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The main purpose of *Master Planning* is to synchronize the flow of materials along the entire supply chain. Master Planning supports mid-term decisions on the efficient utilization of production, transport, supply capacities, seasonal stock as well as on the balancing of supply and demand. As a result of this synchronization, production and distribution entities are able to reduce their inventory levels. Without centralized Master Planning, larger buffers are required in order to ensure a continuous flow of material. Coordinated master plans provide the ability to reduce these safety buffers by decreasing the variance of production and distribution quantities.

To synchronize the flow of materials effectively it is important to decide how available capacities of each entity of the supply chain will be used. As Master Planning covers mid-term decisions (see Chap. 4), it is necessary to consider at least one seasonal cycle to be able to balance all demand peaks. The decisions on production, transport (and sometimes, sales) quantities need to be addressed simultaneously while minimizing total costs for inventory, overtime, production and transportation.

The results of Master Planning are targets/instructions for Production Planning and Scheduling, Distribution and Transport Planning as well as Purchasing

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and Material Requirements Planning. For example, the Production Planning and Scheduling module has to consider the amount of planned stock at the end of each master planning period and the reserved capacity up to the planning horizon. The use of specific transportation lines and capacities are examples of instructions for Distribution and Transport Planning. Section 8.1 will illustrate the Master Planning decisions and results in detail.

However, it is not possible and not recommended to perform optimization on detailed data. Master Planning needs the aggregation of products and materials to product groups and material groups, respectively, and concentration on bottleneck resources. Not only can a reduction in data be achieved, but the uncertainty in mid-term data and the model's complexity can also be reduced. Model building including the aggregation and disaggregation processes is discussed in Sect. 8.2.

A master plan should be generated centrally and updated periodically. These tasks can be divided into several steps as described in Sect. 8.3.

An important extension of Master Planning is Sales and Operations Planning (S&OP). A description from a modeling and process perspective will be given in Sect. 8.4.

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## 8.1 The Decision Situation

Based on demand data from the Demand Planning module, Master Planning has to create an aggregated production and distribution plan for all supply chain entities. It is important to account for the available capacity and dependencies between the different production and distribution stages. Such a capacitated plan for the entire supply chain leads to a synchronized flow of materials without creating large buffers between these entities.

To make use of the Master Planning module it is necessary that production and transport quantities can be split and produced in different periods. Furthermore, intermediates and products should be stockable (at least for several periods) to be able to balance capacities by building up inventories. Because Master Planning is a deterministic planning module, reasonable results can only be expected for production processes having low output variances.

The following options have to be evaluated if bottlenecks on production resources occur:

- Produce in earlier periods while increasing seasonal stock
- Produce at alternative sites with higher production and/or transport costs
- Produce in alternative production modes with higher production costs
- Buy products from a vendor with higher costs than your own manufacturing costs
- Work overtime to fulfill the given demand with increased production costs and possible additional fixed costs.

It is also possible that a bottleneck occurs on transportation lines. In this case the following alternatives have to be taken into consideration:

- Produce and ship in earlier periods while increasing seasonal stock in a distribution center

- Distribute products using alternative transportation modes with different capacities and costs
- Deliver to customers from another distribution center.

In order to solve these problems optimally, one must consider the supply chain as a whole and generate a solution with a centralized view while considering all relevant costs and constraints. Otherwise, decentral approaches lead to bottlenecks at other locations and suboptimal solutions.

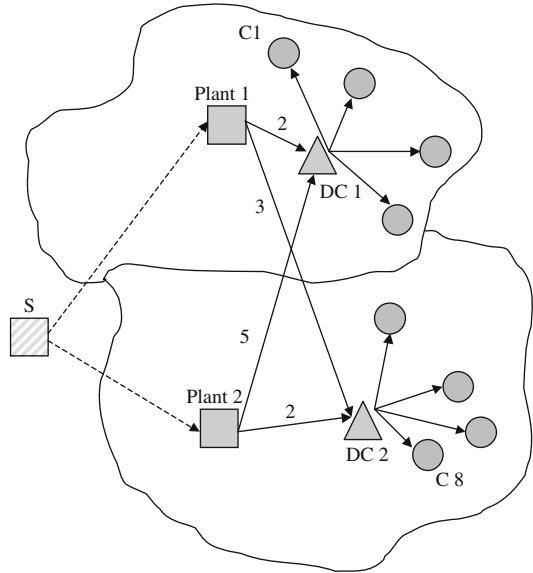
Apart from production and transportation, further trade-offs may become relevant for Master Planning. A frequent trade-off is the right choice of the sales quantities. It may be beneficial not to fulfill the complete demand (forecast), e.g., if regular capacities are insufficient and overtime costs would exceed the margins of products sold. In addition, there are some industry sectors with specific requirements. In process industries, the impact of setup activities is often so large that a meaningful master plan has to include lot-sizing decisions. Also “green supply chains” raise a couple of challenges. Examples are restrictions on gas emissions (e.g., Mirzapour Al-e-hashem et al. 2013), which often can be modeled by standard APS techniques via additional capacity constraints, and reverse logistics networks (e.g., Cardoso et al. 2013). Moreover, legal requirements such as duty (e.g., Oh and Karimi 2006) and taxation (e.g., Sousa et al. 2011) are of growing importance.

