EVIDENCE OF THE RELEVANCE OF MASTER PRODUCTION SCHEDULING FOR HIERARCHICAL PRODUCTION PLANNING

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KEYWORDS

Hierarchical production planning, aggregate production planning, master production scheduling, material requirement planning, planned independent requirements.

ABSTRACT

This paper deals with the significance of master production scheduling for hierarchical production planning.

Production planning in a typical manufacturing organization is a sequence of complex decisions which depends on a number of factors, such as number of products, complexity of products, number of production sites, and number of work centres in each production site.

The main idea in hierarchical production planning is to break down larger problems into smaller, more manageable sub problems.

Starting with aggregate production planning, the benefits of using master production scheduling for material requirements planning will be conveyed.

The main benefit of master production scheduling is more detailed planning. The production groups are thereby disaggregated into final products and the production site disaggregated into work centres. In order to plan capacities, resource profiles are used. By working with resource profiles production lead time data are taken into account to provide time-phased projections of the capacity requirements for each work centre (Vollmann et al. 2005).

The case study will show that more accurate planning and consideration of production lead time through master production scheduling results in a demand program that can be realized without shortages or delays.

INTRODUCTION

In the simultaneous planning approach all relevant decision parameters for the production program planning are taken into account at the same time. A high number of parameters and their mutual dependencies lead to very long computation times. Another disadvantage of this approach is that not all data are available at the same time and at the same level of detail.

In contrast, in the hierarchical production planning approach (Herrmann 2011), the complex singular problem of production planning is replaced by several manageable problems. These problems are solved successively. The individual solutions are then combined into one overall solution. This successive planning concept is implemented in most commercial production planning and control systems.

In this planning concept aggregation plays an important role. There are three different types of aggregation. The aggregation of time especially the period size, decision variables like grouping of products or constraints like grouping of machines to work centers or production sites (Stadtler 1988 and Gebhard 2009).

The hierarchical production planning approach is attributed to Hax and Meal 1975. This paper is based on a hierarchical planning concept that is expanded by limited capacities of resources, as suggested in Drexl et al. 1994. Typical hierarchical production planning is shown in figure 1.

The hierarchical production planning approach consists of the following steps: Aggregate production planning, master production scheduling, material requirements planning and scheduling.

The period size is freely scalable for each step and depends primarily on the planned product and the associated product structure tree.

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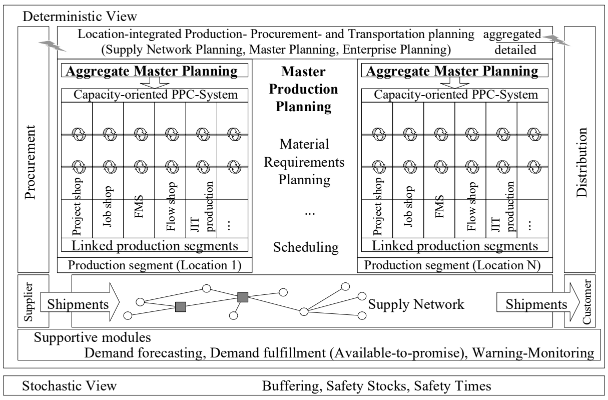

Figure 1. Overview Production Planning and Control (Günther and Tempelmeier 2014)

AGGREGATE PRODUCTION PLANNING

Aggregate production planning predicts the planned independent requirements for one production site on a product group level based on demand forecasts. It is used by companies which offer a large spectrum of end products. It is difficult to predict the requirements for each individual product. Any forecast for a product has a forecast error. If the forecasts for individual products are summarized by prognosticating a product group, the forecast error is reduced due to variance reduction. The main benefit is the more accurate demand for planning process.

The planning horizon at this step covers at least one year, typically covering one seasonal demand pattern of the product group. So the planning horizon will typically cover between one and two years. The planning horizon will typically have a granularity of quarters, months or weeks.

MASTER PRODUCTION SCHEDULING

Master production scheduling determines the quantities of final products for a medium term period (several weeks to one quarter of a year). Therefore, aggregate production planning provides guidelines for master production scheduling in regard to the minimum production quantity and maximum overload capacity. The planning horizon will typically cover a medium term period (several weeks, to one quarter of a year). Master production scheduling is based on demand forecast for final products. The planning horizon will typically have a granularity of weeks.

