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ARTICLE

**A method for the hierarchical planning of structure, dimension and material requirements of manufacturing systems**

Thorsten Timm<sup>†</sup> and Alexander Blecken<sup>\*†‡</sup>

<sup>†</sup>*Heinz Nixdorf Institute, Fürstenallee 11, 33102 Paderborn, Germany*

<sup>‡</sup>*University of Paderborn, Warburger Str. 100, 33100 Paderborn, Germany*

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Growing competition creates pressure among companies to run their production in a cost optimal way and yet adapt immediately to changes in their environmental conditions. Decisions must always consider the integration of the companies in globalised markets on both the demand and supply side. This paper deals with the optimal planning of decisions concerning the structure and dimension of production facilities. The methods used for material requirements planning (MRP) are selected and configured according to these decisions. These decision problems are represented in the form of four hierarchically layered partial models, each of them realised and iteratively solved by a mathematical optimisation model. The hierarchical planning method is evaluated using a practical case example based on a valve production system of a manufacturing company.

**Keywords:** Material Requirements Planning, Manufacturing Systems, Hierarchical Planning, Master Planning, Coordination Process

**1. Introduction**

Restrictions of logistical and regulative nature between countries and enterprises have been continuously diminishing over the past years. On the regulative layer, this is reinforced by the introduction of bilateral as well as multi-lateral agreements to reduce trade barriers and harmonize international norms and regulations. The scale effects resulting from the increasing traffic of goods between those countries as well as the technological progress lead to reduced transport costs and thus a further reduction in logistical barriers. Hence, enterprises which traditionally have focused on spatially restricted markets or regions become increasingly international and extend their activities. A number

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\*Corresponding author. Email: alexander.blecken@hni.upb.de

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5 of implications follow for enterprises which serve as customers as well as suppliers on  
6 globalised markets: As customer, the enterprise not only purchases the materials and  
7 auxiliary means of production but also requests human resource capacity in a labour  
8 market. These resources need to be efficiently allocated under consideration of market  
9 demand.

10 One result of this development is the trend to concentrate on core competencies, which  
11 can be observed across industries at manufacturing companies. Manufacturing companies  
12 which assemble the final product, so-called original equipment manufacturers (OEMs),  
13 do so based on pre-fabricated modules. These modules are manufactured by other com-  
14 panies such that an ever more complex enterprise network becomes responsible for the  
15 production of the final product. Value creation is distributed over more and more partic-  
16 ipants in the production network; the fraction of the OEM has reduced approximately  
17 to only a mere 10% of overall value creation (see Kühn 2004, p. 33).

18 From the perspective of a company, it first needs to be established what an efficient  
19 resource allocation under these restrictions is. The foundation for a decision needs to  
20 be laid which clarifies where the respective sections of value creation are executed and  
21 whether this will be done in-house or outsourced to a supplier. Among various other  
22 factors, currently existing infrastructure such as production facilities, know-how and  
23 skills of the employees, as well as existing supplier relationships need to be incorporated  
24 in the decision making. Concurrently, it needs to be guaranteed that the temporal delays  
25 due to the selected links in the supply chain do not endanger the targeted service level  
26 and delivery reliability. Framework requirements concerning production lots und times  
27 need to be coordinated internally as well as with suppliers and required or implicitly  
28 derived stock levels need to be ascertained. In particular, the variability of products and  
29 modules on the separate production levels have to be incorporated in the planning.

30 This paper is structured as follows. Section 2 separates specific planning tasks and  
31 identifies their inter-dependencies in order to be able to construct hierarchical decision  
32 layers. In Section 3 relevant related contributions on hierarchical planning of manufactur-  
33 ing systems are analysed. The hierarchical planning method with the respective partial  
34 models is then constructed in Section 4. In Section 5 a case example shows how our  
35 method can be employed in practice with the example of a valve production system of a  
36 manufacturing company. Section 6 summarises the findings and concludes the paper.

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## 2. Hierarchical Planning of Manufacturing Systems

The hierarchical manufacturing planning method developed here is geared to set the  
manufacturing structure and layout (structuring task), to determine the throughput of  
all entities under consideration of time (dimensioning task), and to select and configure  
planning methods and procedures (mid-term material requirements planning). The de-  
veloped models describe the delimited choice of manufacturing planning tasks in the form  
of a number of quantitative partial models. These partial models are hierarchically con-  
nected by process definitions and can thus be used as manufacturing planning methods  
when sequentially computed by a solver.

Alternatively, it would be conceivable to solve the prior manufacturing planning tasks  
in an aggregate planning model (see Kistner and Steven 2001). Aggregate production  
planning simultaneously establishes optimal production, inventory and employment levels  
over a given finite planning horizon to meet the total demand for all products that share  
the same limited resources (Nam and Logendran 1992, Buffa and Taubert 1972). In

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5 an early work Nam and Logendran (1992) provide a structured overview of existing  
6 aggregate production planning approaches. The authors note that despite the numerous  
7 sources, very few aggregate production planning techniques have been implemented in  
8 industrial situations. Here, a hierarchical planning method is chosen as most promising  
9 approach. The partitioning of the manufacturing planning tasks in several partial models  
10 is sensible due to a number of reasons:

- 11 • Due to the high overall complexity of comprehensively planning the structure, di-  
12 mension and material requirements of a manufacturing system, the use of a holistic  
13 model would in practice lead to intolerably long computation times when using an  
14 optimisation software (see McKay *et al.* 1995, Silver and Peterson 1985).
- 15 • A number of time horizons can be examined on the various layers of the hierarchical  
16 planning model. Hence, different levels of aggregation can be used to efficiently solve  
17 the problem also for partial models with a longer time horizon. When analysing shorter  
18 time horizons, a more detailed data basis is used. This results in a reduction of the  
19 number of data to be collected and maintained as well as to improvements in com-  
20 putation time for the individual partial models. For a longer time horizon, a detailed  
21 data basis is infeasible, in particular due to forecasting problems.
- 22 • Moreover, integrated holistic planning of all aspects of a manufacturing system is  
23 infeasible since the control of such a system requires the continuous adaptation of  
24 some parts of the system, while others remain constant for a longer period of time.  
25 When using partial models, this sort of control is enabled by the separate replanning  
26 of individual partial models.

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31 The partitioning of the entire planning task in a set of hierarchically layered partial  
32 models is a two-stage process. In a first step, the relevant manufacturing planning tasks  
33 are identified (Section 2.1). Thereafter, these planning tasks are aggregated according to  
34 a number of criteria such that the simultaneous solution of the separate groups by one  
35 single model is enabled and thus, partial models for each aggregated group can be built  
36 (Section 2.2).

37 The separate partial models are then connected by coordination processes. A solution  
38 for the entire planning system is retrieved by the coordinated solution of the partial mod-  
39 els as well as the dynamic integration of feedback loops, i.e. information is transmitted  
40 from the subordinate to the super ordinate layers. While this method does not always  
41 yield the optimal solution, it is tried to sensibly partition the planning tasks in partial  
42 models and to integrate feedback loops to find an overall good solution.

### 43 44 45 46 **2.1. Manufacturing Planning Tasks**

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48 The following manufacturing planning tasks can be identified (see Hayes and Wheelwright  
49 1984, Günther and Tempelmeier 2005, p. 8):

- 50 • **Development of the asset (machine) inventory:** Machines can be acquired or  
51 sold. Implicitly, location decisions are also derived here. The aspects capacity and  
52 production structure are thus determined.
- 53 • **Development of the labour force:** Employees can be hired or dismissed. The avail-  
54 ability of employees (both initially and during the course of time) and their respective  
55 skills and qualifications need to be considered when planning the aspect human re-  
56 sources.
- 57 • **Development of employee qualifications:** Each employee possesses a unique set  
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of initial qualifications. This set can be expanded by training measures to acquire new qualifications.