To generate feasible targets, a concept of anticipation is necessary. This concept should predict the (aggregate) outcomes of lower levels’ decision-making procedures that result from given targets as precisely as possible within the context of Master Planning. This prediction should be less complex than performing complete planning runs at the lower planning levels. A simple example for anticipation is to reduce the periods’ production capacity by a fixed amount to consider setup times expected from lot wise production. However, in production processes with varying setup times dependent on the product mix, this concept may not be accurate enough; therefore, more appropriate solutions for anticipating setup decisions have to be found (for further information see Schneeweiss 2003; approaches for accurate anticipation of lot-sizing and scheduling decisions are given, for example, in Rohde 2004 and Stadtler 1988).

The following paragraph introduces a small example to depict this decision situation. It will be used to illustrate the decisions of Master Planning and show the effects, results and the data used.

The example supply chain in Fig. 8.1 has two production sites (Plant 1 and Plant 2) as well as two distribution centers (DC 1 and DC 2). Two different products are produced in each plant in a single-stage process. The customers are supplied from their local *distribution center* (DC), which usually receives products from the nearest production site. However, it is possible to receive products from the plant in the other region. Such a delivery will increase transport costs per unit. Inventory for finished products is exclusively located at the DCs. The regular production capacity of each production unit is 80 h per week (two shifts, 5 days). It is possible to extend this capacity by working overtime.

**Fig. 8.1** Example of a supply chain



**Table 8.1** Seasonal demand peak

Quarter	1	2	3	4
Demand	12	13	10	45
Capacity available	20	20	20	20

In introducing a third production unit (supplier S), a multi-stage production problem and, in this example, a common capacity restriction for the production of parts, has to be considered. In the remainder of this chapter the third production unit will not be regarded.

### 8.1.1 Planning Horizon and Periods

The planning horizon is characterized by the interval of time for which plans are generated. It is important to select a planning horizon that covers at least one seasonal cycle. Otherwise, there would be no possibility to balance capacities throughout a season, and hence, peaks in demand would possibly not be covered. If, for example, demand peaks were to occur in the last quarter of a year, and only half a year were considered, it might not be possible to balance this peak during planning of the second half (see following simplified example, Tables 8.1, 8.2, and 8.3). Often, the planning horizon for Master Planning covers 12 months.

Table 8.1 shows the quarterly demand and the available capacity. Producing one part takes one capacity unit. If it is not possible to extend capacity, a plan with a horizon of two quarters would lead to the infeasible plan shown in Table 8.2. Considering a whole seasonal cycle (in this case four quarters), a feasible plan can be derived (see Table 8.3).

**Table 8.2** Infeasible solution

Quarter	1	2	3	4
Demand	12	13	10	45
Capacity available	20	20	20	20
Capacity used	12	13	20	<b>35</b>

**Table 8.3** Feasible solution

Quarter	1	2	3	4
Demand	12	13	10	45
Capacity available	20	20	20	20
Capacity used	20	20	20	20

As we have already seen in the previous example, the planning horizon is divided into several periods, the so-called *time buckets*. The length of these periods (often a week or month) must be chosen carefully with respect to the lead-times at every stage of the supply chain. In *bucket-oriented* Master Planning, the lead-time of each process<sup>1</sup> that uses potential bottleneck resources is usually defined as one time bucket or an integer multiple. A potential bottleneck resource might cause delays (waiting times) due to a high utilization rate. It is also possible that one might neglect the lead-time of some activities performed on non-bottleneck resources. Then, a part has to be produced in the same bucket as its predecessor and successor, respectively. This imprecision may lead to instructions that may not be disaggregated into feasible schedules at the lower planning levels, but then, shorter planned lead-times are possible. On the other hand, using one bucket or an integer multiple regularly leads to more appropriate instructions, but artificially extends the planned lead-times.

Shorter time buckets result in a more accurate representation of the decision situation and the lead-time modeling, but imply a higher complexity for the planning problem. Higher complexity, inaccuracy of data in future periods and the increasing expenditure for collecting data emphasize the trade-off between accuracy and complexity. Only the use of big time buckets allows for the planning of quantities, but not for individual orders or product units.

Another possibility is the use of varying lengths for different periods; that is, the first periods are represented by shorter time buckets to enable more exact planning on current data. The more one reaches the planning horizon, the bigger the chosen time buckets are. However, this approach poses problems with the modeling of lead-time offsets between production and distribution stages (see also Chap. 4).

To work on current data, it is necessary to update the master plan at discrete intervals of time. Thus, new and more reliable demand forecasts as well as known customer orders are considered in the new planning run. During the *frozen horizon* (see also Chap. 4), the master plan is implemented. Looking several periods ahead is necessary to be able to balance demand and capacities as already mentioned.

<sup>1</sup>Here, a process is an aggregation of several successive production and transportation activities (see also Sect. 8.2.3).

### 8.1.2 Decisions

Master Planning has to deal with the trade-off between costs for inventories, production, transports and capacity extension. The corresponding quantities that are produced, moved or stored need to be determined in the master planning process.

Production quantities (for each time bucket and product group) are mainly determined by the production costs and the available capacity. Capacity extensions have to be modeled as decision variables in Master Planning if production quantities also depend on these enhancements. Not only production capacity, but also transport capacity on the links between plants, warehouses and customers needs to be planned in Master Planning. Decisions on setups and changeovers are taken into account in Master Planning only if lot sizes usually cover more than a period's demand. Otherwise, the decision is left to Production Planning and Scheduling, and setup times are anticipated in Master Planning.