At this stage the periods of aggregate production planning are disaggregated into smaller periods which are used in master production scheduling. Also the production groups are disaggregated into final products and the production site is disaggregated into work centres.

To reduce the complexity of disaggregation, in aggregate production planning and master production scheduling the same period size is used.

MATERIAL REQUIREMENTS PLANNING

The main task of material requirements planning is to determine the secondary requirements. It is a process of translating primary requirements into component part requirements which considers existing inventories and scheduled receipts (Kurbel 2013).

The planning horizon at this step covers usually one week and as period size is there will be used size days or shifts.

At these step typically lot size planning is also done. The main task of lot sizing is to minimize set up and storage costs (Herrmann 2009).

Material requirements planning determines the quantities and the completion dates for a short-term periode (several days) based on the results of the master production scheduling.

The result of the material requirements are planned orders.

SCHEDULING

At these step a production order is allocated to a concrete machine. Scheduling determines the exact processing times and the order of the operations on the machines.

Also important for scheduling are the capacities which can be used. These depends on capacity and maintenance data of machines, but also of factory calendars and shift models (Kurbel 2013).

CASE STUDY

In this paper it will be discussed, whether aggregate production planning is sufficient to get a realizable demand programm or whether master production scheduling is needed.

The point of this paper is best illustrated by following a clear example from a case study.

In order to clearly highlight the benefiting effects, it is assumed that the predicted planned independent requirements are identical to the real customer requirements.

To be able to compare results, the period size of aggregate production planning and of master production scheduling is the same.

The planning horizon starts in period 1 and ends with the last customer demand in period 10.

In this case study one production site with two work centres is considered. The capacity of each work centre is 500 hours per period. So the production site has a capacity of 1000 hours per period. In this case study the human capacity is equal the technical capacity and there is no additional capacity.

The production site produces one production group (P). The production group (P) consists of one final product

(E). The final product (E) consists of one component (V). The product structure tree is shown in figure 2.

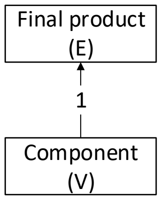

Figure 2. Product structure tree of the final product

The final product (E) is produced in work centre A and needs 4 hours of capacity per unit, the component (V) is produced in work centre B and needs 6 hours of capacity per unit. So the production group (P) needs in the production site a capacity of 10 hours per unit.

The estimated lead time for the final product (E) and the component (V) is 1 period. No set-up time is needed and there are no set-up costs. The inventory holding costs (h_k) are 2 € per unit.

The derived requirements (dependent requirements) to all components are produced just in time.

In this case study the model of a closed production is used. Closed production is characterized by the fact that each planned order has to be finished and stored, before it can be further processed or shipped (Herrmann 2011).

The demand for this case study is shown in table 1.

Table 1. Demand

Period (t)	1	2	3	4	5	6	7	8	9	10	$\sum$
Demand (d_t^A) [units]	0	0	0	0	80	100	120	100	80	120	600

The production program will be created once with the LP-Model for aggregate production planning and once with the LP-Model for the master production scheduling, which are located in the same named sections.

LP MODEL FOR AGGREGATE PRODUCTION PLANNING

The following shows the LP model for aggregate production planning (Günther and Tempelmeier 2014).

Parameters:

- K — Number of product groups $(1 \leq k \leq K)$.
- T — Length of the planning interval $(1 \leq t \leq T)$.
- b_t — Maximum technical production capacity in period t $\forall\, 1 \leq t \leq T$.
- co_t — Costs for one unit overtime in period t $\forall\, 1 \leq t \leq T$.
- $d^A_{k,t}$ — Demand for product group k in period t $\forall\, 1 \leq k \leq K$ and $1 \leq t \leq T$.
- h_k — Inventory holding costs for one unit of product group k $\forall\, 1 \leq k \leq K$.
- n_t^{max} — Maximum normal human capacity in period t $\forall\, 1 \leq t \leq T$.
- o_t^{max} — Maximum overtime in period t $\forall\, 1 \leq t \leq T$.
- tb_k — Human capacity absorption factor for one unit of product group k $\forall\, 1 \leq k \leq K$.
- tc_k — Technical capacity absorption factor for one unit of product group k $\forall\, 1 \leq k \leq K$.