- **Make-or-Buy decisions:** For all parts which can either be produced in-house or purchased externally, a decision needs to be taken by which MRP procedure these parts are scheduled for the manufacturing process. This task defines the manufacturing or production depth.
- **Selection of alternative manufacturing processes:** A process alternative defines the number, nature and sequence of process steps to manufacture a specific part. According to Günther and Tempelmeier (2005), this is equivalent to the selection of a production technology. In our case example as presented in Section 5, for instance, the alternative manufacturing processes to produce a valve body are chipping and casting.
- **Selection and configuration of disposition strategies:** A consumption-oriented or demand-oriented disposition strategy needs to be selected for each part.<sup>1</sup> Thereupon, planning and control methods are determined. Configuration of consumption-oriented disposition is achieved by the parameters reorder level, the decision whether to use order cycles, and the determination of lot sizes.
- **Definition of stock echelons:** In order to guarantee a pre-determined lead time for customers, stock echelons need to be defined enabling independent planning between any two manufacturing processes. This task is of elevated importance since the definition and allocation of stock echelons has implications on the selection and parameterization of planning and control concepts.

## 2.2. Construction of Partial Models

Since the partial models are to be used independently from each other for planning manufacturing systems, tasks which are mutually dependent need to be solved in one common partial model. Figure 1 displays the decisive dependencies between the tasks on the first planning layer. Decisions concerning the manufacturing processes, make-or-buy as well as machine (asset) stock are tightly coupled. Machines are only required for the manufacturing processes actually executed. Conversely the selection of manufacturing processes needs to be based on costs. Here, the required machines are a decisive factor. Furthermore, the make-or-buy decision is directly connected with the machine stock. Purchased items do not require capacities in the manufacturing system. External purchasing, however, competes with the acquisition of machines to produce that item.

While the decisions concerned with the labour force and the employee qualifications are also coupled with the other decisions taken on this layer, it may be assumed that the dependency of this coupling is uni-directional. A prerequisite for this simplifying assumption is that the fraction of the costs incurred by the wages and salaries associated with the manufacturing process are relatively low compared to further costs such as capital costs, holding costs and depreciation of machines and equipment etc.

Two partial models can be distinguished here. The first model deals with decisions related to alternative manufacturing processes, make-or-buy and machine stock. This model will be referred to as partial model I. The second model is based on the decisions of partial model I and optimises the labour force and the development of the skills and qualifications. It will be referred to as partial model II.

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<sup>1</sup>In a consumption-oriented strategy orders are triggered only by the current inventory level, in a demand-oriented strategy orders are triggered by the (planned) production programme.

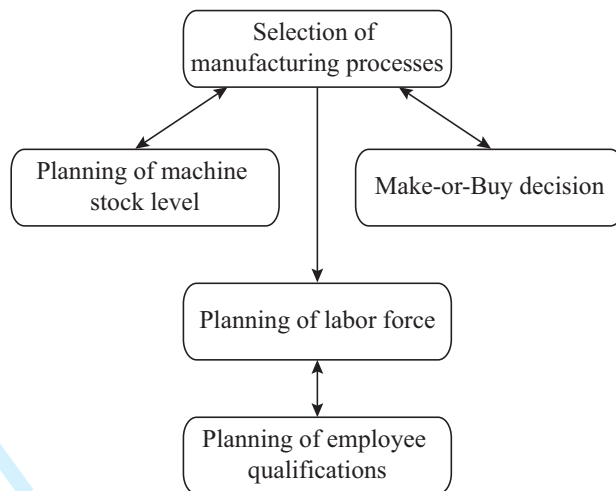


Figure 1.: Dependencies of planning tasks

On a second layer with shorter time horizons, two further partial models can be identified. Partial model III comprises the decision whether to use a consumption-oriented or demand-oriented disposition strategy, the definition of stock echelons, the decision whether to use order cycles, and sets the reorder level. Partial model IV eventually defines lot sizes for production and call-offs from external suppliers.

This paper focuses on the construction of partial models I and II. While these partial models will be elaborated in detail, partial models III and IV will only be described functionally. Their development has been carried out analogously to partial models I and II.

### 3. State of the Art

The handling of complex and extensive planning tasks leads to infeasible lead times for practical applications when employing optimal solution methods. The simultaneous planning of a comprehensive model in combination with a solver constitutes one solution method for the overall planning task. However, when dealing with planning tasks of considerable size, this method leads to long execution times despite ever-increasing computing power. Another problem encountered in the industrial practice is that it may only be required to come up with the solution for a limited number of planning tasks. When using comprehensive models, this always requires a new solution for the entire planning task. In order to circumvent these problems, hierarchical planning methods are employed.

A historical review of hierarchical production planning with its origins in scientific management and the applicability of hierarchical planning in manufacturing is provided by McKay *et al.* (1995). The authors elaborate the origins of hierarchical production planning and its underlying principles in order to support the understanding and where hierarchical production planning is suitable and warranted. They assert that the hierarchical planning paradigm is a descriptive model that serves to guide organizational design, structure information flows, and decompose large problems into manageable components.

Schneeweiss (1998) created the foundations of a conceptual framework for the hierarchical modelling of planning problems. He describes hierarchical planning problems in the form of stochastic dynamic programs. The starting point of a stochastic program is

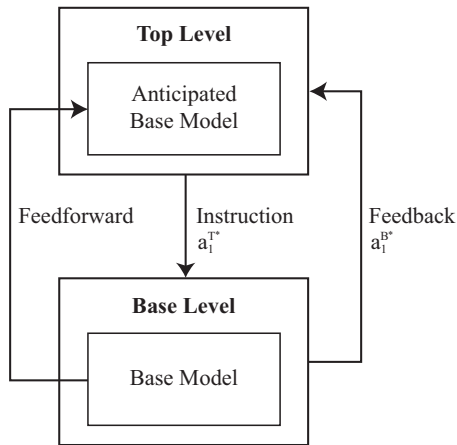


Figure 2.: General hierarchical planning according to Schneeweiss

the  $N$ -stage optimisation criterion  $\mathcal{C}$  further to a state transition relationship as given by the following equations.

$$\mathcal{C} = \mathcal{E} \left\{ \sum_{t=0}^N \mathcal{C}_t(z_{t+1}, a_t) \right\} \quad (1)$$

$$z_{t+1} = G_t(z_t, a_t, r_t) \quad (2)$$

It holds that  $N$  is the number of stages in the dynamic program,  $\mathcal{C}_t$  is the optimisation criterion,  $z_t$  the state,  $a_t$  the decision and  $r_t$  the stochastic interference for each stage  $t$ . Hence,  $\mathcal{C}$  constitutes the expected value over the sum of the values of the optimisation criteria over all stages. The state transition relationship reveals how the state of the sequent stage can be deduced from the state of stage  $t$ , the decision on this stage as well as the stochastic interference.

From this mapping of hierarchical planning on dynamic programming, Schneeweiss (1998) deduces the general scheme of hierarchical planning as depicted in Figure 2. The information on the base model used in top level for its anticipation is represented as feed forward influence. The outcome  $a_1^{T*}$  of the top level is indicated as instruction. Additionally to the top-down influence, a feedback loop is introduced. The results of the planning on the base level can thus lead to replanning on the top level. The final decisions are taken in the form of a multi-staged negotiation process between the levels. A feedback loop is not mandatory in a hierarchical planning system.

When developing a conceptual framework of hierarchical enterprise systems, Rieper (1979) develops a three-layered hierarchical system. The basic two-layered structure of this approach (one of the layers is subsequently split up into two sub layers) does not allow for a direct effect of decisions taken on the super ordinate system, i.e. the enterprise information and decision system, on the system environment as envisioned by the conceptual framework of Schneeweiss (1998). The enterprise information and decision system simply determines control values for the system on the subordinate level, i.e. the enterprise realisation system. To the largest degree, the enterprise realisation system in this approach is equivalent to the layer Operational Control in the model of Anthony (1965).