While transport capacities only set a frame for the quantities that can be carried from A to B, the decision on the transport quantity (for every product group and time bucket) also needs to be addressed. Generally, linear transport costs are considered in mid-term planning. Hence, it is only possible to determine the quantities, not the detailed loading of single transportation means. This is to be done in Transport Planning for Procurement and Distribution (see Chap. 12).

With regard to the sales quantities, there are two major modeling approaches: (1) The sales quantities are set equal to the forecast. They are considered as fixed input parameters and not as (variable) decisions within Master Planning. (2) Decisions about sales quantities are explicitly included. That means, there is the option for not fulfilling the forecast when appropriate. Here we can further distinguish two subcases. First, unfulfilled demand is backordered. That is, customers wait for the fulfillment of the outstanding orders in case of shortages. Hence, the unfulfilled forecast quantities will enter as "new" demands into the system in the next period. The backorder case is especially relevant for seller markets and customer-specific products. Second, missed sales are assumed to be lost. For example, customers will buy from a competitor (as it is possible in commodity markets) or choose a different product. The forecast can be considered as upper bound on the sales quantities then.

Case (1) is the best choice if it is a priori clear that deviating from the forecast will lead to suboptimal results. Indicators for that are flexible capacities and high contribution margins or large penalties for late delivery. Case (2) should be chosen if production capacities are too small for covering the whole demand, while not being extendable at medium term (this occurs frequently in process industries, see Timpe and Kallrath 2000 for a corresponding model formulation). A particular motivation for case (2) with lost sales can be that production costs exceed the gains from serving specific customers or product portfolios. Note that this trade-off is covered by S&OP, too.

If production, transport, and sales quantities are determined, the stock levels are known. Inventory variables are used to account for inventory holding costs.

For sake of simplicity, our *example* assumes that sales quantities are fixed. Hence, its decision variables are:

- Production quantities for every product, period and plant
- Transport quantities on every transportation link from plant to DC, for every product and period
- Ending inventory level for every product, period and DC
- Overtime for every plant in every period.

### 8.1.3 Objectives

As described in the previous section, a model for Master Planning has to respect several restrictions when *minimizing total costs*. The costs affecting the objective function depend on the decision situation. In Master Planning they do not have to be as precise as, for example, within accounting systems; they are only incorporated to find out the most economical decision(s). A simple example may clarify this. If two products share a common bottleneck, it is only necessary to know which of the two products has the least inventory cost per capacity unit used. This will be the product to stock first, irrespective of “correct costs,” as long as the relation between the costs remains valid.

In most master planning settings, products can be stored at each production site and DC, respectively. Therefore, the inventory holding costs (e.g. for working capital, handling) have to be part of the objective function. Furthermore, the ability of extending capacity has to be taken into account. The corresponding costs need to be considered in the objective function. Also, variable production costs may differ between production sites, and thus, are part of the master planning process. If lot-sizing decisions should be made in Master Planning, it is necessary to incorporate costs for setups as well.

The different prices of the suppliers have to be considered in the objective function if Master Planning models are extended to optimize supply decisions.

Every stage of the production-distribution network is connected to other entities of the supply chain by transportation links, which are associated with transport costs. Usually, only variable linear cost rates for each transportation link and an adequate lead-time offset are considered in mid-term Master Planning.

In case where the forecast is taken as an upper bound for the sales quantities (case (2) with lost sales in Sect. 8.1.2), the objective can best be described by maximizing the contribution margin, i.e., variable profit minus variable costs (see Fleischmann and Meyr 2003 for an example. Note that this objective can equivalently be modeled as cost minimization, setting penalty costs for lost sales equal to the contribution margins).

The objective function of the simplified *example* minimizes the sum of

- Production costs
- Inventory holding costs
- Additional costs for using overtime
- Transport costs.

### 8.1.4 Data

Master Planning receives data from different systems and modules. The forecast data, which describe the demand of each product (group) in each period in the planning horizon, are a result of Demand Planning.

Capacities need to be incorporated for each potential bottleneck resource (e.g. machines, warehouses, transportation). Transport capacities need not to be modeled if a company engages a third-party logistics provider who ensures an availability of 100%. But if capacity has to be extended on condition that cost rates increase, this additional amount of capacity and the respective cost rates have to be considered. For the calculation of necessary capacity, production efficiency and production coefficients have to be part of the model.

The BOMs of all products (groups) form the basis of the material flows within the model and provide the information on input-output coefficients. For every storage node (e.g. warehouse, work-in-process inventory) minimum (e.g. safety stocks and estimated lot-sizing stocks) and maximum stock levels (e.g. shelf lives) need to be defined for each product (group).

Additionally, all cost elements mentioned above are input to the model.

Data for the *example* are

- Forecasts for each sales region and product in every period
- Available regular capacity for each plant (machine) and period
- Maximum overtime in each plant
- The production efficiency of products produced at specific plants (e.g. in tons of finished products per hour)
- The current stock levels at each DC and for every product
- The minimum stock levels at each DC and for every product.

### 8.1.5 Results

The results of Master Planning are the optimized values of decision variables, which are instructions to other planning modules. Some decision variables have only planning character and are never (directly) implemented as they are determined in other modules in more detail (e.g. production quantities are planned in Production Planning and Scheduling).

