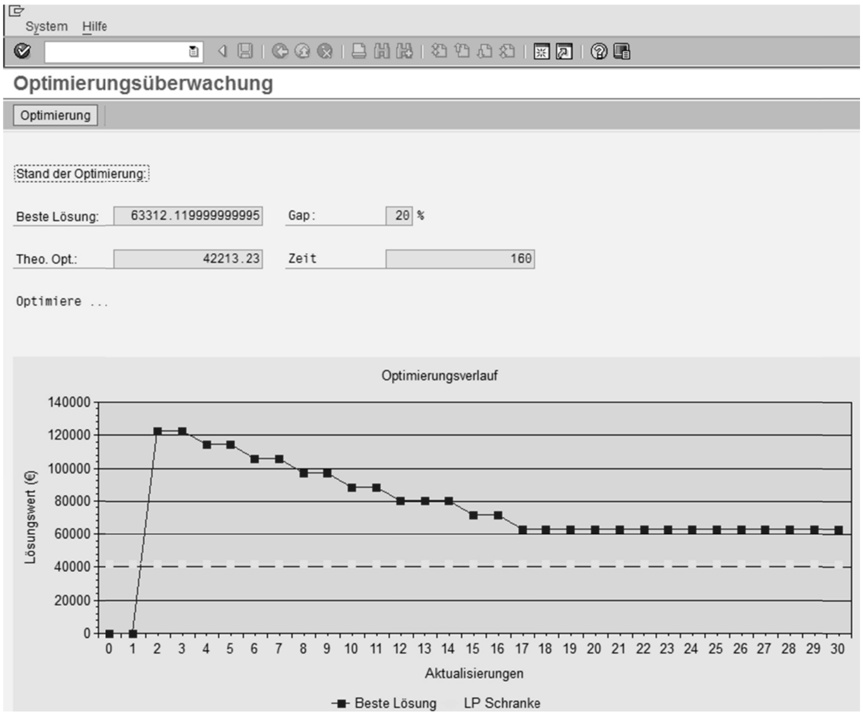


Figure 31: Visualization of Optimization Process

The optimization process is visualized in a screen presenting the theoretical LP optimum and found integer solutions.

Intermediate Document objects are used to transfer the planning results to SAP in order to be able to communicate asynchronously. The mid-term planning visualization looks like this:

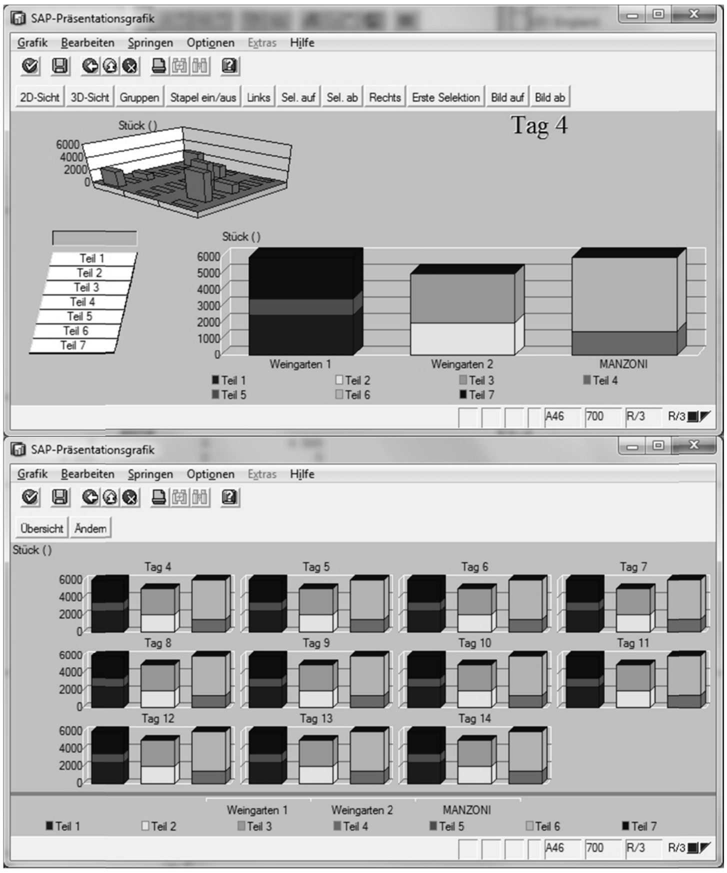
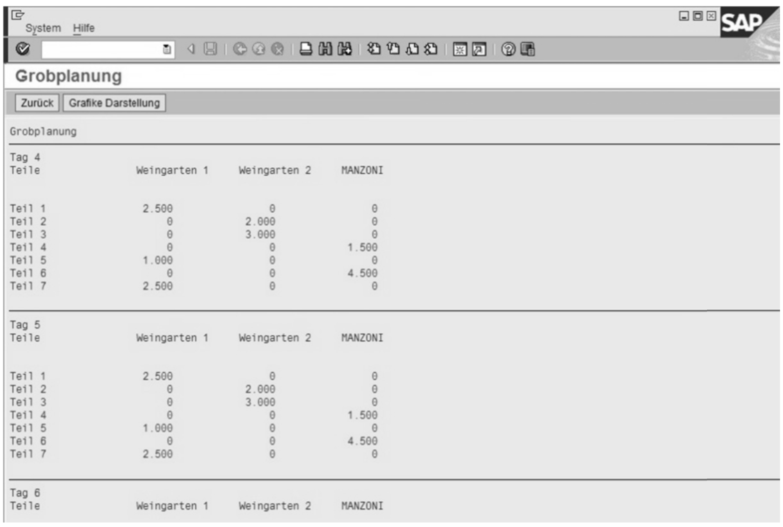


