

The first application systems for manufacturing companies in the 1960s were systems for *material requirements planning (MRP)*. Even though the roots of MRP are fairly old, most of the MRP functionality is still available in today's ERP systems. In this chapter, the master data for MRP are described, followed by an explanation of the main functional areas supported by MRP.

Some of the vendors of MRP systems were computer manufacturers such as IBM, Honeywell Bull, Digital Equipment, and Siemens. These companies tried to penetrate the business sector with computers, which they would otherwise only be able to sell to military and scientific institutions. A well-known MRP system dating back to 1968 was IBM's *PICS (Production Information and Control System)*, later extended to *COPICS (Communication-Oriented Production Information and Control System)*.

Systems like PICS primarily supported material requirements planning and inventory control for manufacturing companies doing business in the US market. This is worth mentioning because many assumptions underlying conventional MRP systems are derived from the circumstances particular to this market in the 1960s and 1970s. The market was a sellers' market. Most manufacturing companies produced large quantities of identical goods in batch production, stored these goods in a warehouse, sold them to customers as long as they could satisfy the demand, and then produced

another large batch. Other companies continuously produced the goods in mass production and sold them to the customers.

In business terms, this means that the framework for production planning, and in particular for material requirements planning, was characterized by:

- A standard production program (on the product group or individual product level)
- Well-defined product structures
- Uniform or otherwise known demand curves
- Mass or large-series production

It is also worth noting that these characteristics are no longer typical of today's market and manufacturing environment, nor have they been for smaller economies outside North America. In the USA, the customer did not play any significant role in the production planning of the 1960s and 1970s. However, the situation has dramatically changed since then. Today, it is the customer who influences many aspects of material requirements and manufacturing resource planning. In the Sects. 2.2 and 2.3, some implications of customer orientation on material requirements planning will be discussed.

The main task of a conventional MRP system is to support the planning of material requirements on all manufacturing levels, starting with the production program for end products and including inventory management and procurement. However, most dedicated MRP systems

have ceased to exist. They eventually evolved into MRP II systems and later into ERP systems where the core MRP functionality is still available.

2.1 Master Data for MRP

The data structures used in business information systems can be divided into two categories: master data and transaction data. *Master data* are data that exist independent of specific orders (customer, production, purchase, transport orders, etc.). Master data constitute the frame in which the planning and controlling of orders takes place.

Transaction data are created during business operations, for example, when a customer places an order, procurement initiates a purchase from a supplier, production planning releases a production order, or dispatching prepares a shipment to the customer.

Master data are the foundation of any business information system. Without reliable and robust master data, planning and controlling of an enterprise are not possible. Henning Kagermann, the former CEO of SAP, and Hubert Österle, a professor of business informatics at the University of Sankt Gallen, stressed the importance of *master data management* in their book on modern business concepts:

“Master data identify and describe all the important business objects, for example business partners, employees, articles, bills of materials, equipment and accounts. Since all business activities such as quotes, orders, postings, payment receipts and transport orders refer to the master data, these data are the basis of any coordination effort. However, the high expenditures for the construction and maintenance of the master data exhibit their benefits only indirectly – via the processes that use the data. Therefore master data projects have a much lower priority than they should have. Master data management needs support from the management and endurance. New tools for master data management can noticeably reduce the effort for the cleaning up and maintaining of master data” (Kagermann and Österle 2006, pp. 231–232, author’s translation).

The most important master data for production planning and control are data concerning:

- Parts
- Product structures
- Operations
- Routings
- Operating facilities or work centers
- Manufacturing structures

These as well as other types of master data will be discussed in more detail below. *Entity-relationship diagrams* will at times be used for the purpose of illustration. The notation of these diagrams is explained in Appendix A.1.

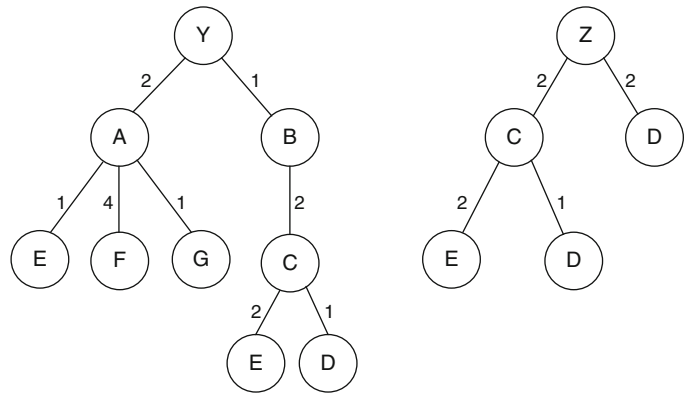
2.1.1 Parts and Product Structures

Part master data play a central role in every manufacturing application system. The generic term “part” comprises assemblies, component parts, raw materials, end products, and more. It refers to all parts of the end product, including the end product itself and all other components needed to produce the end product. In addition to “part,” the terms “material,” “article,” and “product” are also in use. In SAP ERP, for example, the parts are called materials.