Therefore, the most important results are the planned capacity usage (in each bucket for every resource (group) and transportation link) and the amount of seasonal stock at the end of each time bucket. Both cannot be determined in the short-term planning modules because they need to be calculated under the consideration of an entire seasonal cycle. Production capacities are input to Production Planning and Scheduling. Seasonal stocks (possibly plus additional other stock targets), at the end of each Master Planning bucket, provide minimum stock levels in detailed scheduling.



Capacity extensions need to be decided during the frozen period as they often cannot be influenced in the short term. The same applies to procurement decisions for special materials with long lead-times or those that are purchased on the basis of a basic agreement.

Results in the *example* are

- Seasonal stock, which is the difference between the minimum stock and the planned inventory level, for every product, period and DC
- Amount of overtime for every plant in every period that should be reserved.

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## 8.2 Model Building

In most APS, Master Planning is described by a *Linear Programming* (LP) model with continuous variables. However, some constraints (including binary and integer variables, respectively) imply to convert the LP model to a more complex *Mixed Integer Programming* (MIP) model. Solution approaches for LP and MIP models are described in Chap. 30. In this section we will illustrate the steps of building a Master Planning model, and we will illustrate how complexity depends on the decisions modeled. Furthermore, it will be explained how complexity can be reduced by aggregation and how penalty costs should be used for finding (feasible) solutions.

Although it is not possible to give a comprehensive survey of all possible decisions, this chapter will show the dependence between complexity and most common decisions. In contrast to a perfect representation of reality, Master Planning needs a degree of standardization (i.e. constraints to be modeled, objectives, etc.), at least for a line of business. Thus, it is possible to use a Master Planning module that fits after adjusting parameters (i.e. costs, BOMs and routings, regular capacities, etc.), as opposed to after building new mathematical models and implementing new solvers.

### 8.2.1 Modeling Approach

Figure 8.2 shows a general approach for building a supply chain model that can be applied to most APS.

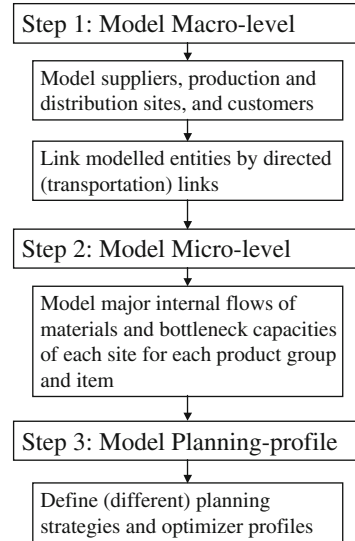
#### Step 1: Model Macro-Level

In the first step, key-customers, key-suppliers, and production and distribution sites of the supply chain are modeled. These entities are connected by directed transportation links. In some APS, transportation links are modeled as entities and not as directed connections.<sup>2</sup> The result of this step is a general network of supply chain entities.

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<sup>2</sup>For example, JDAs' Supply Chain Planner (the former i2 Technologies' Supply Chain Planner, see also Chaps. 18 and 23).

**Fig. 8.2** Building a supply chain model



In our example (Fig. 8.1) the two plants (Plant 1 and Plant 2) and the distribution centers (DC 1 and DC 2) are modeled; that is, their locations and possibly their types (e.g. production entity and distribution entity) are determined. Afterwards, the key-supplier (S) and the key-customers (C 1, . . . , C 8) are specified. The supplier (S) does not represent a potential bottleneck. Hence, he should not explicitly be modeled in this step. The customers represent the demand of products of the supply chain. Finally, the transportation links are modeled. If no transportation constraints are applied, transportation links represent a simple lead-time offset between two stages.

### Step 2: Model Micro-Level

Each entity of the supply chain can be modeled in more detail in the second step, if required. All resource groups that could turn out to become a bottleneck should be modeled for each entity and transportation link. The internal flows of material and the capacities of potential bottlenecks are defined for each product group and item (group). The dependence between product and item groups is modeled by defining input and output materials for each process. Table 8.4 shows selected features that can be modeled in APS.

In our example, capacities and costs are modeled for each entity and transportation link. Plant 1 has a regular capacity of 80 units per time bucket. Each unit of overtime costs 5 monetary units (MU) without fixed costs, and producing one part of Product 1 or Product 2 costs 4 MU. Plant 2 is equally structured except that linear production costs amount to 5 MU for each unit produced. Then, the internal structure of each distribution center is modeled. The storage capacity of each distribution center is limited. DC 1 has linear storage costs for Product 1 of 3 MU per product unit per time bucket and for Product 2 of 2 MU per product unit per time bucket. DC 2 has linear storage costs of 4 and 3 MU for one unit of Product 1

**Table 8.4** Selected model features of Master Planning in APS

Process	Parameter	Characteristics
Procurement	Purchase costs	Linear piecewise linear
	Production costs	Linear piecewise linear
Production	Production quantities	Continuous semi-continuous
	Capacity	Regular capacity enhanced capacity with linear costs per extra unit
	Capacity requirements	Fixed or linear
	Inventory costs	Linear
Storage	Capacity	Regular capacity enhanced capacity with linear costs per extra unit
	Transport costs	Linear piecewise linear
Distribution	Transport quantities	Continuous integer partially integer
	Capacity	Regular capacity enhanced capacity with linear costs per extra unit
	Backorders	Maximum lateness linear penalty costs
Sales	Lost sales	Linear penalty costs

and 2, respectively, per time bucket. Finally, the transportation links are modeled on the micro-level. All transportation links are uncapacitated. Transport costs from Plant 1 to DC 1 are linear with 2 MU per unit of both Products 1 and 2, and to DC 2 costs of 3 MU per product unit are incurred. The transport from Plant 2 to DC 1 and 2 costs 5 and 2 MU per product unit, respectively. Transportation from distribution centers to customers is not relevant.