Variables:

- o_t — Used overtime in period t $\forall\, 1 \leq t \leq T$.
- $x^A_{k,t}$ — Production quantity of product group k in period t $\forall\, 1 \leq k \leq K$ and $1 \leq t \leq T$.
- $y^E_{k,t}$ — Inventory of product group k at the end of period t $\forall\, 1 \leq k \leq K$ and $1 \leq t \leq T$.

Objective function:

The inventory costs for product groups (k) and the cost of additonal capacity are to be minimized.

$$Minimize\ Z = \sum_{k=1}^{K} \sum_{t=1}^{T} h_k \cdot y^E_{k,t} + \sum_{t=1}^{T} co_t \cdot o_t \qquad (1)$$

Constraints:

Inventory balance equation: (2)

$$y^E_{k,t-1} + x^A_{k,t} - y^E_{k,t} = d^A_{k,t}\ \forall\, 1 \leq k \leq K \text{ and } 1 \leq t \leq T$$

Human capacity constraints: (3)

$$\sum_{k=1}^{K} tb_k \cdot x^A_{k,t} - o_t \leq n_t^{max}\ \forall\, 1 \leq t \leq T$$

Technical capacity constraints: (4)

$$\sum_{k=1}^{K} tc_k \cdot x^A_{k,t} - o_t \leq b_t\ \forall\, 1 \leq t \leq T$$

Additional capacity constraints: (5)

$$o_t \leq o_t^{max}\ \forall\, 1 \leq t \leq T$$

Non-negativity constraints for all variables: (6)

$$x^A_{k,t}, y^E_{k,t}, o_t \geq 0\ \forall\, 1 \leq k \leq K \text{ and } 1 \leq t \leq T$$

Initialization of the starting inventory: (7)

$y^E_{k,0}$ given $\forall\ 1 \leq k \leq K$

Minimization problem:

Minimize Z.

AGGREGATE PRODUCTION PLANNING

Solution of Aggregate Production Planning

The optimal solution of the LP-Model of aggregate production planning is shown in table 2 and illustrated in figure 3. The objective is 120€. Because of the usage of a LP-Model there is no shortage.

Table 2. Solution of aggregate production planning

Period (t)	1	2	3	4	5	6	7	8	9	10	$\sum$
$\mathrm{d}^{\mathrm{A}}_{\mathrm{E,t}}$ [units]	0	0	0	0	80	100	120	100	80	120	600
$\mathrm{x}^{\mathrm{A}}_{\mathrm{E,t}}$ [units]	0	0	0	100	100	100	100	100	100	0	600
$\mathrm{y}^{\mathrm{E}}_{\mathrm{E,t}}$ [units]	0	0	0	0	20	20	0	0	20	0	60

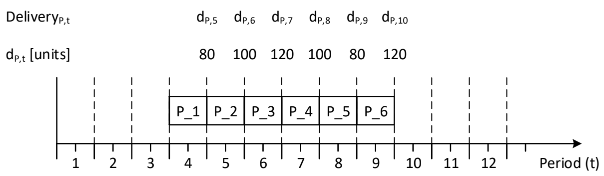

Figure 3. Solution of aggregate production planning

Realization of Aggregate Production Planning

The situation changes completely, when we look at the realization of the solution. Because of a delay no costumer requirements can be satisfied in time. The total shortage in the planning period is 1320 units and the total delay in periods is 13. The inventory holding costs will increase from 120 € to 160 €.

The realization of the solution is shown in table 3 and illustrated in figure 4. The first three periods do not contain demand or planned orders. For this reason they are not mentioned in the table.

Table 3. Realization of aggregate production planning

Period (t)	4	5	6	7	8	9	10	11	12	13	$\sum$
Demand ($\mathrm{d}^{\mathrm{A}}_{\mathrm{E,t}}$)	0	80	100	120	100	80	120	0	0	0	600
Planned order$^{\mathrm{A}}_{\mathrm{E,t}}$	100	100	100	100	100	100	0	0	0	0	600
Receipt$^{\mathrm{A}}_{\mathrm{E,t}}$	0	0	0	100	100	100	100	100	0	100	600
Delivery$^{\mathrm{A}}_{\mathrm{E,t}}$	0	0	0	80	100	120	100	80	0	120	600
Delay in periods	0	0	0	2	2	2	2	2	0	3	13
Inventory$^{\mathrm{E}}_{\mathrm{E,t}}$	0	0	0	20	20	0	0	20	20	0	80
Shortage$^{\mathrm{E}}_{\mathrm{E,t}}$	0	80	180	220	220	180	200	120	120	0	1320