Considering the number of parts and the number of attributes, part master data are usually quite substantial. Important attributes (or fields) of part master data include the following:

- Part number
- Variant code
- Part name
- Part description
- Part type (e.g., finished product, assembly, and additional material)
- Measuring unit (e.g., piece, kg, and m)
- Form identification
- Drawing number
- Basic material
- Planning type (e.g., in-house production and consumption-driven MRP)
- Replenishment time
- Scrap factor for quantity-dependent scrap
- Scrap factor for setup-dependent scrap
- Date from which the master record is valid
- Date up to which the master record is valid
- Date of the last modification

Fig. 2.1 Product structure trees (“consists of”)



- Date of the first creation
- Person in charge

Often, many more attributes are used to describe parts. For example, the part master data managed by SAP ERP (called material master data) exhibit more than 400 attributes. The number of attributes and the degree to which the attributes are differentiated depend on, among other things, which business areas are covered by the ERP solution, whether or not related application systems (e.g., CAD for construction, CAM for manufacturing, and SCM for delivery) are available, and whether or not interfaces for these systems exist.

The various attributes are sometimes categorized in data groups such as:

- Identification data (part number, etc.)
- Classification data (technical classification)
- Design data (measurements, etc.)
- Planning data (procurement type, lot size, etc.)
- Demand data (accumulated demand, etc.)
- Inventory data (warehouse stock, etc.)
- Distribution data (selling price, etc.)
- Procurement data (buying price, etc.)
- Manufacturing data (throughput time, etc.)
- Costing data (machine cost, inventory cost, etc.)

In SAP ERP, for example, attributes are divided into 28 categories called “views” (because they reflect the user’s “view” of the data, i.e., the various forms in which the data is presented to the user).

Not all fields shown in a part master-data form are necessarily attributes of a database table with the name “part.” In fact, many of the shown

values are just calculated or taken from other tables. For example, the warehouse stock as it appears in a part master-data form is, as a rule, retrieved and aggregated from several database tables, which are maintained for different inventory locations.

Product Structures Product structures show what parts make up a product. This composition is often depicted as a tree. The edges of the tree represent either “consists of” or “goes into” relationships, depending on the perspective. Figure 2.1 shows two simplified product structure trees for the end products Y and Z. The numbers on the edges are quantity coefficients. Y consists of two units of A and one unit of B. Conversely, A and B go into Y with 2 and 1 units, respectively.

Reversing the perspective, so that the leaves of one or more product structure trees become the roots and the end products are the leaves (“goes into” relationship), creates trees like those in Fig. 2.2. The figure directly shows where a given part is needed. For example, part E goes directly into part A with one unit and into part C with two units, as well as indirectly into parts Z, B, and twice (through parts A and B) into part Y.

The two different perspectives can be combined into a so-called *Gozinto graph*. The name “Gozinto” is supposedly derived from the words “goes into.” A Gozinto graph allows for network structures that avoid redundant branches and nodes. For example, in Fig. 2.1, part C is shown twice, and part D is shown three times. In a Gozinto graph, as in Fig. 2.3, parts C and D

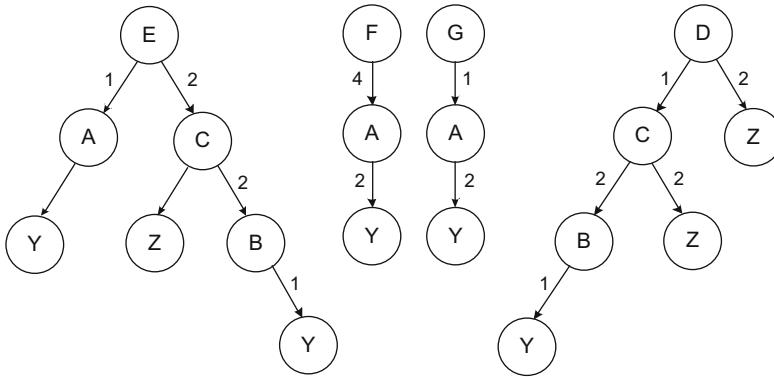


Fig. 2.2 Reversed product structure trees (“goes into”)

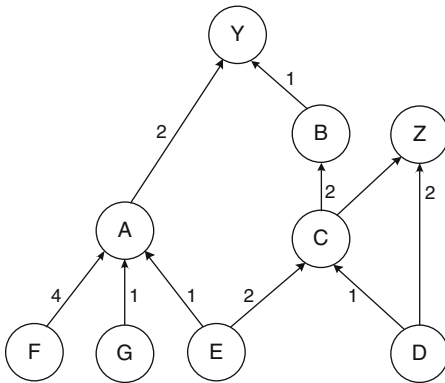


Fig. 2.3 Product structure as a Gozinto graph

appear only once. D goes into C and Z, and C goes into B and Z.