**Step 3: Model Planning-Profile**

The last step is to define a planning-profile. Defining the planning-profile includes the definition of resource calendars, planning strategies for heuristic approaches and profiles for optimizers. Planning strategies could include how a first feasible solution is generated and how improvements are obtained. Optimizer profiles could include different weights for parts of the objective function (inventory costs, transport costs, etc.). For example, an optimizer profile that forces production output could be chosen within a growing market. One way to force production output could be setting a lower weight on penalties for capacity enhancements and a higher weight on penalties for unfulfilled demand.

The example of this chapter should be solved by Linear Programming. The only objective is to minimize total costs resulting from inventories, production, overtime and transportation. A planning-profile would instruct the Master Planning module to use an LP-solver without special weights (or with equal weights) for the different parts of the objective function.

## 8.2.2 Model Complexity

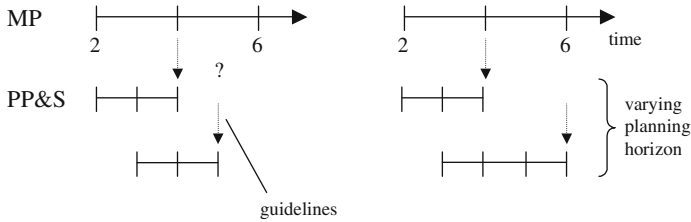
Model complexity and optimization run time are (strongly) correlated. For this reason, it is important to know which decisions lead to which complexity of the model. Thus, it is possible to decide on the trade-off between accuracy and run time. The more accurate a model should be, the more the decisions are to be mapped. But this implies increased run time and expenditure for collecting data. The following paragraphs show the correlation between decisions described in this chapter and a model's complexity.

The main *quantity decisions* that have to be taken into consideration in a Master Planning model are production, transport, and sales quantities. For these quantities integer values are mostly negligible at this aggregation level. Mainly, they are used to reserve capacity on potential bottleneck resources. Because these are rough capacity bookings, it is justifiable to abstract from integer values. If different production or transportation modes can be used partially, additional quantity decisions for each mode, product and period are necessary. Other important quantity decisions are stock levels. They result from corresponding production and transport quantities as well as stock levels of the previous period.

*Capacity decisions* occur only if it is possible not to utilize complete regular capacity or to enhance capacity of certain supply chain entities. One aspect of enhancing regular capacity is working overtime. This implies a new decision on the amount of overtime in each period for each resource. Additional costs have to be gathered. Binary decisions have to be made if extra shifts are introduced in certain periods (and for certain resources) to take fixed costs for a shift into account (e.g. personnel costs for a complete shift). Thereby, the problem is much harder. Performance adjustments of machines usually lead to non-linear optimization models. Computational efforts increase, and thus, solvability of such models, decrease sharply.

*Decisions concerning production and transportation processes* are, for example, decisions about the usage of alternative routings. Such additional decisions and more data will increase the model's complexity. However, if it is not possible to split production and transport quantities to different resources—e.g. supply customers from at least one distribution center—process modes have to be considered. In contrast to the quantity decision on different modes as described above, additional binary decisions on the chosen process mode have to be made.

If *lot-sizing decisions* have to be included in Master Planning, (at least) one additional binary decision is required for each product and period. This increases the complexity significantly. Therefore, much caution is needed here when defining



**Fig. 8.3** Aggregation of time

the modeling scope. In particular, modeling minor setups (low setup costs and time) explicitly is usually counterproductive at the Master Planning level.

### 8.2.3 Aggregation and Disaggregation

Another way to reduce complexity of the model is *aggregation*. Aggregation is the reasonable grouping and consolidation of time, decision variables and data to achieve complexity reduction for the model and the amount of data (Stadtler 1988, p. 80). The accuracy of data can be enhanced by less variance within an aggregated group, and higher planning levels are unburdened from detailed information.

Furthermore, inaccuracy increases in future periods. This inaccuracy, e.g. in case of the demand of product groups, can be balanced by reasonable aggregation if forecast errors of products within a group are not totally correlated. Therefore, capacity requirements for aggregated product groups (as a result of Master Planning) are more accurate, even for future periods.

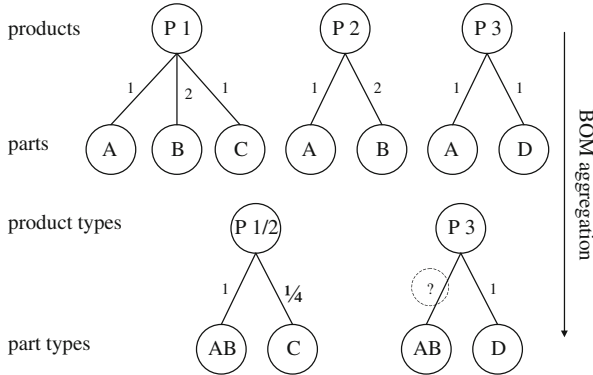
Aggregation of time, decision variables and data will be depicted in the following text. Regularly, these alternatives are used simultaneously.