Figure 32: Mid-Term Planning Results in SAP

Production amounts of each part on every machine are visualized for each day in separate bar charts. Exact production quantities can be checked in another overview containing a more detailed list:



Grobplanung

Zurück | Grafike Darstellung

Grobplanung

Tag 4

Teile	Weingarten 1	Weingarten 2	MANZONI
Teil 1	2.500	0	0
Teil 2	0	2.000	0
Teil 3	0	3.000	0
Teil 4	0	0	1.500
Teil 5	1.000	0	0
Teil 6	0	0	4.500
Teil 7	2.500	0	0

Tag 5

Teile	Weingarten 1	Weingarten 2	MANZONI
Teil 1	2.500	0	0
Teil 2	0	2.000	0
Teil 3	0	3.000	0
Teil 4	0	0	1.500
Teil 5	1.000	0	0
Teil 6	0	0	4.500
Teil 7	2.500	0	0

Tag 6

Teile	Weingarten 1	Weingarten 2	MANZONI

Figure 33: Mid-Term Lots in SAP

Short-term schedules are presented in Gantt charts[169] integrated into SAP.

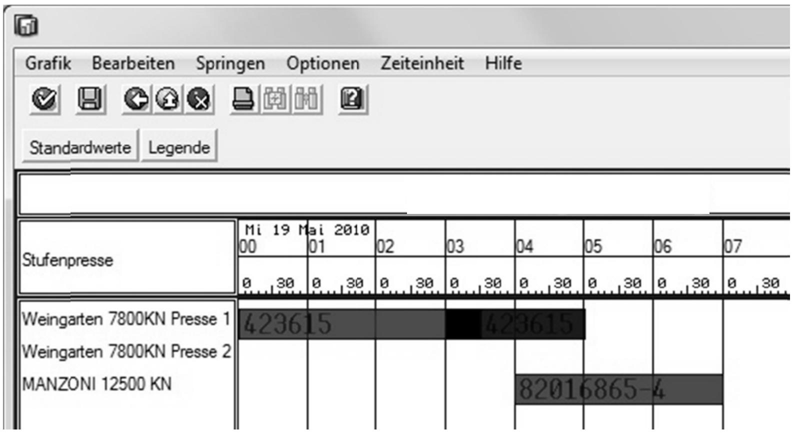


Figure 34: Short-Term Schedule Visualization in SAP

The displayed user interfaces[170] can then be directly used by production planners, raw material requirements planners, the loading equipment management department and the personnel planning department. The management of rights and roles for the specific views can then be done by SAP managers.

6.3 Evaluation

6.3.1 Planning Results

The following sub-sections present planning results which were transferred into practice. Planning results were transferred into practice for a period of one month. A representative subset of planning results is depicted in order to explain the results and to show how the practical constraints are represented in the planning results. Lot Sizing Plans were generated for the two molding presses Weingarten I 7800KN and Weingarten II 7800KN. All the tests were executed using the previously named implemented Java method using IBM ® ILOG CPLEX 12.1 as optimization software on a customary computer with an 2,4 GHz Intel ® I5 CPU with 2 GB RAM.

[169] According to [ZB05], Gantt charts are suitable for visualizing machine schedules.

[170] The visualization of the results is integrated using the SAP Graphics library BC_FES_GRA.