A product structure, like any other higher-order tree, can be transformed into a binary tree, as long as the information on the edges is preserved. Fig. 2.4 shows this transformation for the product structures Y and Z. In comparison to the original tree, the following changes should be noted:

- The edges of the tree now have a different meaning. An edge that leads to the *left* child of a node indicates the first part of the next level that goes directly into the parent node.
- An edge that leads to the *right* child of a node indicates the next part on the same level that goes directly into the same parent node as its predecessor.
- The information on the original edges must be preserved during the transformation. This

means that the quantity coefficients, and possibly more information, have to be stored elsewhere because the original edges no longer exist. In the figure, the edges of the original product structure trees are drawn with dotted lines.

A binary tree such as the one shown in Fig. 2.4 is a symbolic representation of a single-level bill of materials (BOM). Bills of materials are discussed below.

Product structures ultimately express *relationships between parts*. Using entity-relationship terminology, a product structure can be regarded as a relationship connecting objects of the same entity type with each other.

Figure 2.5 shows this situation with the help of a “structure” relationship type, which can be interpreted both as a “consists of” and a “goes into” relationship. The cardinalities indicate that a part can consist of any number of other parts but also of no other parts (e.g., a raw material or an externally procured part). Conversely, it is possible for a part to go into any number of other parts or into no other part (e.g., an end product).

Out of the large number of part and product structure attributes, only the “part-id” and the “quantity” are shown in the diagram. The part-id attribute is important because it can be used to uniquely identify a particular structure relationship (i.e., one edge of a product structure tree).

At first glance, Fig. 2.5 seems to express only the relationships between parts involving two

Fig. 2.4 Product structure, transformed into a binary tree

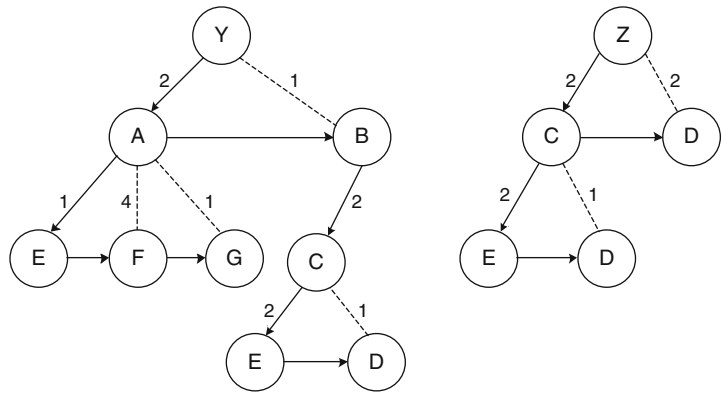
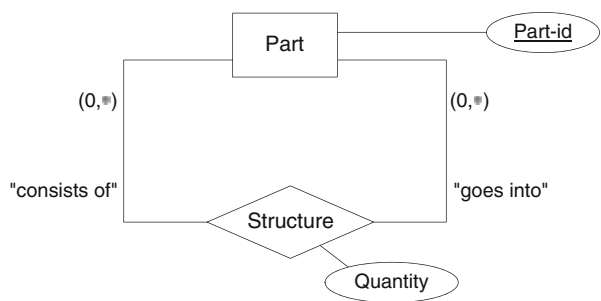


Fig. 2.5 Product structure as a relationship type in an ER diagram



levels and not the multilevel structures that were shown in the earlier figures. However, multilevel structures can be easily generated through appropriate database queries. For this purpose, the part-ids of related subordinate and superordinate parts are employed to link single-level structures into a multilevel structure.

The ER model of Fig. 2.5 can be mapped to a relational database with the help of two tables, “part” and “structure.” In relational notation (see Appendix A.2), these two tables are defined as follows:

Part (part-id, part name, part type, unit of measurement. . .)

Structure (upper-part-id, lower-part-id, quantity, valid-from. . .)

The “structure” table has a composite key, indicating the two part entities to be linked. Graphically speaking, the “upper-part-id” attribute identifies the parent node in the product structure, while the “lower-part-id” identifies the child node.

Figure 2.6 exemplifies a product structure tree of an electric motor with part number “E10.” Figure 2.7, which is based on this product

structure, exhibits two tables—one with the parts and the other with the relationships between parts—according to the E10 product structure.

The part table shows, along with the part number (“part-id”), three additional attributes. The “part type” attribute has values that are abbreviations of in-house production (I), external procurement (E), end product (P), assembly (A), raw material (R), consumables (C), etc. For example, ER stands for external procurement/raw material.

In the “structure” table, the first line uniquely identifies the edge between the end product “electric motor” (upper-part-id “E10”) and the assembly “complete casing” (lower-part-id “901”). The most important attribute of the structure relationship, in addition to the keys, is the quantity.