#### Aggregation of Time

Aggregation of time is the consolidation of several smaller periods to one large period. It is not reasonable to perform Master Planning, for example, in daily time buckets. Collecting data that are adequate enough for such small time buckets for 1 year in the future, which is mostly the planning horizon in mid-term planning, is nearly inoperable. Therefore, Master Planning is regularly performed in weekly or monthly time buckets. If different intervals of time buckets are used on different planning levels, the disaggregation process raises the problem of giving targets for periods in the dependent planning level that do not correspond to the end of a time bucket in the upper level. To resolve this problem, varying planning horizons on lower planning levels can be chosen (see Fig. 8.3).

#### Aggregation of Decision Variables

Generally, aggregation of decision variables refers to the consolidation of production quantities. In the case of Master Planning, transport quantities also have



**Fig. 8.4** BOM aggregation (following Stadler 1988, p. 90)

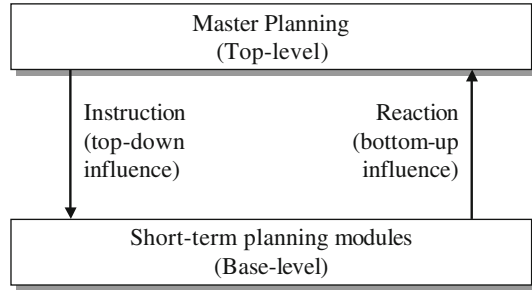
to be aggregated. Bitran et al. (1982) suggest aggregating products with similar production costs, inventory costs and seasonal demand to product types. Products with similar setup costs and *identical* BOMs are aggregated to product families. A main problem in Master Planning, which is not regarded by the authors, is the aggregation of products in a multi-stage production process with *non-identical* BOMs. The similarity of BOMs *and* transportation lines is very important. But the question of what similarity means remains unanswered. Figure 8.4 illustrates the problem of aggregating BOMs. Products P 1 and P 2 are aggregated to product type P 1/2 with the average quotas of demand of P 1/2 of  $\frac{1}{4}$  for P 1 and  $\frac{3}{4}$  for P 2. Parts A and B are aggregated to part type AB. The aggregated BOM for P 1/2 shows that one part of P 1/2 needs one part of type AB and  $\frac{1}{4}$  part of part C (caused by the average quota for demand). Producing one part of type AB means producing one part of A and two parts of B. The problem is to determine a coefficient for the need for type AB in product P 3 (an aggregation procedure for a sequence of operations is discussed in Stadler 1996, 1998). Shapiro (1999) remarks with his 80/20-rule that in most practical cases about 20% of the products with the lowest revenues regularly make the main product variety. Thus, these products can be aggregated to fewer groups while those with high revenues should be aggregated very carefully and selectively.

It is important to perform an aggregation with respect to the decisions that have to be made. If setup costs are negligible for a certain supply chain, it does not make sense to build product groups with respect to similar setup costs. No product characteristic, important for a Master Planning decision, should be lost within the aggregation process.

### Aggregation of Data

The aggregation of data is the grouping of, for example, production capacities, transport capacities, inventory capacities, purchasing bounds and demand data. Demand data are derived from the Demand Planning module and have to be aggregated

**Fig. 8.5** Instruction and reaction in Master Planning (following Schneeweiss 2003, p. 17)



with respect to the aggregation of products. Particularly, aggregating resources to resource groups cannot be done without considering product aggregation. There should be as few interdependencies as possible between combinations of products and resources. Transport capacities, especially in Master Planning, have to be considered in addition to production and inventory capacities. Due to the various interdependencies between decision variables and data, these aggregations should be done simultaneously.

### 8.2.4 Relations to Short-Term Planning Modules

Master Planning interacts with all short-term planning modules by sending instructions and receiving reactions (see Fig. 8.5). Furthermore, master plans provide valuable input for collaboration modules and strategic planning tasks such as mid-term purchasing plans or average capacity utilization in different scenarios (see also Chaps. 13 and 14).

Instructions can be classified as primal and dual instructions (Stadler 1988, p. 129). The first type directly influences the decision space of the base-level model (here: the short-term planning modules) by providing constraints such as available capacity and target inventory at the end of a period. The second one influences the objective function of the base-level model by setting cost parameters.

After a planning run for the short-term modules is performed, Master Planning is able to receive feedback/reactions from the base-level. Instructions that lead to infeasibilities have to be eliminated or weakened. By changing some selected Master Planning parameters, e.g. maximum capacity available, elimination of particular infeasibilities can be achieved.

To avoid a multitude of instruction/reaction loops, an anticipated model of the base-level should predict the outcome of the planning run of this level according to given instructions (see also Sect. 8.1).

Finally, ex-post feedback, gathered after executing the short-term plans, provides input, e.g. current inventory levels or durable changes in availability of capacity, to the Master Planning module.

As part of model building, the coupling parameters, i.e. instructions, reactions and ex-post feedback parameters, have to be defined (see also Chap.4).

Additionally, the type of the coupling relations (e.g. minimum/maximum requirements, equality) and the points of time in which to transfer the coupling parameters have to be assigned (Stadtler 1988, pp. 129–138). To build the anticipated base-level model, the main influences of the short-term planning decisions within Master Planning have to be identified. For example, lot-sizes and setup-times resulting from Production Planning & Scheduling might be anticipated.