6.3.1.1 Sample Mid-Term Planning Results

First, mid-term planning results will be explained. Planned production amounts are output in table form for each machine. In order to get a better overview, production amounts are visualized using bar charts:

		Date											
		29.01.2011	30.01.2011	31.01.2011	01.02.2011	02.02.2011	03.02.2011	04.02.2011	05.02.2011	06.02.2011	07.02.2011	08.02.2011	09.02.2011
Part ID	82411909-5,86 & 82352228-5,86	17070	3414				6828						
	82007975-5 & 82007975-4								5032				
	423615 & 523615						7546						
	82650191-4 & 82650191-5			10782	16173	16176				16173	16173	16173	10782
	311357,85			8632					17264				
	82352228-4,86 & 82411909-4,86							17070					
	411359,85 & 411360,85												4857

Figure 35: Production Amounts: Weingarten I Stamping Machine

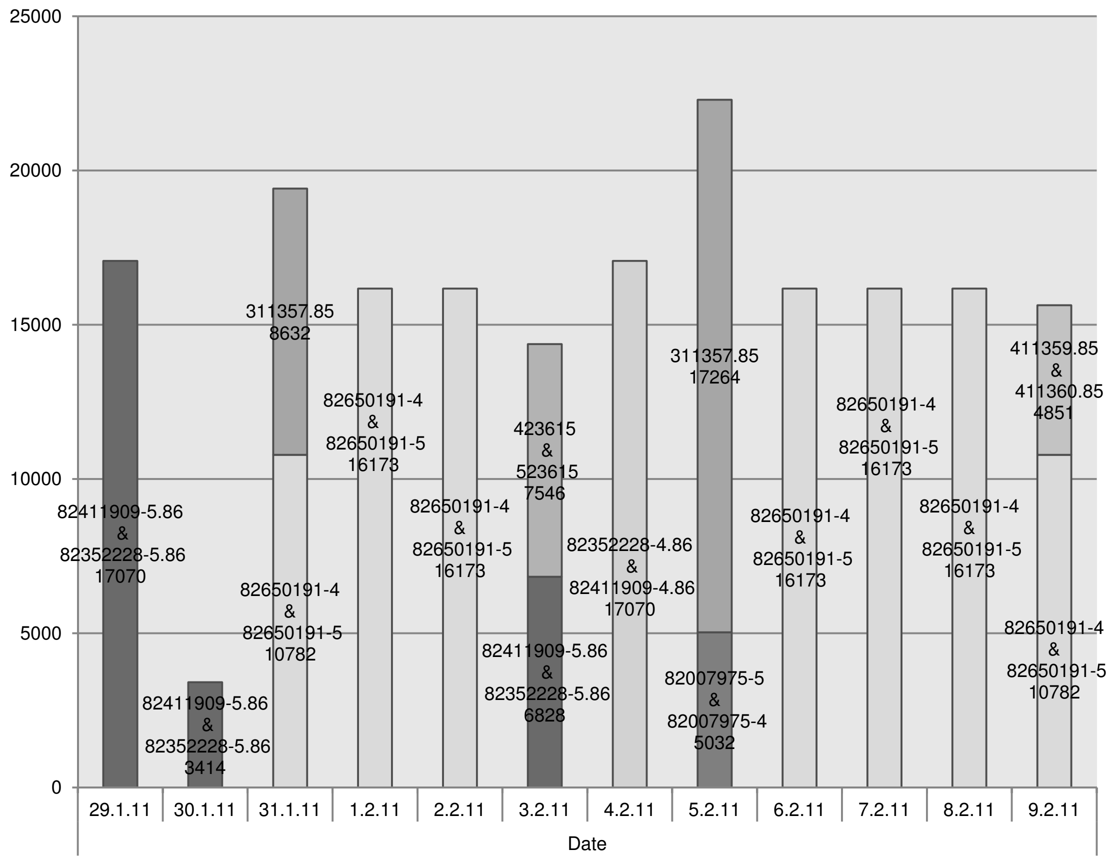


Figure 36: Visualization of Production Amounts Weingarten I

		Date											
		29.01.2011	30.01.2011	31.01.2011	01.02.2011	02.02.2011	03.02.2011	04.02.2011	05.02.2011	06.02.2011	07.02.2011	08.02.2011	09.02.2011
Part ID	82028724-4.65 & 82028724-5.65			3295	3295	3295							
	430923 &									3234			
	520890 &		6468										
	82028724-4.64 & 82028724-5.64										6590	6590	
	82016865-4									5390			
	82650192-5 & 82650192-4	24150	9660				19320	24150	14490				24150
	420889 & 420890											3234	
	82016885-4								7672				
	511359.85 & 511360.85			4851									
	82028724-4 & 82028724-5			6590	13180	19770				6590	9885	6590	