Boysen *et al.* (2007) introduce a hierarchical planning method for variant flow produc-



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tion. This approach is geared directly towards the requirements of variant flow production as faced by the automotive or electronics industries. The planning tasks tackled by the model of Boysen *et al.* (2007) differ from the planning tasks as derived in Section 2.1.

Gebhard and Kuhn (2007) design a two-step hierarchical planning method for manufacturing planning. On the super ordinate planning layer (aggregated planning) decisions with medium-term time horizons are taken concerning seasonal stock levels and extension of available capacities with overtime. On the subordinate layer short-term (operational) production plans are developed. A mathematical model is presented which is used to solve each planning task.

A number of other studies on hierarchical planning of manufacturing and production systems exist. Hatchuel *et al.* (1997) show that significant lead time performance improvements can result from integrated strategies for planning and scheduling decisions. Omar and Bennell (2009) and Omar and Teo (2007) derive mathematical models for master production scheduling in process industries. The effects of demand pattern, replanning periodicity, setup costs and unit production cost on the performance are examined. Kanyalkar and Adil (2005) develop a linear programming model which derives a production and disposition plan in a multi-site production facility scenario with substitutable capacities serving multiple selling locations. The authors use varying time grids and planning horizons for the planning levels to address the computational complexity.

The majority of existing approaches to hierarchical planning of manufacturing systems focus on the short-term time horizon and address lot sizing or scheduling problems, see for instance Ebadian *et al.* (2009), Toledo *et al.* (2009), Sawik (2006), Dumoulin and Vercellis (2000). However, integrated approaches incorporating both short-term and long-term time horizons which enable partial (re-) planning of tactical and operational decisions and which integrate with existing business information systems, remain scarce.

#### 4. Hierarchical Planning Method

The objective is to develop a method which can be integrated into Advanced Planning System (APS) frameworks as defined by Reuter and Rohde (2008). Hence, it becomes possible that our system can be used together with modules of existing software. On the other hand, the question tackled by our research goes beyond the functionality and planning horizon of APS systems. In particular, the planning and definition of asset (machine) inventory levels or the planning of human resources including training measures exceed the features of APS systems. Figure 3 shows how the hierarchical planning method is integrated into Rohde's APS framework. The shaded areas are addressed by the method developed here.

Based on the procedure model by Gebhard and Kuhn (2007) which considers the uncertainty of future development of demand, the future is represented in scenarios in the mathematical models developed here. Each scenario is attributed with a certain likelihood proportional to the probability of occurrence. These likelihoods will be used as weighting factors in the objective function. Thus, various sources can be used to support the planning decisions, multiple perspectives of stakeholders can be integrated, and even exceptional circumstances and events can be accounted for by assigning a respective (small) probability of occurrence.

The future evolution of the system environment (especially the development of demand) is not given deterministically, but depends on factors which are not susceptible to the decision makers of an enterprise. Thus, various scenarios are devised which deliver

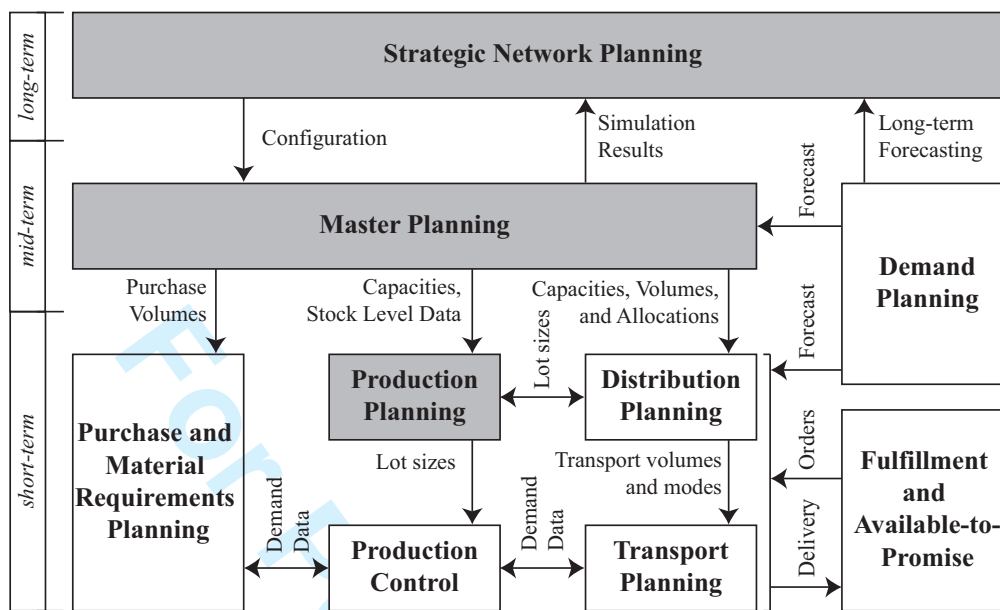


Figure 3.: Integration of the hierarchical planning method into APS framework

consistent prospects of likely future developments. The partial models concurrently take the various possible evolution paths into account and come up with a solution adapted to the occurrence of the individual scenarios.

The scenarios are arranged in a tree structure, in which one scenario is always the successor of one other scenario (with the exception of the root scenario which does not have a predecessor scenario). When constructing the scenario tree,  $n^P + 1$  periods and  $n^S + 1$  scenarios are defined, whereas the root of the tree (the root scenario) is always scenario 0.

All partial models as presented in the following sections have been developed based on the Multi Level Capacitated Lot-Sizing Problem (MLCLSP) model. The MLCLSP assumes a finite planning horizon divided into discrete time periods. There are a number of items with period-specific external demands. The items are produced in a multi-stage production process on non-identical resources with limited period-specific capacities. A review of research streams on dynamic lotsizing with capacity constraints including a thorough introduction of the basic MLCLSP model is given by Buschkuehl *et al.* (2010). For each of the partial models, the basic MLCLSP model has been extended appropriately. Below, the specific extensions are elaborated in detail for each of the partial models.

The four partial models used in our planning method are described in Sections 4.1 to 4.4. Indices are standardised for all models and shown in Table 1. All further notation is introduced in the respective sections. Hence, Tables 2 and 3 present symbols and functions of partial model I. Table 4 introduces additional symbols of partial model II.

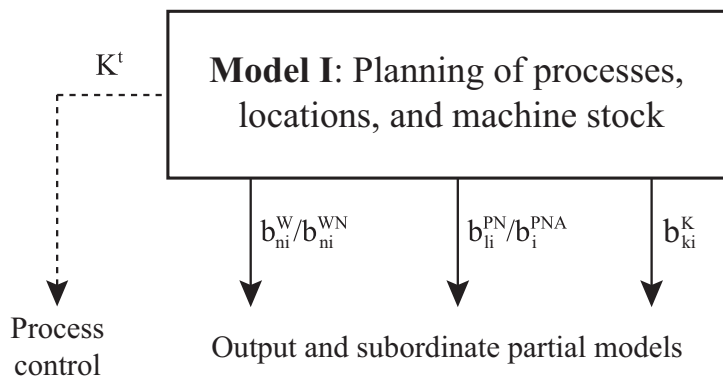


Figure 4.: Outcome of partial model I

Index	Definition
$i$	Period
$j$	Scenario
$k$	Part
$l$	Process alternative
$m$	Technology
$n$	Machine
$o$	Employee
$p$	Qualification

Table 1.: Notation: Indices

#### 4.1. Partial Model I

This partial model integrates the manufacturing planning tasks selection of manufacturing processes, optimisation of machine (asset) stock and make-or-buy decisions into a single mathematical programme. Implicitly, location decisions are taken (via the choice of machines) and the core competences and thus the optimal manufacturing depth of the enterprise and the individual locations are determined. Parts which promise a cost reduction at the same quality when production is outsourced cannot represent a core competence of the enterprise. Such parts are identified as purchase parts by the model and marked accordingly.