### 8.2.5 Using Penalty Costs

A model's solution is guided by the costs chosen within the objective function. By introducing certain costs that exceed the relevant costs for decisions (see Sect. 8.1.3), these decisions are penalized. Normally, relevant costs for decisions differ from costs used for accounting, e.g. only variable production costs are considered without depreciations on resources or apportionments of indirect costs. *Penalty costs* are used to represent constraints that are not explicitly modeled. Consider the case where sales quantities are fixed to the demand forecast (case (1) in Sect. 8.1.2). Here it may be necessary to penalize unfulfilled demand to avoid infeasible plans. Similarly, if setup times are not explicitly considered, the loss of time on a bottleneck resource can be penalized by costs correlated to this loss of time.

To be able to interpret the costs of the objective function correctly, it is important to separate the costs according to accounting and penalty costs. Regularly, penalty costs exceed other cost parameters by a very high amount. To obtain the "regular" costs of a master plan, not only the penalized costs of a solution, this separation is indispensable. Among others, the following penalties can be inserted in the objective function:

- Setup costs to penalize the loss of time on bottleneck resources (if not explicitly modeled)
- Costs for backorders and lost sales of finished products and parts (see Sect. 8.1.3)
- Costs for enhancing capacity (especially overtime) to penalize its use explicitly
- Additional production costs for certain sites to penalize, for example, minor quality
- Penalty costs for excessive inventory of customer specific products.

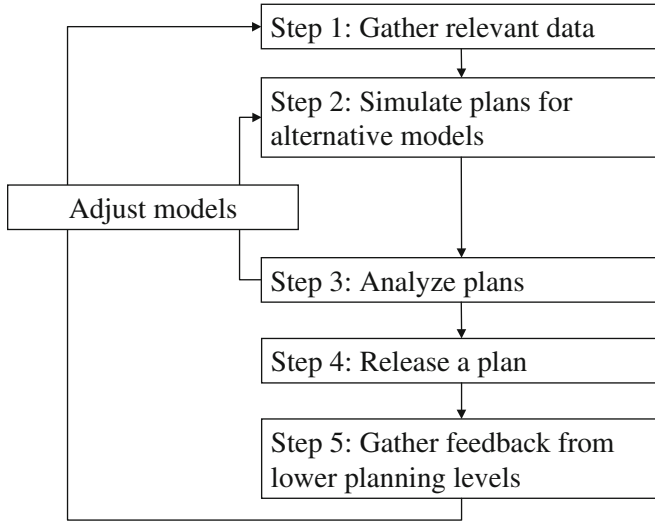
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## 8.3 Generating a Plan

This section illustrates which steps have to be performed to generate a master plan (see Fig. 8.6) and how to use Master Planning effectively.

As already mentioned, the master plan is updated successively, e.g. in weeks or months. Thus, new and accurate information such as actual stock levels and new demand data are taken into consideration. It is necessary to gather all relevant data before performing a new planning run (see Sect. 8.1). This can be a hard task as data are mostly kept in different systems throughout the entire supply chain. However,





**Fig. 8.6** Steps in Master Planning

**Table 8.5** Demand data

Period		1	2	3	4	5
Product 1	Sales region 1	20	30	30	50	40
Product 2	Sales region 1	50	40	60	40	50
Product 1	Sales region 2	40	30	30	40	40
Product 2	Sales region 2	50	40	50	60	50

to obtain accurate plans this task has to be done very seriously. To minimize expenditure in gathering data, a high degree of automation to execute this process is recommended. For the previous example, the parameters described in Sect. 8.2.1 and the demand data shown in Table 8.5 have been gathered.

Most APS provide the possibility to simulate alternatives. Several models can be built to verify, for example, different supply chain configurations or samples for shifts. Furthermore, this simulation can be used to reduce the number of decisions that have to be made. For example, *dual values* of decision variables (see Chap. 30) can be used after analyzing the plans to derive actions for enhancing regular capacity.

The master plan does not necessarily need to be the outcome of an LP or MIP solver. These outcomes are often unreproducible for human planners. Thus, insufficient acceptance of automatically generated plans can be observed. Following the ideas of the OPT philosophy (Goldratt 1988), an alternative approach comprises four steps:

1. Generate an unconstrained supply chain model, disregarding all purchasing, production and distribution capacities.
2. Find the optimal solution of the model.

**Table 8.6** Production quantities

Period		1	2	3	4	5
Product 1	Plant 1	30	30	30	50	40
Product 2	Plant 1	50	50	50	40	50
Product 1	Plant 2	30	30	30	40	40
Product 2	Plant 2	50	40	50	60	50

**Table 8.7** Costs for five periods

Production	3,780.00
Overtime	250.00
Transportation	1,690.00
Inventory	20.00

3. Analyze the solution regarding overloaded capacities. Stop, if no use of capacity exceeds upper (or lower) limits.
4. Select the essential resources of the supply chain of those exceeding capacity limits. Take actions to adjust the violated capacity constraints and insert those fixed capacities into the supply chain model. Proceed with step 2.