Figure 37: Production Amounts: Weingarten II Stamping Machine

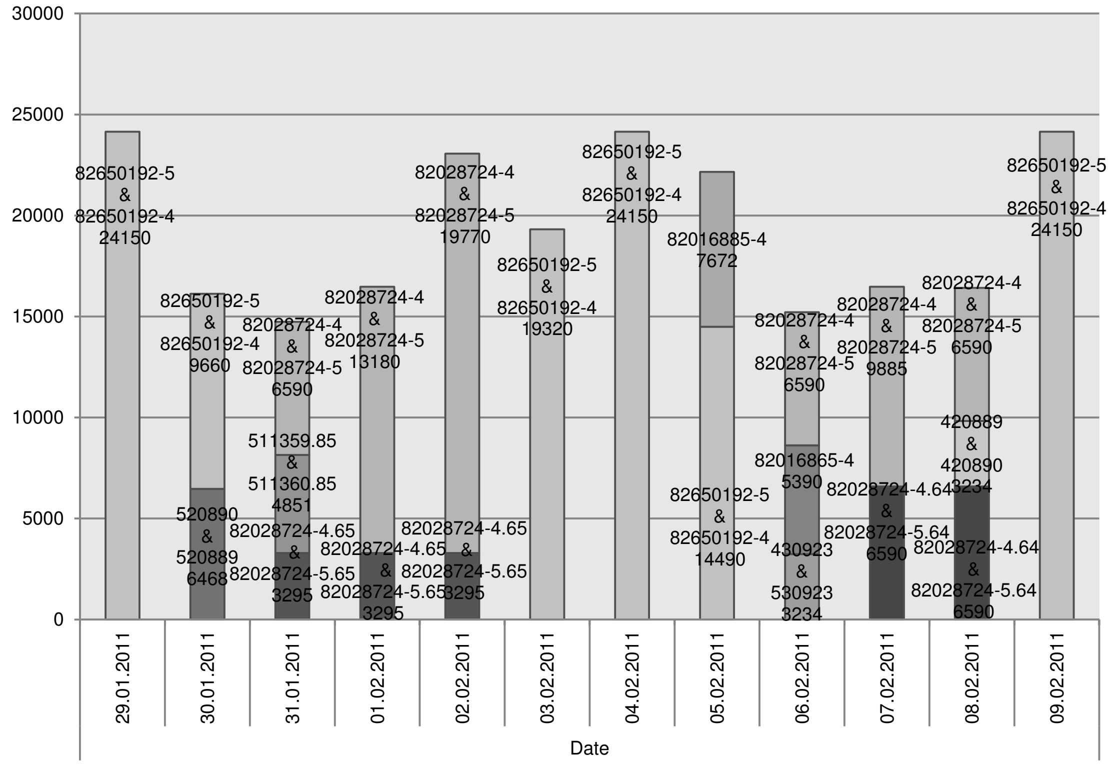


Figure 38: Visualization of Production Amounts Weingarten II

Production speeds differ from part to part. Therefore, the utilization of a machine cannot be directly obtained by analyzing production quantities. For this purpose, a capacity utilization bar chart is provided as well:

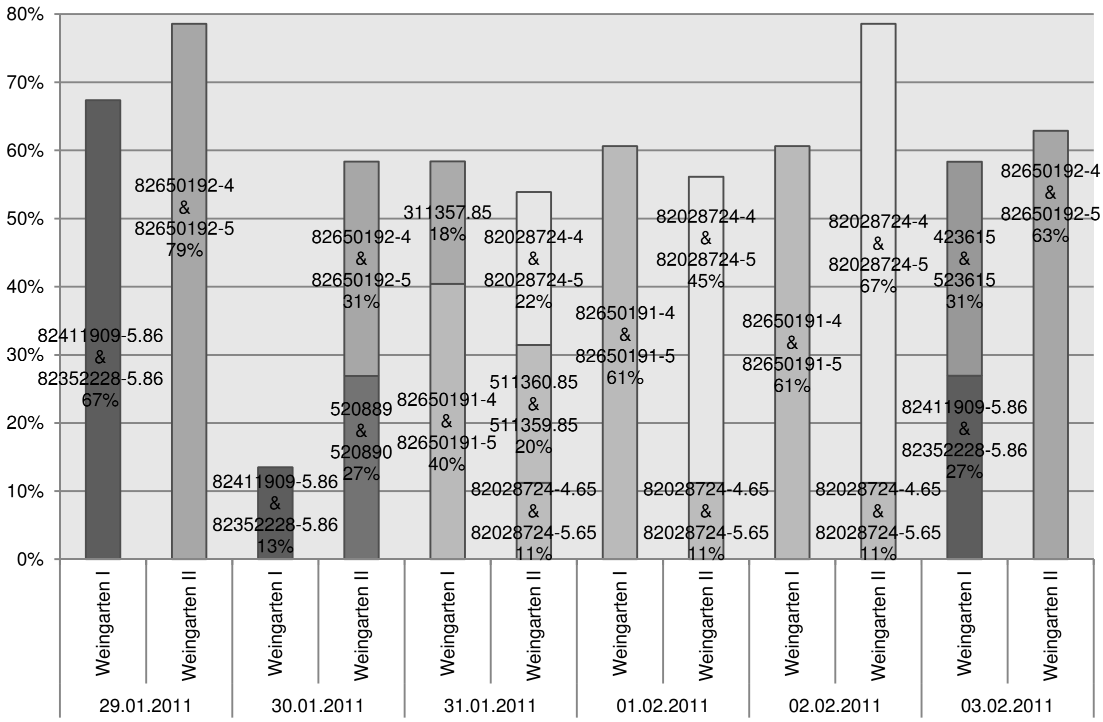


Figure 39: Combined Utilization Chart (1)