A number of other attributes may also appear in a “structure” table. Just as with the part master data, the type and number of attributes are dependent upon the level of detail and the application environment. Typical fields of a structure table include:

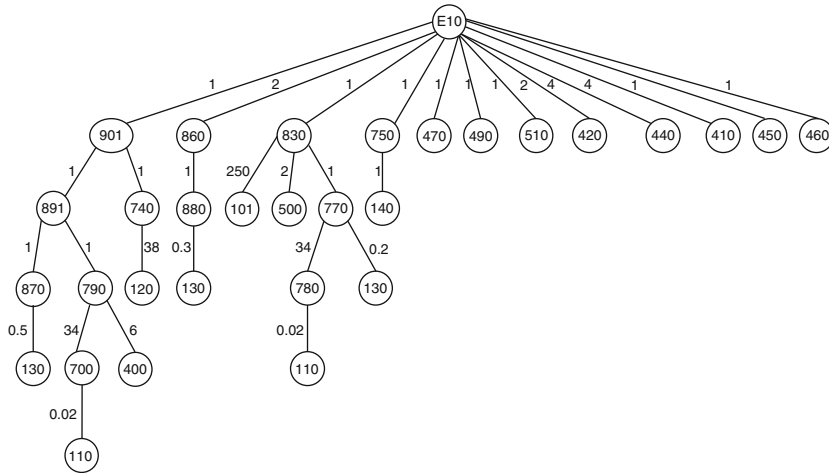


Fig. 2.6 Product structure of an electric motor

Part					Structure			
Part-id	Part name	Part type	Unit	...	Upper part-id	Lower-part-id	Quantity	...
E10	Electric motor	IP	pc		E10	901	1	
901	Case (complete)	IA	pc		E10	860	2	
891	Case with laminations	II	pc		E10	830	1	
880	Bearing cap (aluminum)	II	pc		E10	750	1	
870	Housing block (aluminum)	II	pc		E10	510	1	
860	Bearing cap with breakout	IA	pc		E10	490	1	
830	Arbor (complete)	IA	pc		E10	470	1	
790	Plate packet (complete)	IA	pc		E10	460	1	
780	Muller plate	II	pc		E10	450	1	
770	Base plate 30x40 cm	IA	pc		E10	440	4	
750	Muller plate packet (complete)	IA	pc		E10	420	2	
740	Stator winding	II	pc		E10	410	4	
700	Stator plate muller	II	pc		901	891	1	
510	Junction plate box cap	EA	pc		901	740	1	
500	Roller bearing	EA	pc		891	870	1	
490	Junction plate 3-pin	EA	pc		891	790	1	
470	Nut M 4	EC	pc		880	130	0.3	
460	Rigid coupling ∅ 14 mm	EA	pc		870	130	0.5	
450	Capacitor 16 µF	EA	pc		860	880	1	
440	Hex nut M 4x200	EC	pc		830	770	1	
420	Hex nut M 4x10	EC	pc		830	500	2	
410	Hex nut M 8x30	EC	pc		830	101	250	
400	Rivet 4x150 mm	EC	pc		790	700	34	
140	Sheet metal board St 37	ER	pc		790	400	6	
130	Aluminum bar	ER	kg		780	110	0.02	
120	Copper wire ∅ 0.5 mm	EC	m		770	780	34	
110	Electrical sheet coil 200 mm	EC	m		770	130	0.2	
101	Round bar 37x30 mm	ER	pc		750	140	1	
					740	120	38	
					700	110	0.02	

Fig. 2.7 Database tables “part” and “structure” (electric motor)

- Upper-part-id
- Lower-part-id
- Variant code
- Quantity coefficient
- Structure type (e.g., is the quantity coefficient dependent on the quantity of the upper part?)
- Scrap factor for structure-dependent scrap
- Date from which the master record is valid

- Date to which the master record is valid
- Date of the last modification
- Date of the first creation
- Person in charge

Important uses of product structures include (1) compiling bills of materials and where-used lists and (2) determining dependent requirements for material planning.

Dependent material requirements, that is, the quantities of lower-level parts needed to produce the planned end products (or other higher-level parts), are calculated with the help of the quantity coefficients, which are stored in the “quantity” column of the “structure” table. Sect. 2.3.2 will discuss the calculation process in more detail.

Bills of Materials A bill of materials (BOM) represents a product structure together with essential information about the nodes (i.e., part master data) in the form of a list. Each row shows one subordinate part. The parts are described by part number, part name, quantity needed for the upper part, etc. In this way, a bill of materials describes the composition of an end product or an intermediate product (assembly).

Bills of materials are especially relevant in *discrete manufacturing*, that is, in manufacturing processes in which the quantities are mostly measured in discrete units (pieces). This is typically the case when assembly plays a dominant role, for example, in the production of machines, bicycles, or furniture.