The outcome of partial model I is presented in Figure 4. The variable  $K^t$  is a performance indicator which depends on the results of partial model I and partial model II. The output variables resulting from the planning of partial model I and are used for the entire planning system are indicated beneath the model. An input variable for the model is the number of machines from which those are selected that are used to manufacture the required parts in each period. Alternatively, purchasing terms of possible suppliers are represented. The various manufacturing processes of parts are modelled as technologies. A technology represents manufacturing processes as input-output-processes. It describes a process in which one or more input factors are consumed and one or more machines are employed in the production of one or more outputs. Through the extension of the MLCLSP model with technologies, it becomes possible to model processes which employ

more than one machine only. Other limitations of the MLCLSP model such as that the capacity needed to produce a part using a technology must be allocated within one time period, are not avoided by this approach. Also, the modelling of the required labour force for executing the manufacturing processes in a mathematical form is enabled. The latter extension will only be introduced in partial model II, since the availability of employees to execute the technologies is implicitly presumed here. Further input variables for this model are the different demand forecasts separated by scenarios, the limitation of the number of set-ups, machine capacity as well as manufacturing alternatives with their respective technologies.

Symbol	Definition
$b_{ki}^K$	Binary variable showing if part $k$ is a purchase part in period $i$
$b_{lm}^P$	Binary variable showing if process alternative $l$ allows the use of technology $m$
$b_{li}^{PN}$	Binary variable showing if process alternative $l$ is used in period $i$
$b_l^{PN0}$	Binary variable showing if process alternative $l$ is used in the original scenario
$b_i^{PNA}$	Binary variable, which signals the change in the process alternative used in period $i$
$b_{mnj}^{RT}$	Binary set-up variable showing if machine $n$ is equipped for development of technology $m$ in scenario $j$
$b_{ni}^W$	Binary variable showing if machine $n$ is available in period $i$
$b_n^{W0}$	Binary variable showing if machine $n$ is available in the original scenario
$b_{ni}^{WN}$	Binary variable showing if machine $n$ is procured in period $i$
$c_n^F$	Fixed costs which accrue in every scenario in which machine $n$ is available
$c_k^K$	Unit purchasing price per part $k$
$c_k^L$	Holding cost rate per unit quantity of part $k$ at the end of a period
$c_n^N$	Cost of new acquisition of machine $n$
$c_n^P$	Production cost rate per time unit of machine $n$
$c^{PNA}$	Cost of changing the use of a process alternative
$c_n^R$	Set-up cost rate of time unit for machine $n$
$c_k^V$	Delay cost rate per unit quantity for backorders from part $k$ at the end of one period
$c^Z$	Calculatory interest factor of the enterprise per period in the tactical planning models
$M$	Sufficiently large number
$n_{kj}^B$	Primary demand for part $k$ in scenario $j$
$n^E$	Number of parts
$n^P$	Number of observed periods (planning horizon) (without the initial period with index 0)
$n^{PA}$	Number of process alternatives
$n_m^{RTmax}$	Maximum number of set-up operations for execution of technology $m$ per period
$n^S$	Number of observed scenarios (without the root scenario with index 0)
$n^T$	Number of technologies
$n_{km}^{TB}$	Required input of part $k$ for executing one unit of technology $m$
$n_{km}^{TE}$	Output of part $k$ for executing one unit of technology $m$

$n^W$	Number of machines
$t_{ni}^{KW}$	Capacity of machine $n$ in period $i$ in time units
$t_{mn}^{RT}$	Time required to set up machine $n$ in order to execute technology $m$
$t_{mn}^{TW}$	Processing time at machine $j$ for the execution of one unit of technology $m$
$x_{kj}^K$	Purchase volume of part $k$ in scenario $j$
$x_{kj}^L$	Inventory or backorder of part $k$ at the end of scenario $j$
$x_{mj}^T$	Number of units of technology $m$ executed in scenario $j$

Table 2.: Notation: Symbols partial model I

Function	Definition
$\nu : \{0 \dots n^S\} \rightarrow \{0 \dots n^S\} \cup \emptyset$	Function mapping each period in the time model of the operative planning to a period in the time model of the tactical planning
$\pi : \{0 \dots n^S\} \rightarrow \{0 \dots n^S\}$	Function assigning a period to every scenario
$\omega : \{0 \dots n^S\} \rightarrow ]0 \dots 1]$	Function assigning a probability of occurrence to every scenario

Table 3.: Notation: Functions partial model I

Equations (3) to (16) represent the mathematical model of the selection of production processes and the asset (machine) stock level. The model extends the MLCLSP model by the following notions:

- (1) Selection of different production processes to produce parts
- (2) Availability of machines in each period is not given deterministically. Rather, acquisition or disposal is part of the planning task and thereupon availability is derived
- (3) Use of technologies for modelling the production processes
- (4) Integration of planning uncertainty by parallel scenarios for each period
- (5) Determination of machine utilisation for each machine in each period

$$\begin{aligned}
 \min \quad & \sum_{j=0}^{n^S} \omega(j) \cdot (1 + c^Z)^{-\pi(j)} \cdot \left[ \sum_{n=1}^{n^W} \sum_{m=1}^{n^T} (b_{mnj}^{RT} \cdot t_{mn}^{RT} \cdot c_n^R + x_{mj}^T \cdot t_{mn}^{TW} \cdot c_n^P) \right. \\
 & + \sum_{k=1}^{n^E} (\max(x_{kj}^L, 0) \cdot c_k^L - \min(x_{kj}^L, 0) \cdot c_k^V) + \sum_{k=1}^{n^E} x_{kj}^K \cdot c_k^K \\
 & \left. + \sum_{n=1}^{n^W} (b_{n\pi(j)}^W \cdot c_n^F + b_{n\pi(j)}^{WN} \cdot c_n^N) + b_{\pi(j)}^{PNA} \cdot c^{PNA} \right] \quad (3)
 \end{aligned}$$

Expression (3) represents the objective function which minimises the expected value of the aggregated cost over all scenarios. Each scenario  $j$  is weighted with a likelihood  $\omega(j)$  and costs are devalued with the calculatory interest factor  $c^Z$ . The summands represent the costs for changing process alternatives, variable production and setup costs, inventory holding and penalty costs for delays. Additionally to the cost factors considered in the MLCLSP model, costs for external purchasing of parts, the procurement of machines and fixed costs for existing machines are considered in order to enable the optimisation of the machine stock level over the scenario tree. Costs for external purchasing are assumed to be linear. The objective function is subject to a number of restrictions.

$$n_m^{RT_{max}} \geq \sum_{n=1}^{n^W} b_{mnj}^{RT} \quad \forall m \in \{1 \dots n^T\}, \forall j \in \{0 \dots n^S\} \quad (4)$$

$$x_{mj}^T \leq M \cdot b_{mnj}^{RT} \quad \forall m \in \{1 \dots n^T\}, \forall n \in \{1 \dots n^W\}, \forall j \in \{0 \dots n^S\} \quad (5)$$

Constraint (4) limits the number of setups. Setup actions are represented by the binary variable  $b_{mnj}^{RT}$  which is 1, if machine  $n$  is setup to execute technology  $m$  in scenario  $j$ . Constraint (5) restricts the executable technologies to those for which the machines can be setup.