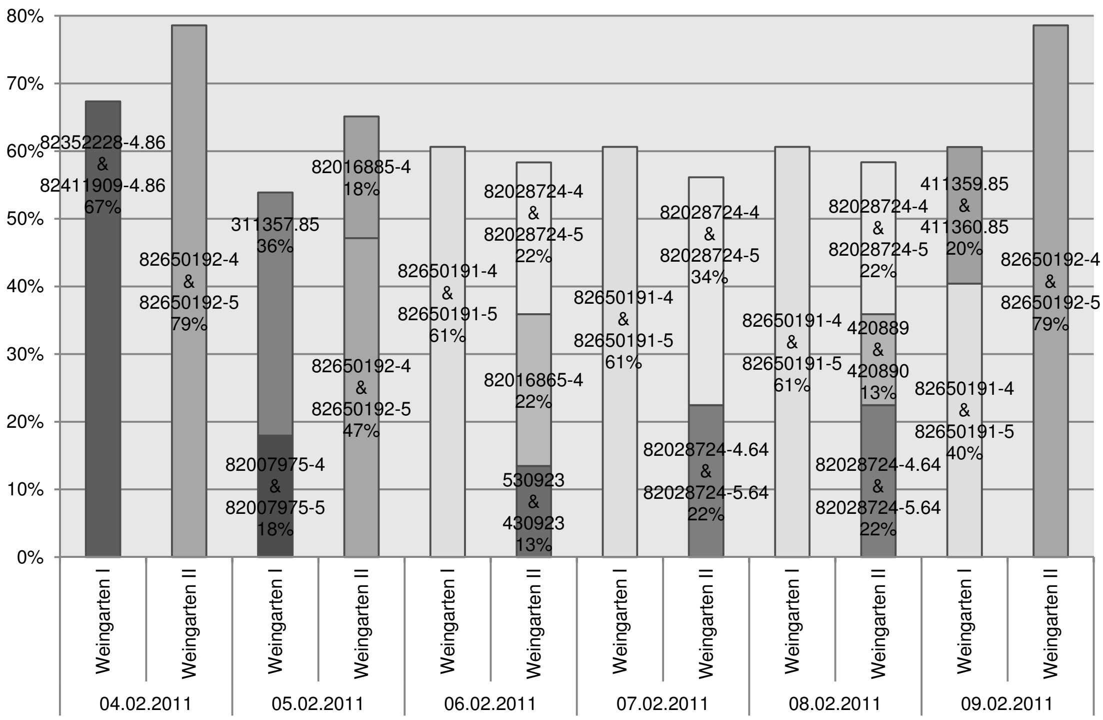


Figure 40: Combined Utilization Chart (2)

The utilization charts show that the utilization capacity limit of 80 % is never exceeded. In actual practice, the maximum utilization is set to 65 %. Thirty-five per cent of the daily capacity is subtracted as a fixed rate for set-ups, coil changes and other machine-related activities or smaller disruptions. In this method, a fixed set-up time is taken into account so that capacity is only reduced by 20 % to cover activities like coil changes and other machine-related activities or disruptions.

Taking customer demands, maintenance, and so on into account, the following cost-optimal personnel plan was calculated:

	Day type	Maximum Simultaneously Deployed Staplers	Estimated Maximum of Simultaneously Deployed Set-up Teams
29.01.11	Working Day	2	0
30.01.11	Sunday	2	1
31.01.11	Working Day	4	1
01.02.11	Working Day	4	0
02.02.11	Working Day	4	0
03.02.11	Working Day	4	1
04.02.11	Working Day	4	0
05.02.11	Working Day	4	1
06.02.11	Sunday	2	0
07.02.11	Working Day	2	1
08.02.11	Working Day	2	1
09.02.11	Working Day	4	1

Figure 41: Personnel Mid-Term Plan

It can be seen that this method tries to reduce personnel deployment on more expensive days (Sundays) in order to reduce personnel costs. As other constraints have to be considered, it is not possible to reduce the personnel needed to zero every Sunday. The exact number of set-up teams can be determined during short-term planning as set-up activities are precisely scheduled.