The opposite of discrete manufacturing is *continuous manufacturing*, which occurs particularly in the chemical and pharmaceutical industry. There, the equivalent of a bill of materials is a *formulation*. The main difference between a bill of materials and a formulation is that the quantities are measured in continuous units (kilogram, ton, liter, etc.) and that the product structure graphs are not necessarily trees but may contain cycles. A cycle means that in order to manufacture a product, the product itself is needed.

In this book, we will focus on discrete manufacturing using bills of materials, although

a number of similar problems also occur in continuous manufacturing.

Bills of materials are employed for various purposes: requirements planning, assembly, computer-aided design, etc. The content, structure, and format of a bill of materials depend on the intended use. Hence, a number of labels exist, for example, planning BOM, assembly BOM, manufacturing BOM etc.

Different types of bills of materials exhibit different structures, depending on how much structural information is mapped to the bill. Relating to this, three types can be determined:

1. *Single-level bills of materials* are used to define the immediate components of a higher-level part, that is, what lower-level parts go *directly* into the higher-level part. A single-level bill of materials typically shows the assemblies (plus other parts) an end product is made of. However, it can be used for any part, depicting the next-level decomposition of the part.
2. *Multilevel bills of materials*, unlike single-level, expand the higher-level part down *all* levels of the product structure. This type of bill displays the entire product structure tree in the form of a list. The upper-part/lower-part relationships are indicated with level numbers.

Figure 2.8 gives an example using the electric motor with part number E10 (cf. Fig. 2.6). A bill like this is easily created from the tables “part” and “structure” in Fig. 2.7 with the help of a simple database query. It should be noted that the rows of this bill of materials correspond to the level 2 nodes of a binary tree created as the one in Fig. 2.4.

3. *Summarized bills of materials* indicate all parts that go into a product, but do not reflect the structure of the product. This means that the tree is “compressed” into one level. When

Fig. 2.8 Single-level BOM for electric motor E10

Single-level Bill of Materials					Page 1
Part: Electric motor, part-id: E10					
Part-id	Part name	Unit	Quantity	...	
901	Case (complete)	pc	1		
860	Bearing cap with breakout	pc	2		
830	Arbor (complete)	pc	1		
750	Base plate 30x40 cm	pc	1		
510	Junction plate box cap	pc	1		
490	Junction plate 3-pin	pc	1		
470	Nut M 4	pc	1		
460	Rigid coupling Ø 14 mm	pc	1		
450	Capacitor 16 µF	pc	1		
440	Hex nut M 4x200	pc	4		
420	Hex nut M 4x10	pc	2		
410	Hex nut M 8x30	pc	4		

Fig. 2.9 Multilevel BOM for electric motor E10

Multi-level Bill of Materials					Page 1
Part: Electric motor, Part-id: E10					
Level	Part-id	Part name	Unit	Quantity	...
1	901	Case (complete)	pc	1	
. 2	891	Case with laminations	pc	1	
. . 3	870	Housing block (aluminum)	pc	1	
. . . 4	130	Aluminum bar	kg	0.5	
. . 3	790	Plate packet (complete)	pc	1	
. . . 4	700	Stator plate muller	pc	34	
. . . . 5	110	Electrical sheet coil 200 mm	m	0.02	
. . . 4	400	Rivet 4x150 mm	pc	6	
. 2	740	Stator winding	pc	1	
. . 3	120	Copper wire Ø 0.5 mm	m	38	
1	830	Arbor (complete)	pc	1	
. 2	770	Muller plate packet (complete)	pc	1	
. . 3	780	Muller plate	pc	34	
. . . 4	110	Electrical sheet coil 200 mm	m	0.02	
. . 3	130	Aluminum bar	kg	0.2	
. 2	500	Roller bearing	pc	2	
. 2	101	Round bar 37x30 mm	pc	250	
1	860	Bearing cap with breakout	pc	2	
. 2	880	Bearing cap (aluminum)	pc	1	
. . 3	130	Aluminum bar	kg	0.3	
1	750	Base plate 30x40 cm	pc	1	
. 2	140	Sheet metal board St 37	pc	1	
1	510	Junction plate box cap	pc	1	
1	490	Junction plate 3-pin	pc	1	
1	470	Nut M 4	pc	1	
1	460	Rigid coupling Ø 14 mm	pc	1	
1	450	Capacitor 16 µF	pc	1	
1	440	Hex nut M 4x200	pc	4	
1	420	Hex nut M 4x10	pc	2	
1	410	Hex nut M 8x30	pc	4	