$$\sum_{m=1}^{n^T} (b_{mnj}^{RT} \cdot t_{mn}^{RT} + x_{mj}^T \cdot t_{mn}^{TW}) \leq t_{n\pi(j)}^{KW} \cdot b_{n\pi(j)}^W \quad \forall n \in \{1 \dots n^W\}, \forall j \in \{0 \dots n^S\} \quad (6)$$

$$x_{kj}^L = x_{k\nu(j)}^L + \sum_{m=1}^{n^T} (x_{mj}^T \cdot n_{km}^{TE} - n_{km}^{TB} \cdot x_{mj}^T) + x_{kj}^K - n_{kj}^B \quad (7)$$

$$\forall k \in \{1 \dots n^E\}, \forall j \in \{0 \dots n^S\}$$

Constraint (6) restricts the up-time of machines. On the one hand, the sum over all technologies is calculated such that the setup and production time in the new model can be calculated. On the other hand, the capacity of each machine is multiplied with the binary variable  $b_{ni}^W$  for each scenario in order to incorporate optimised machine availability. Constraint (7) calculates the inventory available at the end of each period for every scenario. Noteworthy is the second summand on the right side, which adds the manufactured quantity of the respective part. The third summand serves to model the external procurement of parts. Transport times are not included here since the time grid in this partial model is assumed to be large enough to allow the omission of transport delays.

$$b_{ni}^W \leq b_{n(i-1)}^W + b_{ni}^{WN} \quad \forall n \in \{1 \dots n^W\}, \forall i \in \{1 \dots n^P\} \quad (8)$$

$$x_{kj}^K \leq b_{k\pi(j)}^K \cdot M \quad \forall k \in \{1 \dots n^E\}, \forall j \in \{0 \dots n^S\} \quad (9)$$

$$\sum_{m=1}^{n^T} x_{mj}^T \cdot n_{km}^{TE} \leq (1 - b_{k\pi(j)}^K) \cdot M \quad \forall k \in \{1 \dots n^E\}, \forall j \in \{0 \dots n^S\} \quad (10)$$

In Constraint (8) the binary variable  $b_{ni}^{WN}$  is adjusted. This variable signals the introduction of machine  $n$  in period  $i$ . Likewise, the binary variable  $b_{ni}^W$  is adjusted which signals the availability of machine  $n$  in period  $i$ . Constraint (9) limits the volume of purchase parts in such a way that these can only be purchased in a scenario if they are marked as purchase parts by the binary variable  $b_{ki}^K$ . Constraint (10) ensures in the other direction that purchase parts cannot be manufactured in-house. In order to achieve that, the output sum over all technologies is calculated and multiplied by the inverse value of  $b_{ki}^K$  and limited with a sufficiently large number  $M$ .

$$x_{mj}^T \leq M \cdot \sum_{l=1}^{n^{PA}} b_{lm}^P \cdot b_{l\pi(j)}^{PN} \quad \forall m \in \{1 \dots n^T\}, \forall j \in \{0 \dots n^S\} \quad (11)$$

$$\sum_{l=1}^{n^{PA}} b_{li}^{PN} = 1 \quad \forall i \in \{0 \dots n^P\} \quad (12)$$

$$b_i^{PNA} \geq b_{li}^{PN} - b_{l(i-1)}^{PN} \quad \forall l \in \{1 \dots n^{PA}\}, \forall i \in \{1 \dots n^P\} \quad (13)$$

Constraint (11) ensures that exclusively those technologies are used which are available in the selected process alternative. Through the multiplication with a sufficiently large number  $M$  the part can serve as the upper limit for  $x_{mj}^T$ . Constraint (12) limits the number of employable process alternatives in a single period to 1. Constraint (13) adjusts the binary variable which signals a change in the selected process alternative.

$$x_{k0}^L = 0 \quad \forall k \in \{1 \dots n^E\} \quad (14)$$

$$b_{n0}^W \leq b_n^{W0} \quad \forall n \in \{1 \dots n^W\} \quad (15)$$

$$b_{i0}^{PN} = b_i^{PN0} \quad \forall i \in \{1 \dots n^{PA}\} \quad (16)$$

Constraint (14) initialises the inventory in the original scenario with 0 (alternatively any current inventory level). Constraints (15) and (16) initialise the availability of machines and the usage of process alternatives in the original scenario. Finally, a number of non-negativity constraints which are not shown in detail here, complete partial model I.

#### 4.2. Partial Model II

Partial model II deals with supporting decisions related to the planning of human resources, decisions concerned with determining which employees shall acquire new skills or qualifications and how the human resource structure can be optimally planned taking into account the temporal dynamic of external factors. The mathematical model concerned with asset planning, as presented in the previous section, determined the availability of machines for each period which serves as input parameter for partial model II. The number of technologies (and thus the volume of in-house production) is not considered as fixed input parameter since the optimisation in partial model II also incorporates the planning of human resources and an efficient resource allocation differing from the plain asset (machine) stock optimisation is conceivable.

The upshot of partial model II is presented in Figure 5. The matrix  $b_{oi}^M$  displays whether

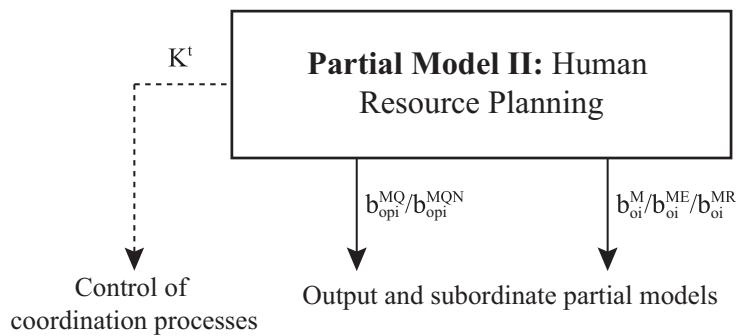


Figure 5.: Outcome of partial model II

an employee  $o$  is employed during period  $i$  and thus available for labour. The variables  $b_{oi}^{ME}$  and  $b_{oi}^{MR}$  denote changes in this matrix. On the other hand, the matrix of binary variables  $b_{opi}^{MQ}$  indicates if a specific skill is available for a specific employee and period. Parallel, the matrix  $b_{opi}^{MQN}$  presents if an employee has newly acquired a specific skill. The results of this partial model are used as input for a performance indicator  $K^t$ , which is used to control the coordination process between the partial models.

Symbol	Definition
$b_{oi}^M$	Binary variable showing if employee $o$ is available during period $i$
$b_o^{M0}$	Binary variable showing if employee $o$ is employed
$b_{oi}^{ME}$	Binary variable showing if employee $o$ has been reappointed in period $i$
$b_{opi}^{MQ}$	Binary variable showing if employee $o$ possesses qualification $p$ in period $i$
$b_{op}^{MQ0}$	Binary variable showing if employee $o$ currently possesses qualification $p$
$b_{opi}^{MQN}$	Binary variable showing if employee $o$ is added (learns) qualification $p$ in period $i$
$b_{oi}^{MR}$	Binary variable showing if employee $o$ is discharged in period $i$
$c_o^M$	Base wage of employee $o$ per period
$c^{ME}$	Cost of hiring one employee
$c^{MR}$	Cost of dismissal of one employee
$c_p^Q$	Cost of funding a training measure to acquire qualification $p$
$c_o^U$	Cost of time unit for overtime of employee $o$
$n^M$	Number of employees
$n^Q$	Number of qualifications
$n^{Umax}$	Upper limit of overtime per employee and period
$t_p^L$	Time required to learn qualification $p$
$t_{oi}^M$	Available base work time of employee $o$ in period $i$
$t_{mp}^{TQ}$	Time required by an employee with qualification $p$ to execute one unit of technology $m$
$x_{poj}^{QM}$	Number of time units spent by employee $o$ applying qualification $p$ in scenario $j$
$x_{oj}^U$	Hours of overtime spent by employee $o$ in scenario $j$

Table 4.: Notation: Additional symbols partial model II



Equations (17) to (33) represent the mathematical model of the human resource planning. This model extends the MLCLSP model by the following notions:

- (1) Usage of varying scenarios in order to enable the presentation of alternative developments, especially with respect to demand
- (2) Availability of employees
- (3) Skills and qualifications of employees and acquisition of new qualifications

$$\begin{aligned} \min \quad & \sum_{j=0}^{n^S} \omega(j) \cdot (1 + c^Z)^{-\pi(j)} \cdot \left[ \sum_{n=1}^{n^W} \sum_{m=1}^{n^T} (b_{mnj}^{RT} \cdot t_{mn}^{RT} \cdot c_n^R + x_{mj}^T \cdot t_{mn}^{TW} \cdot c_n^P) \right. \\ & + \sum_{k=1}^{n^E} x_{kj}^K \cdot c_k^K + \sum_{k=1}^{n^E} (\max(x_{kj}^L, 0) \cdot c_k^L - \min(x_{kj}^L, 0) \cdot c_k^V) \\ & \left. + \sum_{o=1}^{n^M} \left( b_{o\pi(j)}^M \cdot c_o^M + x_{oj}^U \cdot c_o^U + b_{o\pi(j)}^{ME} \cdot c^{ME} + b_{o\pi(j)}^{MR} \cdot c^{MR} + \sum_{p=1}^{n^Q} b_{op\pi(j)}^{MQN} \cdot c_p^Q \right) \right] \end{aligned} \quad (17)$$

Expression (17) is the objective function of partial model II. In comparison to the MLCLSP model, the objective function is extended with the last sum over all employees  $n^M$  by wage costs, costs for hirings and dismissals of employees and the costs for acquiring new skills and qualifications. Furthermore, every scenario  $j$  is weighted with a likelihood  $\omega(j)$ . Costs are devalued with the calculatory interest factor  $c^Z$ . The first summand represents the base wages of the employees as product of the matrix  $b_{oi}^M$  (indicating employee availability) and the base wage vector  $c_o^M$ . Further costs are incurred by overtime represented by the product of required overtime  $x_{oj}^U$  and the respective costs  $c_o^U$ . The following two summands add the costs for hiring and dismissals of employees. The last summand represents costs of training measures. The objective function is subject to a number of restrictions, presented in the following.

$$n_m^{RTmax} \geq \sum_{n=1}^{n^W} b_{mnj}^{RT} \quad \forall m \in \{1 \dots n^T\}, \forall j \in \{0 \dots n^S\} \quad (18)$$

$$x_{mj}^T \leq M \cdot b_{mnj}^{RT} \quad \forall m \in \{1 \dots n^T\}, \forall n \in \{1 \dots n^W\}, \forall j \in \{0 \dots n^S\} \quad (19)$$

Constraint (18) is identical to Constraint (4) and limits the number of setups. Likewise, Constraint (19) is identical to Constraint (5) and limits the executable technologies to those for which the machines can be setup.

$$\sum_{m=1}^{n^T} (b_{mnj}^{RT} \cdot t_{mn}^{RT} + x_{mj}^T \cdot t_{mn}^{TW}) \leq t_{n\pi(j)}^{KW} \cdot b_{n\pi(j)}^W \quad \forall n \in \{1 \dots n^W\}, \forall j \in \{0 \dots n^S\} \quad (20)$$

$$x_{kj}^L = x_{k\nu(j)}^L + \sum_{m=1}^{n^T} (x_{mj}^T \cdot n_{km}^{TE} - n_{km}^{TB} \cdot x_{mj}^T) + x_{kj}^K - n_{kj}^B \quad (21)$$

$$\forall k \in \{1 \dots n^E\}, \forall j \in \{0 \dots n^S\}$$

Constraint (20) limits machine up-time. It needs to be considered that  $b_{ni}^W$  is not a variable in this model but a matrix of given constants; the availability of machines which has been determined by the preceding partial model is considered an input to this model. The inventory at the end of the period as calculated in Constraint (21) is equivalent to the model of the asset (machine) inventory planning, see Constraint (7).

$$\sum_{m=1}^{n^T} x_{mj}^T \cdot t_{mp}^{TQ} \leq \sum_{o=1}^{n^M} x_{poj}^{QM} \quad \forall j \in \{0 \dots n^S\}, \forall p \in \{1 \dots n^Q\} \quad (22)$$

$$\sum_{p=1}^{n^Q} (x_{poj}^{QM} + b_{op\pi(j)}^{MQN} \cdot t_p^L) \leq b_{o\pi(j)}^M \cdot t_{o\pi(j)}^M + x_{oj}^U \quad \forall o \in \{1 \dots n^M\}, \forall j \in \{0 \dots n^S\} \quad (23)$$

The mapping of employees to the usage of their qualifications is achieved through the variable  $x_{poj}^{QM}$ . This variable represents the number of time units spent by employee  $o$  applying qualification  $p$  in scenario  $j$ . Constraint (22) ensures that the number of time units spent by employees performing a skill equals the time needed for the technology being used. Constraint (23) limits the available working time of each employee for each period. The first summand is the accumulated time required by the training of skills for each employee. The second summand adds the times required for training measures, where the vector  $t_p^L$  determines the time required for each specific training. The upper limit of working time is the sum of the contractual base working time  $t_{oi}^M$  and the amount of overtime  $x_{oj}^U$ . The binary variable  $b_{oi}^M$  considers whether an employee is actually available in the respective period.

$$x_{poj}^{QM} \leq M \cdot b_{op\pi(j)}^{MQ} \quad \forall p \in \{1 \dots n^Q\}, \forall o \in \{1 \dots n^M\}, \forall j \in \{1 \dots n^S\} \quad (24)$$

$$b_{opi}^{MQ} \leq b_{op(i-1)}^{MQ} + b_{opi}^{MQN} \quad \forall o \in \{1 \dots n^M\}, \forall p \in \{1 \dots n^Q\}, \forall i \in \{1 \dots n^P\} \quad (25)$$

$$x_{oj}^U \leq n^{U_{max}} \cdot b_{o\pi(j)}^M \quad \forall o \in \{1 \dots n^M\}, \forall j \in \{1 \dots n^S\} \quad (26)$$

Constraint (24) ensures that an employee only uses time applying a qualification if he actually possesses this qualification in the respective period. The skill or qualification matrix is updated according to the newly learned skills in Constraint (25). Constraint (26) limits the amount of overtime to a maximum value of  $n^{U_{max}}$  or 0 if the employee is not hired in the respective period.

$$n_{km}^{TE} \cdot x_{mj}^T \leq M \cdot (1 - b_{k\pi(j)}^K) \quad \forall k \in \{1 \dots n^E\}, \forall j \in \{0 \dots n^S\}, \forall m \in \{1 \dots n^T\} \quad (27)$$

$$x_{kj}^K \leq M \cdot b_{k\pi(j)}^K \quad \forall k \in \{1 \dots n^E\}, \forall j \in \{0 \dots n^S\} \quad (28)$$

$$b_{oi}^{ME} \geq b_{oi}^M - b_{o(i-1)}^M \quad \forall o \in \{1 \dots n^M\}, \forall i \in \{1 \dots n^P\} \quad (29)$$

$$b_{oi}^{MR} \geq b_{o(i-1)}^M - b_{oi}^M \quad \forall o \in \{1 \dots n^M\}, \forall i \in \{1 \dots n^P\} \quad (30)$$

Constraints (27) and (28) ascertain that the parts marked as purchase parts in partial model I are not produced in-house and parts marked as in-house production cannot be externally purchased. Constraints (29) and (30) adjust the binary variables  $b_{oi}^{ME}$  and  $b_{oi}^{MR}$  for employee hirings and dismissals.

$$b_{o0}^M = b_o^{M0} \quad \forall o \in \{1 \dots n^M\} \quad (31)$$

$$b_{op0}^{MQ} \leq b_{op}^{MQ0} \quad \forall o \in \{1 \dots n^M\}, \forall p \in \{1 \dots n^Q\} \quad (32)$$

$$x_{k0}^L = 0 \quad \forall k \in \{1 \dots n^E\} \quad (33)$$

In Constraints (31) and (32) the initial values for the number of employees and the skills matrix are mapped to the binary variables of the original scenario. Constraint (33) sets the inventory in the original scenario to 0. Finally, a number of non-negativity constraints which are not shown in detail here, complete partial model II.