The presented production plans consider maintenance of the dies. In these plans, maintenance is triggered after set down due to product change. There are some parts, like 82028724-4, produced in coupled production with 82028724-5, which are produced on several consecutive days in combination with other parts, that is 82028714-4.64 and 82028724-5.64, without activating maintenance. The IDs differ although the parts are equal. Different IDs are used to distinguish successive processes. Accordingly, the parts are produced with the same dies and no product change and no maintenance is necessary. Three days are required for maintenance and during this time the production of the related part is blocked.

Production quantities are based on raw material units. The number of required steel coils can be calculated using stored part-raw material relations and the raw material usage of the parts. The following table shows the planned maintenance for each die, calculated on the basis of the stored die-part relations.

Furthermore, it provides a raw material procurement plan. As a result of the production plans, required loading equipment can be calculated. The following table shows the planned quantity for every loading equipment type for each day. Consequently, loading equipment procurement is improved due to the reliable calculations provided.

		Date											
	Resource Type Number	29.1.11	30.1.11	31.1.11	1.2.11	2.2.11	3.2.11	4.2.11	5.2.11	6.2.11	7.2.11	8.2.11	9.2.11
Raw Material (number of required coils)	BD 0,80 X 425 GK`HC340LA								2				
	BD 0,85 X 574 GK`HC420LA			3	5	7				2	7	6	
	BD 0,90 X 420 GK`HC380LA									1			
	BD 1,00 X 574 GK`HC420LA						2						
	BD 1,00 X 648 GK`HC380LA									1			
	BD 1,50 X 418 GK`S420MC		2									1	
	BD 1,50 X 597 GK`HC500LA	4	1				2	3					
	BD 1,75 X 410 GK`S420MC								1				
	BD 2,00 X 657 GK`HC340LA			2					4				
	BD 2,10 X 335 GK`DC04-C290			1									1
	BD 3,00 X 264 GK`HSM700HD	4	2				4	5	3				5
	BD 3,00 X 313 GK`S500MC			2	3	3				3	3	3	2
Required Loading Equip-ment	790333 GLT VWK-BO			10					18				7
	790334 GLT VWK-BO	70	40	70	140	210	146	70	46		106	84	
	790444 GLT TK3	76	30				60	76	46				76
	790445 GLT TK3			34	50	50					50	50	34
	E-303480 VCI-FOLIE			26	26	26					52	52	
Die Maintenance Schedule	W001208000001							M	M	M			
	W000220000001										M	M	M
	W080036000-					M	M	M			M	M	M
	W020100200001									M	M	M	
	W020100300001			M	M	M		M	M	M			
	W020072500001	M	M				M	M	M				M
	W020544700001	M	M				M	M	M				
	W000163100001			M	M	M							
	W080038000-				M	M	M						
	W000158900001									M	M	M	
	W001200700001									M	M	M	

Figure 42: Raw Material Units Procurement Plan

6.3.1.2 Sample Short-Term Planning Results

The standard form for presenting short-term planning results within the short-term lot sizing and scheduling method are Gantt charts. The level of detail is determined by the granularity of the short-term planning method, which is the size of small buckets. In this case, each small bucket is 30 minutes long.