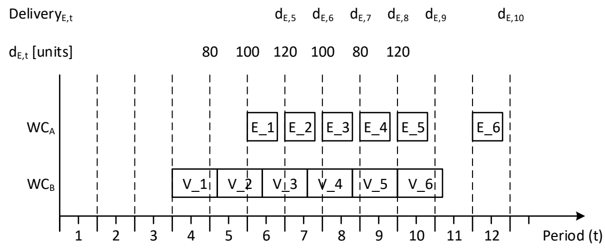

Figure 4. Realization of aggregate production planning

LP-MODEL FOR MASTER PRODUCTION SCHEDULING

The following shows the LP model for master production scheduling. (Günther and Tempelmeier 2014)

Parameters:

J Number of production segments $(1 \leq j \leq J)$.

K Number of products $(1 \leq k \leq K)$.

T Length of the planning interval $(1 \leq t \leq T)$.

$b_{j,t}$ Production capacity of production segment j in period t $\forall\ 1 \leq j \leq J$ and $1 \leq t \leq T$.

$co_{j,t}$ Costs for one unit overtime in production segment j in period t $\forall\ 1 \leq j \leq J$ and $1 \leq t \leq T$.

$d^A_{k,t}$ Demand for product k in period t $\forall\ 1 \leq k \leq K$ and $1 \leq t \leq T$.

$f_{j,k,z}$ Capacity absorption factor for product k with respect to production segment j in offset period z $\forall\ 1 \leq j \leq J$, $1 \leq k \leq K$ and $1 \leq z \leq Z_k$.

h_k Inventory holding costs for one unit of product k $\forall\ 1 \leq k \leq K$.

$o^{max}_{j,t}$ Maximum additional capacity in production segment j in period t $\forall\ 1 \leq j \leq J$ and $1 \leq t \leq T$.

Z_k Maximum lead time for product k $(1 \leq k \leq K)$.

Variables:

$o_{j,t}$ Used overtime in production segment j in period t $\forall\ 1 \leq j \leq J$ and $1 \leq t \leq T$.

$x^A_{k,t}$ Production quantity of product k in period t $\forall\ 1 \leq k \leq K$ and $1 \leq t \leq T$.

$y^E_{k,t}$ Inventory of product k at the end of period t $\forall\ 1 \leq k \leq K$ and $1 \leq t \leq T$.

Objective function:

The inventory costs for product (k) and the cost of additional capacity are to be minimized.

$$Minimize\ Z = \sum_{k=1}^{K} \sum_{t=1}^{T} h_k \cdot y^E_{k,t} + \sum_{t=1}^{T} \sum_{j=1}^{J} co_{j,t} \cdot o_{j,t} \tag{8}$$

Constraints:

Conditional statement inventory balance equation: (9)

$y^{E}_{k,t-1} - y^{E}_{k,t} = d^{A}_{k,t}$ $\forall$ $1 \leq k \leq K$ and $1 \leq t \leq Z_k$

$y^{E}_{k,t-1} + x^{A}_{k,t} - y^{E}_{k,t} = d^{A}_{k,t}$ $\forall$ $1 \leq k \leq K$
and $Z_k + 1 \leq t \leq T$

Capacity constraints: (10)

$$\sum_{k=1}^{K} \sum_{z=0}^{Z_k} f_{j,k,z} \cdot x_{k,t+z} - o_{j,t} \leq b_{j,t}$$

$\forall$ $1 \leq j \leq J$ and $1 \leq t \leq T$

Additional capacity constraint: (11)

$o_{j,t} \leq o^{max}_{j,t}$ $\forall$ $1 \leq j \leq J$ and $1 \leq t \leq T$

Non-negativity constraints for all variables: (12)

$x^{A}_{k,t}, y^{E}_{k,t}, o_{j,t} \geq 0$ $\forall$ $1 \leq k \leq K$ and $1 \leq t \leq T$

Initialization of the starting inventory: (13)

$y^{E}_{k,0}$ given $\forall$ $1 \leq k \leq K$

Minimization problem:

Minimize Z.

MASTER PRODUCTION SCHEDULING

Solution of Master Production Scheduling

The optimal solution of the LP-Model of master production scheduling is shown in table 4 and illustrated in figure 5. The objective is 872€.