### 4.3. Partial Model III

The definition of stock echelons and the involved determination of reorder levels for parts planned with a consumption-oriented disposition strategy is an MRP procedure and will be tackled in an integrated mathematical model. The objective of this model is to position stock echelons in such a way that, on the one hand, the required lead time can be guaranteed. On the other hand, inventory costs including capital holding costs need to be kept minimal. The required maximum lead time is an input parameter to this partial model. It limits the critical path of production and replenishment times of all parts which are required for a final product and not served from a stock echelon.

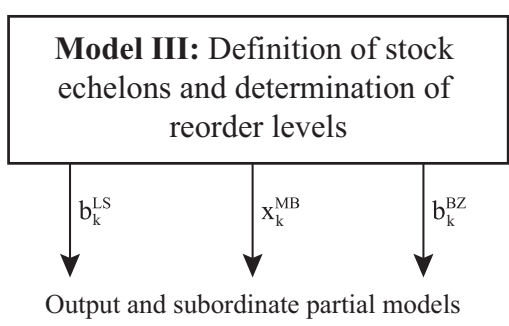


Figure 6.: Outcome of partial model III

As depicted by Figure 6, the output of this model is the binary variable  $b_k^{LS}$  which

determines for each part whether a stock echelon is defined. The variable  $x_k^{MB}$  defines the reorder levels for those parts which are to be planned with consumption-oriented disposition strategies. The binary variable  $b_k^{BZ}$  marks whether the disposition of the part is clocked by an order cycle to reach a better sequence planning depending on the load of the required machines.

#### 4.4. *Partial Model IV*

Based on the results of partial model III, partial model IV adjusts the consumption-oriented disposition strategies for the relevant parts. Particularly, the lot size is a decisive factor since it determines the actual costs per unit of the individual parts.

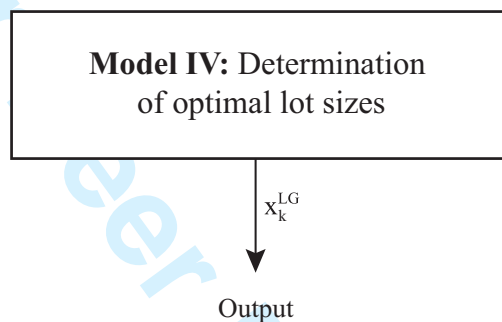


Figure 7.: Outcome of partial model IV

Sole outcome of partial model IV is the variable  $x_k^{LG}$  which determines the lot size of part  $k$ . Furthermore, indicators for control of the coordination processes are derived from this partial model as shown in Figure 7.

#### 4.5. *Coordination Processes*

Coordination processes connecting partial models I through IV are defined in order to use them for the hierarchical planning of structure, dimension and material requirements of manufacturing systems. By complementing planning processes starting at partial models III and IV, the manufacturing system can also be planned solely based on these partial models and hence adapt to changing environmental conditions. If required, the planning can be extended on the layer of the super ordinate partial models I and II. The coordination processes determine at which time or event which optimisation model replans one of the partial models and how the results of the replanning will be used subsequently.

The coordination processes are controlled by indicators derived from the partial models. These indicators allow deciding whether a solution fulfils all requirements of the strategic goals. It is conceivable to guarantee the compliance with these requirements already when formulating the planning models by adding respective restrictions. However, this could cause problems in finding feasible solutions for the partial models and the planning would consequently not come to a final result. Therefore, the indicators are used afterwards by the coordination processes. Since the focus of this paper is put on partial models I and II, a detailed description of the coordination processes is omitted here.

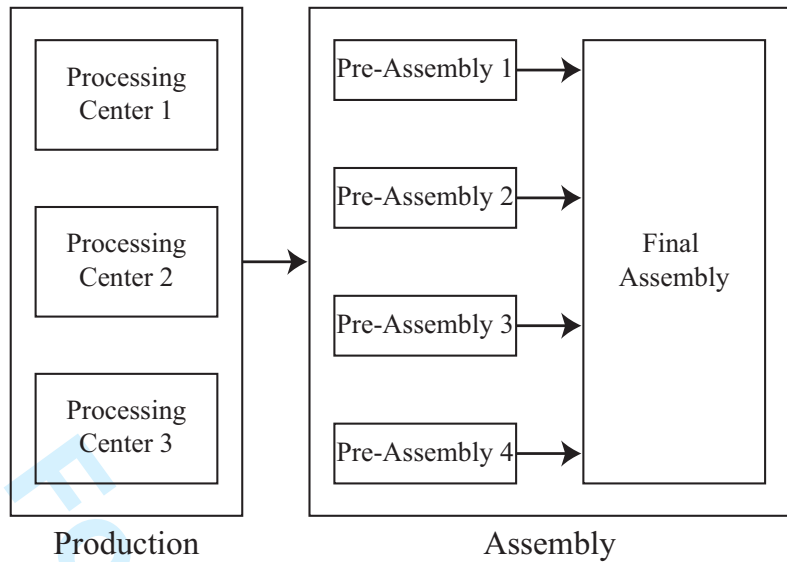


Figure 8.: Structure of production (as-is state)

## 5. Case Example

### 5.1. Scenario

A case example served to assess the applicability, feasibility and performance of the developed hierarchical planning method. Here, pneumatic valve modules (in the following called valve modules) geared to control braking systems of rail vehicles are manufactured in a two-stage production process.<sup>1</sup> These valve modules exist in a number of variants resulting from the various intended usages. Based on properties such as performance, robustness, durability, and general layout 40 different products (or product variants) can be distinguished. For each product variant primary demand from the final customer can exist.

The two-stage production process is currently structured in a machining (chipping) production section and an assembly section as illustrated in Figure 8. Both sections of the production process are carried out in the same plant. The assembly section consists of four pre-assembly lines and one final assembly line which are directly connected. The pre-assembly lines mount the required components for the final assembly line based on actual demand. Inventory between these lines only exists in the form of small buffers. This has been achieved by the application of the One-Piece-Flow idea (see Lander and Liker 2007), the consistent balancing of lines and the use of small lot sizes at the assembly lines. Thus, the assembly lines can be planned integrately for the purposes of this analysis.

The parts production is carried out in the same location. Three processing centres can be considered for manufacturing the items required as input for the assembly lines. These parts include the valve bodies to which further components are subsequently assembled. While some further items are produced in-house, these are mainly parts which require advanced manufacturing competence and can thus be considered a core competence of

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<sup>1</sup>The case example presented here draws from a case study conducted when carrying out this research. While the production structure and according data are drawn from the case study, some estimations and approximations had to be made. Some of the data has been intentionally altered in order to respect confidentiality of the company and sensitive data. However, these alterations did not have an effect on the results themselves which appropriately reflect the outcome obtained with the original data.

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the company. The allocation in the machining section is performed on a demand-oriented basis. This leads to partially extremely long delivery times and problems with the delivery reliability for the products of the company since long cycle and setup times lead to long replenishment lead times.

On a strategic level, the company has decided that all customer orders are to be filled within a lead time of five days. This delivery time has to be achieved with a delivery reliability of 95%. This decision triggered a comprehensive analysis of the entire planning of structure, dimension and material requirements of the production processes. Specifically, it needs to be examined whether the chipping production, i.e. the machining section of the overall production process, is the appropriate production technology and geared to suffice future customer requirements with respect to delivery time, delivery reliability and costs.