Fig. 2.10 Summarized BOM for electric motor E10

Summarized Bill of Materials			Page 1
Part: Electric motor, Part-id: E10			
Part-id	Part name	Unit	Quantity ...
901	Case (complete)	pc	1
891	Case with laminations	pc	1
880	Bearing cap (aluminum)	pc	2
870	Housing block (aluminum)	pc	1
860	Bearing cap with breakout	pc	2
830	Arbor (complete)	pc	1
790	Plate packet (complete)	pc	1
780	Muller plate	pc	34
770	Muller plate packet (complete)	pc	1
750	Base plate 30x40 cm	pc	1
740	Stator winding	pc	1
700	Stator plate muller	pc	34
510	Junction plate box cap	pc	1
500	Roller bearing	pc	2
490	Junction plate 3-pin	pc	1
470	Nut M 4	pc	1
460	Rigid coupling Ø 14 mm	pc	1
450	Capacitor 16 µF	pc	1
440	Hex nut M 4x200	pc	4
420	Hex nut M 4x10	pc	2
410	Hex nut M 8x30	pc	4
400	Rivet 4x150 mm	pc	6
140	Sheet metal board St 37	pc	1
130	Aluminum bar	kg	1.3
120	Copper wire Ø 0.5 mm	m	38
110	Electrical sheet coil 200 mm	m	1.36
101	Round bar 37x30 mm	pc	250

a part appears more than once in the product structure, its quantities are added. Consequently, the bill shows only the total quantity needed for one unit of the top part (e.g., the end product). Figure 2.10 illustrates this, again using the electric motor example.

The part numbers 880, 130, and 110 are examples showing how several quantities are summarized into one. Because one piece of 880 (bearing cap) is needed for one 860 (bearing cap with breakout) and two pieces of 860 are needed for one E10 (electric motor), the result is that two pieces of 880 are needed for one E10.

How many units of 130 (aluminum bar) are needed for one electric motor E10 can be calcu-

lated by multiplying the quantity coefficients on the edges

$$\frac{870-130 (0.5)}{891-870 (1)} \text{ and } \frac{880-130 (0.3)}{860-880 (1)} \text{ and } \frac{770-130 (0.2)}{830-770 (1)}$$

$$\frac{901-891 (1)}{E10-891 (1)} \text{ and } \frac{E10-860 (2)}{E10-860 (2)} \text{ and } \frac{E10-830 (1)}{E10-830 (1)}$$

and adding up the products

$$0.5 \times 1 \times 1 \times 1 + 0.3 \times 1 \times 2 + 0.2 \times 1 \times 1$$

to 1.3 kg. (This total is shown in the fourth to the last line in the summarized bill of materials in Fig. 2.10).

Where-Used Lists While bills of materials reflect “consists of” relationships between parts,

Fig. 2.11 Multilevel where-used list

Multilevel Where-used List					Page 1
Part: Aluminum bar, Part-id: 130					
Level	Part-id	Part name	Unit	Quantity	...
1	870	Housing block (aluminum)	kg	0.5	
. 2	891	Case with laminations	pc	1	
. . 3	901	Case (complete)	pc	1	
. . . 4	E10	Electric motor	pc	1	
1	880	Bearing cap (aluminum)	kg	0.3	
. 2	860	Bearing cap with breakout	pc	1	
. . 3	E10	Electric motor	pc	2	
1	770	Muller plate packet (complete)	kg	0.2	
. 2	830	Arbor (complete)	pc	1	
. . 3	E10	Electric motor	pc	1	

Fig. 2.12 Summarized where-used list

Summarized Where-used List					Page 1
Part: Aluminum bar, Part-id: 130					
Part-id	Part name	Unit	Quantity	...	
770	Muller plate (complete)	kg	0.2		
830	Arbor (complete)	kg	0.2		
860	Bearing cap with breakout	kg	0.3		
870	Housing block (aluminum)	kg	0.5		
880	Bearing cap (aluminum)	kg	0.3		
891	Case with laminations	kg	0.5		
901	Case (complete)	kg	0.5		
E10	Electric motor	kg	1.3		

where-used lists (part-usage lists) represent “goes into” relationships. Let us take another look at Fig. 2.2. This figure shows that reverse product structure trees can be constructed based on the “goes into” relationships.

As for bills of materials, different types of where-used lists can be identified, according to the degree to which the multilevel structure of the trees is reflected:

- *Single-level where-used lists* comprise all parts into which the given part goes directly. For example, the list for part 130 (aluminum bar, cf. Fig. 2.6) would display parts 870 (with 0.5 units), 880 (with 0.3 units), and 770 (with 0.2 units).
- *Multilevel where-used lists* show all parts into which the given part goes directly or indirectly (through other parts). The hierarchical structure of the tree is preserved and is expressed

with level numbers. Figure 2.11 illustrates the basic idea using part 130 as an example.

- *Summarized where-used lists* include all parts of the “goes into” tree, but the tree is compressed to one level, as in a summarized bill of materials. This means that the quantities are added up. The where-used list that corresponds to Fig. 2.11 is shown in Fig. 2.12.

2.1.2 Product Variants

The term *product variant* is used to describe parts, especially end products, that differ from a basic model. Nowadays, many products are available in multiple versions. This means that the products are not 100 % identical, but vary in some features.