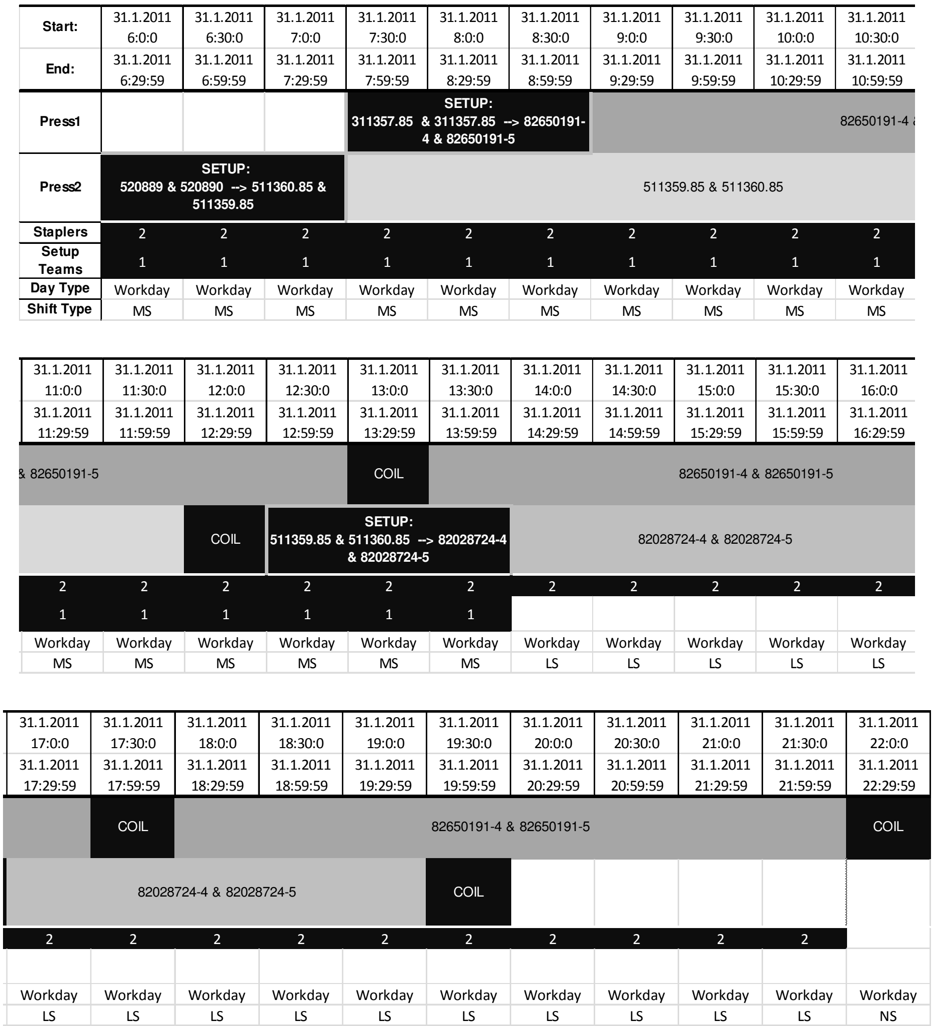


Figure 43: Short-Term Planning Result Visualization

The presented parts show how the number of set-up teams is minimized as simultaneous set-ups at different machines are avoided. The number of stacking personal is minimized and concentrated into shifts if possible. The different day and shift types are considered within the planning procedure and indicated by workday, Sunday, and bank holiday, and further by morning shift (MS), late shift (LS) and night shift (NS). In the first example, stackers are necessary for both machines. Sequence-dependent set-ups are planned and coil changes integrated. The maintenance of the dies is activated after a product change.

6.3.2 Manual vs. Automatically Generated Plans

Up until now, the plans have been created by experts without any mathematical techniques. As the presented method is designed to give decision support, it has to be competitive in comparison to the abilities of the planners, at least in regular cases in which creative decisions and improvisation are not necessary. In this section, a comparison on the basis of the most important costs between manual planning results and automatically generated plans is provided.

The evaluation is based on inventory holding and capital commitment costs c^{ihcc},[171] set-up costs c^{setup} and manufacturing costs c^{man}:

$$c^{ihcc} = \sum_{t \in TM} \sum_{p \in P} cM^{ir} * price_p$$

$$c^{setup} = \sum_{m \in M} \sum_{p \in P} \sum_{tm \in TM} \left(binsM_{m,p,tm} - binsrM_{m,p,tm} \right) * cM^{setup}_{p,tm}$$

$$c^{man} = \sum_{m \in M} \sum_{p \in P} \sum_{tm \in TM} xM_{m,p,tm} * cM^{prod}_{p,tm}$$

Within an evaluation period of one month, the following results were obtained:

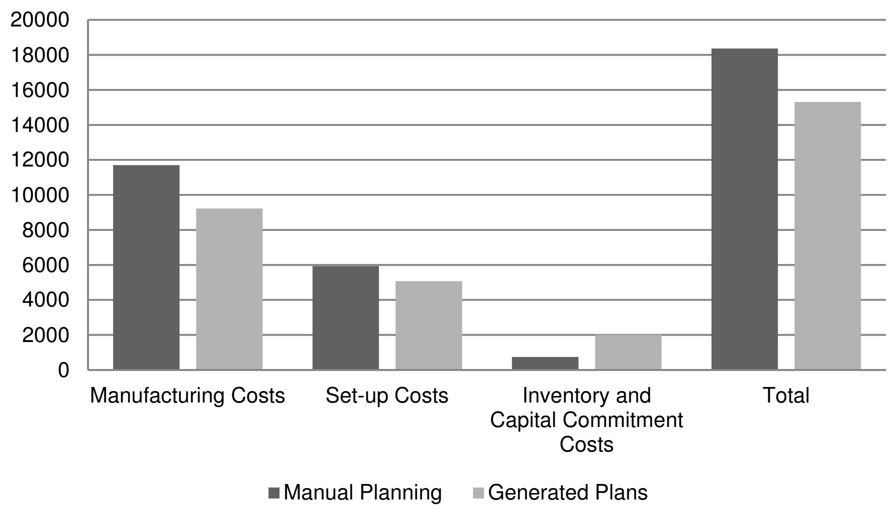


Figure 44: Comparison of Manual and Automatic Planning

[171] The capital commitment and inventory holding cost rate is set to 40 %.