The valve bodies can alternatively be produced by using a different production technology. This can also be done in spatial separation if a respective disposition strategy ensures permanent availability. Hence, an alternative product structure has been developed in which the bodies for the valve modules are not produced by the current processing centres in a chipping production process, but cast. This process cannot be executed by the company itself. A supplier has been identified which would be able to deliver the parts in the required quality. Two central questions arise:

- Shall the valve bodies be produced in-house in the current assembly stations or be outsourced and procured from a supplier who uses an alternative production technology (casting)?
- Which disposition methods are to be used for the respective products and to what value need the parameters be set in order to ensure a delivery reliability of 95%?

## 5.2. Implementation

The models have been built in the CPLEX LP format, which served as input format for the optimisation software ILOG CPLEX, which was used in version 10.1.1. The choice for this optimisation software has been made since CPLEX requires the least computational time for solving mathematical models among the currently available systems. Standard settings have been used for CPLEX except the parameter 'mipgap', which has been set to a value of 0.0005 in order to achieve shortest execution time. The hardware used for optimisation was a standard 2 GHz dual core notebook with 2 GB RAM.

## 5.3. Results

### 5.3.1. Partial Model I

The optimisation of partial model I required 89.95 seconds computation time. The values of the respective variables (not listed in detail here) can be interpreted in the following way:

- (1) The binary variable  $b_{li}^{PN}$  which denotes whether a process alternative  $l$  is used in period  $i$  is set to the value  $l = 1$  for all periods. Thus, production is continued at the current location using the currently employed technology. The production of the valve bodies is continued at the processing centres in the current assembly section of the manufacturing plant.

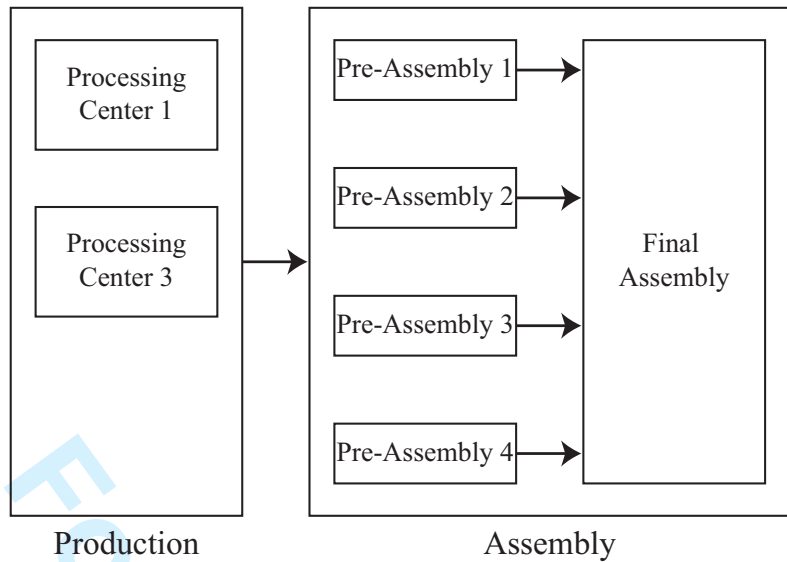


Figure 9.: Structure of production (after optimisation)

(2) The binary  $b_{ni}^W$  which denotes whether machine  $n$  is available in period  $i$  is set to a value of 1 for machine 1 over the entire planning horizon. The final assembly line is required continuously since it is part of process alternative 1. This variable is set to a value of 0 for machine 3 over the entire planning horizon. This means that with the chosen combination of in-house production and outsourcing one of the three processing centres is not required anymore. For machines 2 and 4, the binary variable  $b_{ni}^W$  is first 1 before it switches to 0 towards the end of the planning horizon. This may not be interpreted as a disestablishment of the respective processing centres in those periods. Rather, the reasons why these are no longer required lies in the fact that the required parts for the assembly line are produced in the beginning periods of the planning interval. The existing inventory is then used in the remaining periods. The processing centres should remain for the entire time horizon.

The outcome of the optimisation of partial model I is the production layout as displayed in Figure 9. Production and assembly are continued at their present locations. One processing centre can be omitted which creates additional free space in the production plant.

5.3.2. Partial Model II

The optimisation of partial model II required 72.08 seconds computation time. The values of the respective variables (not listed in detail here) can be interpreted in the following way:

(1) The binary variables  $b_{opi}^{MQ}$  and  $b_{opi}^{MQN}$  that determine which employees are trained to gain certain skills or qualifications show that one employee currently working in the assembly section is trained to acquire the necessary qualifications to be able to work in the processing centres. Thus, this employee can be flexibly used either in the assembly section or in the machining production section and variances in the labour supply can be balanced. This decision goes in accordance with the development of the labour force, which foresees a reduction of currently employed unskilled workers in the processing centres.

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5 (2) The binary variables  $b_{oi}^M$ ,  $b_{oi}^{MR}$  and  $b_{oi}^{ME}$  determine the further evolution of the  
6 labour force. The outcome of the optimisation is that three employees from assem-  
7 bly, one unskilled worker from the processing centres as well as three employees  
8 from the processing centres (two instead of three processing centres) are no longer  
9 required in their present field of responsibility. This reduction in labour force is  
10 significant. During the comprehensive structure, dimension and material require-  
11 ments planning project carried out in this case example, all target times had been  
12 re-established. This has been achieved through actual time measurement during  
13 running production. Furthermore, employees in the production section and as-  
14 sembly section were relieved of auxiliary tasks such that they could concentrate  
15 on the tasks for which they are skilled. Since this measure requires workers for the  
16 centralised material disposition, the reduction in labour force does not necessarily  
17 lead to dismissals.  
18

### 19 20 5.3.3. Partial Model III

21 The optimisation of partial model III required only 0.19 seconds computation time.  
22 The values of the respective variables (not listed in detail here) can be interpreted in the  
23 following way:  
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- 25 (1) The binary variable  $b_k^{BZ}$ , which determines the parts which are planned with an  
26 order cycle, defines an order cycle for all in-house production parts. This results  
27 from the high load of the processing centres and assembly lines in the considered  
28 time horizon. Through the use of order cycles, an optimised sequence planning  
29 can be carried out in regular intervals for all work stations (determined at five  
30 time units in this example).  
31  
32 (2) The binary variable  $b_k^{LS}$ , which defines for which parts inventory shall be held,  
33 determines stock echelons for all parts.  
34  
35 (3) The reorder level  $x_k^{MB}$  is set to values between 7 (for valve modules which are  
36 only ordered in small volumes) and 211 (for add-on parts which are integrated in  
37 various valve modules).  
38

### 39 40 5.3.4. Partial Model IV

41 The optimisation of partial model IV required 7.39 seconds computation time. The  
42 output of this partial model is only one variable:

- 43 (1) The lot sizes  $x_k^{LG}$  are adjusted in the optimisation model for each period. The  
44 limitation to parts planned with a consumption-oriented disposition strategy is  
45 irrelevant here, since partial model III defined a stock echelon for all parts consid-  
46 ered. The lot sizes are chosen in such a way that the desired value for the delivery  
47 reliability is kept under the parameters set by partial model III. The defined lot  
48 sizes vary between 10 and 342.  
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## 52 53 6. Conclusions and Outlook

54 The hierarchical planning method in this paper has been developed in cooperation with  
55 a manufacturing company. The case example described in Section 5 showed that the  
56 planning tasks identified in this company can be solved with the method in time inter-  
57 vals suitable for practical implementation. To integrate the method into the planning  
58 processes of the company, the next steps are to develop user and data interfaces to ex-  
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isting systems and thus, further improving the usability and applicability of the method. Moreover, a fifth partial model is currently under development. It separates the decisions concerning establishing and closing locations from partial model I into a dedicated partial model in order to determine the manufacturing footprint. Hence, the time model for these decisions can be chosen according to the long-term time horizon of these decisions.

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