Automobiles are an obvious example of a product produced in variants. They are based on a certain model but are available with a variety of options. Different engines, transmissions, seats, colors, wheels, with or without fog lamps, cruise control, tow bar, navigation system, etc. are just some of the many options the customer can choose from.

Because of the emphasis on the customer, variant production has become very popular in many industries. This is true both for the consumer market (e.g., automobiles, furniture, and clothing) and the market for investment goods (e.g., machinery). Since customer orientation is an important success factor, companies attempt to serve the individual wishes of their customers as well as possible. Product variants are one means to take individual requirements into account.

The number of possible variants of an end product can be very large. An automobile, for example, can easily have hundreds of thousands or even millions of variants, because there are many ways to combine the customizable features. Assemblies and intermediate parts may also come in many different variants. For example, the cable harness that connects the electric and electronic parts of a VW Passat has approximately 1,000 variants. In other cases, there are only a few possible variants. An electric motor, for example, may be available with 40, 60, or 80 W.

In practice and in the literature, variants are divided into several categories, including structure, quantity, mandatory, optional, and internal variants:

- A *structure variant* is when several different versions of a part are possible and one of these versions goes into the end product (e.g., a 110-, 140-, or 180-hp engine) or when a subpart is optional (e.g., a tow bar).
- A *quantity variant* is when different quantities of one part can be built into the end product (e.g., two or four loudspeakers).
- A *mandatory variant* is when several different versions of a part are possible, one of which *must* go into the end product (e.g., either a 110-, 140-, or 180-hp engine).
- An *optional variant* is when a part can be *added* to the basic model of a product (e.g., fog lights and mobile phone mounting).

- An *internal variant* is a variant that is only relevant in-house and does not have an explicit effect on the end product (e.g., batteries from different manufacturers built into the vehicles, depending on internal procurement and inventory policies).

The terms obviously overlap. Mandatory variants are structure variants. Optional variants are structure (additional tow bar) or quantity (additional loudspeakers) variants. Internal variants are usually structure variants but are not apparent to the client. In practice, structure and quantity variants often appear together.

There are different ways to represent variant product structures: static and dynamic. *Static* means that all possible versions of the product are defined and stored in the database. Each variant is an entity in the master data and can be retrieved from the database when needed. When a product has only a few variants (i.e., not too many combinations of variant features), the variants are usually stored statically in the database.

Dynamic variants, on the other hand, are only created when they are explicitly requested, for example, when a customer orders that particular combinations of features. When there are many possible combinations, dynamic creation of variants is preferred.

Static variants are stored in a conventional way, that is, in database tables such as “part” and “structure.” The part master records will indicate whether a part has variants or not. In the “structure” table, the variants are basically treated as if they were separate parts.

As an example, consider the Figs. 2.13 and 2.14. The end product X comes in two variants, X1 and X2. They differ in that X1 needs an assembly A1, whereas X2 needs A2. A1 is similar to A2 but uses a part E1, whereas A2 uses E2. Consequently, the “structure” table shown in Fig. 2.15 has rows connecting “upper parts” and “lower parts” as follows:

X1-A1	X2-A2
X1-B	X2-B
X1-C	X2-C
A1-E1	A2-E2
A1-D	A2-D

Fig. 2.13 Product structure trees of variants X1 and X2

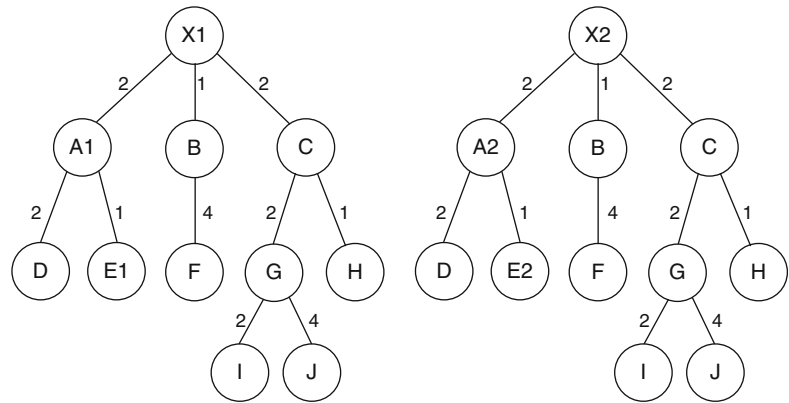
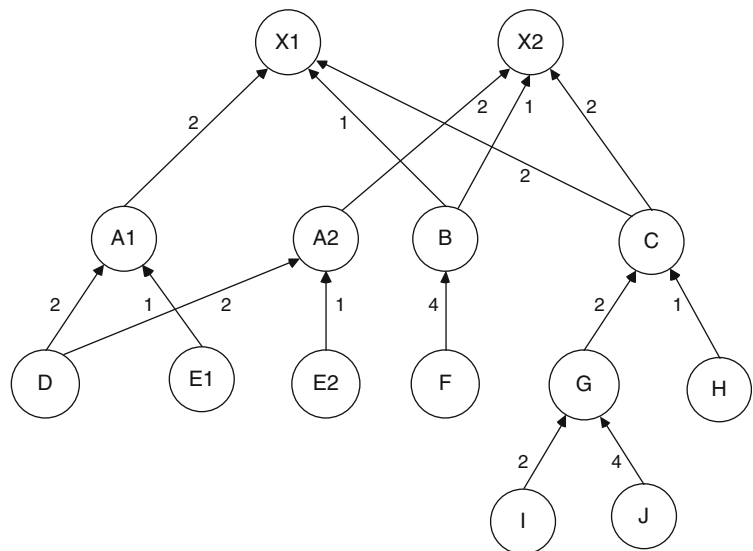