7 Summary and Outlook

7.1 Summary

In this work, a method is developed for solving capacitated lot sizing problems in production control. In order to improve competitiveness, the guarantee of availability towards the customer is the focus. Lot sizing in practice is restricted due to several organizational and technological constraints. Accordingly, all the restrictions which lots and batches are faced with are considered in the developed planning method. The consideration of all available restrictions is necessary to generate feasible plans and schedules which can be applied in practice.

As the production environment is subject to perpetual changes, and disruptions are probable, it is not useful to calculate detailed plans for a long-term horizon. Consequently, a decomposition approach was presented in this work which splits up the time horizon according to the dynamics in demands. Rough planning of lots is carried out for a longer mid-term horizon. Cost-optimal production lots are calculated, taking into consideration restrictions for maximum lot sizes, maintenance of the dies and batched production. With the applied rolling horizon approach, it is not possible to guarantee availability for demands set after the planning horizon. Flexibility of the rolling horizon approach is advantageous, as the plans are constantly updated. Nevertheless, these updates cause high plan nervousness resulting in less user acceptance in practice. In this work, a method is developed which calculates useful ending inventories on the basis of monthly demand data to reduce problems related to the rolling horizon approach.

The planning results of the mid-term lot sizing approach are then used to determine detailed schedules within the short-term lot sizing and scheduling procedure. Under consideration of all constraints, detailed schedules are calculated on the basis of the actual system state with the developed method.

The presented planning method simplifies lot sizing and scheduling. The competitiveness is improved, as relevant products are pre-produced. The negative aspects of the rolling planning approach are avoided by the presented method. In an approval period of one month, manual plans were replaced by the generated plans and overall costs, including set-up team costs, production costs, inventory holding costs and sequence-dependent set-up costs, were reduced significantly. The following table summarizes the qualities of the method presented in this work. A '+' indicates that the method supports the mentioned aspect already. A 'o' indicates that the method can easily be adapted to support this aspect. A '-' indicates that more effort and further research has to be done to support this aspect.

Workforce aspects	Consideration of limited resources (e.g. setup personnel) for special activities over time	+
	Consideration of shift and day dependent production costs (due to e.g. personnel costs)	+
	Categorical shift planning of setup personnel	+
	Personnel planning considering complete shifts	o
	Individual personnel planning	-
Machine aspects	Consideration of machine and part dependent production speeds and capacities	+
	Manual deallocation of machines	+
	Capacity based production levelling	+
	Shift based machine planning	-
	Flexibly changing part-machine relations	o
Dies & Maintenance aspects	Integrated preventive maintenance planning of resources (e.g. dies)	+
	Consideration of maintenance times	+
	Consideration of multiple dies to produce one product	o
	Randomly varying maintenance times	-
Set-up aspects	Coupled production	+
	Sequence dependent set-up costs and times	+
	Consideration of randomly varying set-up times	-
Material procurement aspects	Input or output oriented lots (batched production)	+
	Consideration of capacity reductions due to batched production and input unit changes	+
	Consideration of material inventory	o
	Consideration of input factors varying randomly in size	-
	Simultaneous orientation on inputs and outputs	-
Demand aspects	Consideration of dynamic demands	+
	Improvement of delivery service availability	+
	Consideration of product run-outs	+
	Customer based prioritization of demands	o
	Ease of integration into self-controlled productions	+
Other aspects	Consideration of capital commitment limitations	o
	Consideration of inventory limits	o
	Multi-Level consideration	-
	Consideration of the actual production system state	+
	Applicability coupling of the big bucket and small bucket lot sizing models and decomposition approach in other concepts	+

Figure 45: Appraisal of Presented Method

7.2 Future Outlook

The method was tested at a production plant of an automotive supplier. The object of investigation was a subset of the machines within the molding presses production stage. First, the method should be applied to plan further machines within the molding presses stage. As the same conditions apply to similar machines, only parameters like production speed or set-up times have to be adapted. After that, the method should be extended to further production stages. In order to find an optimum for the whole production, subsequent stages should be considered in a multi-stage lot sizing method. The mid-term planning model could be replaced by an adapted MLCLSP[172]. As complexity grows it will cause performance problems, and so heuristics and other decomposition approaches as well as model improvements will be essential. Other technologies like constraint programming could also be suitable for generating feasible starting solutions.

In summary, it is possible to improve production processes with intelligent planning methods. The development and transfer of methods from operations research for real-life scenarios is still at the beginning. Nevertheless, through the improvement of hardware and software solutions, combined with the scientific progress of recent years, the vision to optimize corporate planning in order to produce at maximum effectiveness comes into reach.

[172] See [Tem06].

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