If each capacity violation is eliminated, the iterative solution matches the solution that is generated by an optimization of the constrained model. Due to the successive generation of the optimal solution, the acceptance of the decision makers increases by providing a better understanding of the system and the model. In contrast to a constrained one-step optimization, alternative capacity adjustments can be discussed and included. It must be pointed out that such an iterative approach requires more time and staff than a constrained optimization, particularly if capacity usage increases. It seems to be advisable to include some known actions to eliminate well known capacity violations in the base supply chain model.

In the next step one has to decide which plan of the simulated alternatives should be released. If this is done manually, subjective estimations influence the decision. On the other hand, influences of not explicitly modeled knowledge (e.g. about important customers) are prevented by an automated decision.

Table 8.6 shows the planned production quantities of our example. The transport quantities correspond to the production quantities, except for transport of Product 1 from Plant 1 to the DCs in the first period. Twenty units of Product 1 produced in Plant 1 are delivered to DC 1, while 10 are delivered to DC 2 to meet the demand of Sales region 2, even though transport costs are higher. Seasonal stock is only built in the second period for Product 2 in DC 1, amounting to 10 product units. Overtime is necessary for both plants in periods four and five. Plant 1 utilizes 10 time units of overtime each, while Plant 2 utilizes 20 and 10 time units, respectively. The costs for the five periods' planning horizon are shown in Table 8.7.

Having forwarded the master plan's instructions to the decentral decision units, detailed plans are generated. The results of these plans have to be gathered to derive important hints for model adjustments. For example, if setups considered by a fixed estimate per period result in infeasible decentral plans, it is necessary to change this amount.

The mid-term purchasing quantities for raw materials from supplier S in our example (see Fig. 8.1) can be derived from the mid-term production plans for plants P1 and P2. These purchasing quantities are input for a collaborative procurement planning process (see Chap. 14). The joint plan of supplier S and plants P1 and P2 then serves as adjusted material constraint. Once an adequate master plan has been generated, decisions of the first period(s) are frozen and the process of rolling schedules is continued.

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## 8.4 Sales and Operations Planning

Sales and Operations Planning (S&OP) is basically a combination of Master Planning with Demand Planning. Traditionally, these tasks are carried out sequentially: The forecast quantities are determined first, and master planning takes them as an input, as explained above. There are two major improvement potentials in this process. First, it may be possible to identify a cheaper solution when sales and production decisions are taken simultaneously. Second, and most important, a strictly successive planning of sales and operations is often suboptimal from an organizational perspective. It is well-known that the supply side (production, logistics, procurement) and the demand side (sales, marketing) have conflicting goals (e.g., Shapiro 1977). Therefore, it is crucial to create a common view on demand and supply decisions, as well as accountability for the results. A precondition for this common view is that everybody involved knows the impact of the S&OP master plan on sales, production quantities, and inventories. This can be supported by simulation and collaboration tools in APS and related software, and a consensus based decision process.

Apart from production and sales, further departments such as finance and product development can participate in the S&OP process. That way, financial constraints regarding the working capital can be taken into account and counter measures can be anticipated. Regarding product development, decisions about product (re-)launches may significantly affect the demand and production resource utilization. Hence, including these decisions into S&OP can improve the quality of the master plan substantially.

As S&OP is an extension of Master Planning, most of the descriptions given in Sects. 8.1–8.3 are valid here, too. The main difference is that the demand forecast is not an input, but a decision within S&OP. The question is not only whether to fulfill the demand forecast, but rather how to design the future demand in terms of promotions, product launches, and so on, in order to maximize the firm's profit.

Below, we will present an extension of our numerical example to S&OP. Consider the two products, with the forecast quantities given in Table 8.5. Let there be one production plant with a maximum capacity of 200, except for periods 3 and 4, where the capacity is 140 due to vacation. Table 8.8 shows the sales plan for these products together with a feasible production plan and the resulting inventory build-up.

**Table 8.8** S&OP planning table

Period		Actual	1	2	3	4	5
Sales plan	Product 1		70	70	90	90	90
	Product 2		90	70	80	100	90
Production plan	Product 1		60	70	90	90	90
	Product 2		80	130	50	50	90
Inventory plan	Product 1	10	0	0	0	0	0
	Product 2	30	20	80	50	0	0

In the S&OP process, all involved parties can take an integrated view on the main outcomes (in our example: production quantities, sales quantities, and inventories). Additional information like financial KPI can be included, too. Based on that, parties can perform what-if analyses to identify plan alternatives that yield an overall improvement. With the knowledge of the data in Table 8.8, the sales manager might raise the question why we have lower production in periods 3 and 4 and inventory build-ups of (the less expensive) product 2. Knowing the answer from production (“vacation close-down in periods 3 and 4”), sales might think about shifting promotional activities from period 4 to period 2 to decrease the inventory build-up. As another example, product development might point out that a major relaunch of product 2 is planned. So the inventory build-up should be done for product 1, instead, to decrease the risk of obsolete inventory.

Supporting the S&OP process by management meetings is recognized to be a key success factor (Lapide 2004). To organize these meetings in an effective way, standard sequences with a formal agenda are necessary (see, e.g., Boyer 2009). An example for such a sequence is given in Wallace (2004):

1. Data gathering: Historical data is collected.
2. Demand planning: The sales forecast is updated.
3. Supply planning: Determine whether the operations plan is feasible.
4. Pre-meeting: Recommendations for top management are prepared, including a description of the issues where no consensus has been reached. Different scenarios may be elaborated.
5. Executive meeting: Conflicts are resolved and the final plan is approved.

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