Table 4. Solution of master production scheduling

Period (t)	1	2	3	4	5	6	7	8	9	10	$\sum$
$\mathrm{d}^{\mathrm{A}}_{\mathrm{E,t}}$ [units]	0	0	0	0	80	100	120	100	80	120	600
$\mathrm{x}^{\mathrm{A}}_{\mathrm{E,t}}$ [units]	0	19	83	83	83	83	83	83	83	0	600
$\mathrm{y}^{\mathrm{E}}_{\mathrm{E,t}}$ [units]	0	0	19	102	105	88	51	34	37	0	436

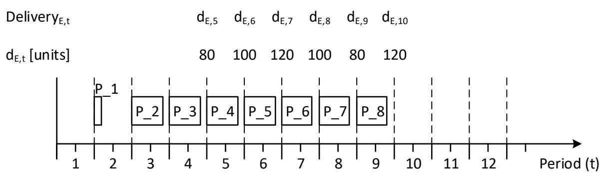

Figure 5. Solution of master production scheduling

Realization of Master Production Scheduling

Because of the usage of resource profiles in master production scheduling, in each period the lots can be processed in any order without exceeding the period capacity. Consequently, no shortage occurs in the individual periods, no matter which processing sequence is applied.

The complete data is shown in table 5 and illustrated in figure 6. The objective is 872€.

Table 5. Realization of master production scheduling

Period (t)	1	2	3	4	5	6	7	8	9	10	$\sum$
Demand ($\mathrm{d}^{\mathrm{A}}_{\mathrm{E,t}}$)	0	0	0	0	80	100	120	100	80	120	600
Planned order$^{\mathrm{A}}_{\mathrm{E,t}}$	0	19	83	83	83	83	83	83	83	0	600
Receipt$^{\mathrm{A}}_{\mathrm{E,t}}$	0	0	19	83	83	83	83	83	83	83	600
Delivery$^{\mathrm{A}}_{\mathrm{E,t}}$	0	0	0	0	80	100	120	100	80	120	600
Delay in periods	0	0	0	0	0	0	0	0	0	0	0
Inventory$^{\mathrm{E}}_{\mathrm{E,t}}$	0	0	19	102	105	88	51	34	37	0	436
Shortage$^{\mathrm{E}}_{\mathrm{E,t}}$	0	0	0	0	0	0	0	0	0	0	0

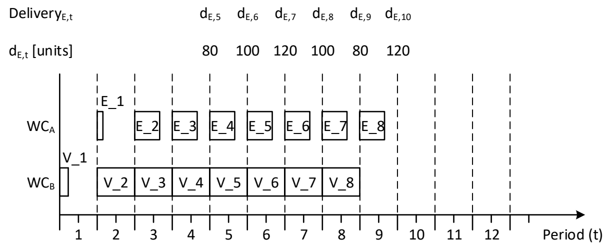

Figure 6. Realization of master production scheduling

RESULTS

While in aggregate production planning capacity planning is done for product groups and production sites master production scheduling is done for final products and work centres. Furthermore master production scheduling takes production lead time into account through the usage of resource profiles (Vollmann et al. 2005).

A resource profile is a time-phased projection of capacity requirements for individual work centres. A resource profile gives information about the capacity requirements for final products in terms of work centres and offset periods.

The time-phased projection takes lead time into account, and so the planned orders start early enough to be produced in time.

This can be seen in this case study. Aggregate production planning starts with the production at the beginning of period 4 to cover the demand of period 5. As we see in the master production scheduling the final product needs two offset periods to be produced in time. Let's take a look what will happen in the case when we give the realization of aggregate production planning 2 offset periods. It should be mentioned that this is not part of the model and is only used for demonstration of the advantage of master production scheduling.

In this case the inventory costs are still 160€. The shortage decreases from 1320 units to 720 units and the delay in periods decreases from 10 to 5. This is a better result than without the consideration of the lead time, but master production scheduling is due to the non-occurrence of a shortage still significantly better.

The complete result is shown in table 6 and in figure 7.

Table 6. Realization of aggregate production planning with consideration of the lead time

Period (t)	4	5	6	7	8	9	10	11	12	13	$\sum$
Demand ($\mathrm{d}^{\mathrm{A}}_{\mathrm{E,t}}$)	0	80	100	120	100	80	120	0	0		600
Planned order$^{\mathrm{A}}_{\mathrm{E,t}}$	100	100	100	100	100	100	0	0	0		600
Receipt$^{\mathrm{A}}_{\mathrm{E,t}}$	0	0	100	100	100	100	100	0	100		600
Delivery$^{\mathrm{A}}_{\mathrm{E,t}}$	0	0	80	100	120	100	80	0	120		600
Delay in periods	0	0	1	1	1	1	1	0	2		7
Inventory$^{\mathrm{E}}_{\mathrm{E,t}}$	0	0	20	20	0	0	20	20	0		80
Shortage$^{\mathrm{E}}_{\mathrm{E,t}}$	0	80	100	120	100	80	120	120	0		720

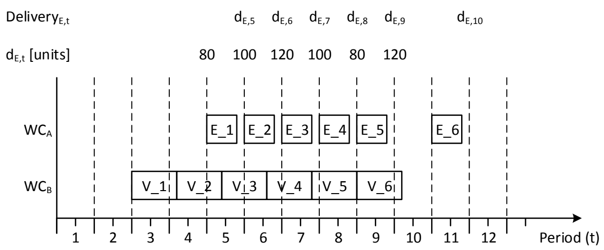

Figure 7. Realization of aggregate production planning with consideration of the lead time

Aggregated production planning, does not create a demand program which can be realized without shortages, despite the consideration of the lead time. To avoid shortages we have to increase the amount of offset periods by two to four. The result is shown in table 7 and in figure 8.

Table 7. Realization of aggregate production planning without delay

Period (t)	4	5	6	7	8	9	10	11	12	13	$\sum$
Demand ($\mathrm{d}^{\mathrm{A}}_{\mathrm{E,t}}$)	0	80	100	120	100	80	120				600
Planned order$^{\mathrm{A}}_{\mathrm{E,t}}$	100	100	100	100	100	100	0				600
Receipt$^{\mathrm{A}}_{\mathrm{E,t}}$	100	100	100	100	100	0	100				600
Delivery$^{\mathrm{A}}_{\mathrm{E,t}}$	0	80	100	120	100	80	120				600
Delay in periods	0	0	0	0	0	0	0				0
Inventory$^{\mathrm{E}}_{\mathrm{E,t}}$	100	120	120	100	100	20	0				560
Shortage$^{\mathrm{E}}_{\mathrm{E,t}}$	0	0	0	0	0	0	0				0

In this case the realization has no shortage as expected. The in inventory holding costs increase to 1020€ and

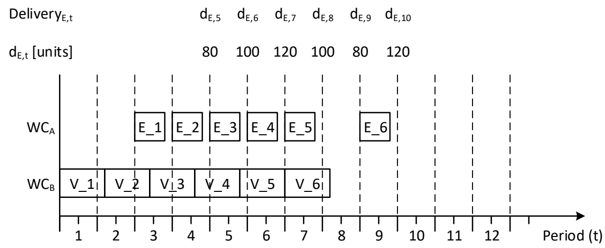

Figure 8. Realization of aggregate production planning without delay

the production has to start in period 1. For comparison the master production scheduling has inventory holding costs of 872€ and starts with the production in period 2.

That aggregated production planning, does not create a demand program which can be realized without shortages, without changing production program manually, is based on the following points:

The first reason for this is that in capacity planning the aggregate production planning considers the production site as a whole, while the master production scheduling considers each work centre separately.

The second and more important reason is the link between the final products, and the required capacity for work centres, which is taken into account by master production scheduling.

In this case study both work centres have the same capacity. The final product (E) needs 4 hours of capacity per unit of work centre A and the component (V) needs 6 hours of capacity per unit of work centre B.

Due to the asymmetric distribution of the capacity needed at the work centre aggregate production planning estimates the possible production quantity ($x^A_{E,t}$) false, aggregate production planning allows a production quantity ($x^A_{E,t}$) of 100 units per period, but there are only 83 units possible per period. Master production scheduling takes the right number of production quantity in account.

The production quantity ($x^A_{E,t}$) of aggregate production planning and master production scheduling can be compared in table 2 and table 4.

CONCLUSION

As shown in this case study, it is to be expected that aggregate production planning leads to shortages. Through a closer examination of the capacity of the master production scheduling, shortages can be avoided.

For this reason, the production planning in the context of hierarchical production planning should be additionally carried out by master production scheduling through upstream aggregated production planning approach.

Through a capacity restriction and the consideration of the exact offset periods on aggregate production planning level shortages are likely to be avoided. This and the relevance of industrial practice have to be further explored.

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