Fig. 2.14 Gozinto graph for variants X1 and X2



While a lot of information is doubled in the product structure trees for X1 and X2 (cf. Fig. 2.13), the Gozinto graph (cf. Fig. 2.14) exhibits less redundancy. Since the database schema for product structures is based on Gozinto graphs and not on trees, there is not much redundancy in the database either.

Figure 2.15 shows that in the “structure” table, redundant branches of the trees appear as rows of the table only once. For example, the subtree for part C occurs twice in the product structures of X1 and X2 but only once in the Gozinto graph and hence only once in the database table.

Nevertheless, some redundancy remains. For example, links from the end product to the assemblies B and C and from the assembly A to

part D are duplicated. This might not look like a big problem, but only because our example is very small. In more realistic product structures, the number of redundant links can be quite large.

Therefore, various formats to store static variants have been proposed and implemented in the past. For example, one format uses fictitious common assemblies (combining all invariant parts into one fictitious group); another format indicates where a variant differs from the basic version with plus (additional part) and minus (part to be omitted) indicators.

A popular format for static variants is a *variant family*. In a variant family, the links connecting a variant part with another part are not handled as individual entities in the “structure”

Fig. 2.15 Variants X1 and X2 in a “structure” table

Structure			
<u>Upper-part-id</u>	<u>Lower-part-id</u>	Quantity	...
X1	A1	2	
X1	B	1	
X1	C	2	
X2	A2	2	
X2	B	1	
X2	C	2	
A1	D	2	
A1	E1	2	
A2	D	2	
A2	E2	1	
B	F	4	
C	G	2	
C	H	1	
G	I	2	
G	J	4	

Fig. 2.16 Variant family X in a “structure” table

Structure				
<u>Upper-part-id</u>	<u>Lower-part-id</u>	Quantity for variant		...
		X1	X2	
X	A1	2		
X	B	1	1	
X	C	2	2	
X	A2		2	
A1	D	2		
A1	E1	1		
A2	D		2	
A2	E2		1	
B	F	4	4	
C	G	2	2	
C	H	1	1	
G	I	2	2	
G	J	4	4	

table but together as a group. For our example, this means that the structure table has several columns that contain quantity coefficients.

Figure 2.16 shows the structure table for a variant family X, which contains the variants X1 and X2. The product structures of X1 and X2 are now defined by those links between “upper parts” and “lower parts” that have an entry in the respective row.

Variant families are also known as “multiple,” “complex,” or “type” bills of materials. They are used both for structure and quantity variants. In any case, the number of possible variants should be small because each variant will add a column to the structure table.

Dynamic variants are often used when products can be customized. Suppose an end product has 50 customizable features, each one coming in 4 different variations. The number of possible feature combinations, and hence the number of variants, is 4^{50} . Storing all variants statically does not make sense, seeing that many of the potential combinations will never occur. Instead, a variant is only created when it is actually requested for a particular order.

Practical solutions often implement an *attribute-value-based approach*. This means that variants are defined with the help of the attributes in which the variants differ. Links in the “structure” table are then uniquely identified by the part numbers

Fig. 2.17 Key attribute “variant code” in a “structure” table

Structure					
Upper-part-id	Lower-part-id	Variant code		Quantity	...
		Attribute	Value		
X	A	C	gr	2	
X	A	C	re	2	
X	A	C	bl	2	
X	B			1	
X	C			2	
A	D			2	
A	E	P	40	1	
A	E	P	60	1	
A	E	P	80	1	
B	F			4	
C	G			2	
C	H			1	
G	I			2	
G	J			4	

of the upper and the lower parts, plus a variant code that defines the attributes of the specific variant under consideration. (In relational terminology, this means that the variant code is also a key attribute.) In this way, variant-specific parts can be marked and tracked down the product structure any number of manufacturing levels.

As an example, let us assume that variant X2 differs from X1 in that the color of assembly group A2 is green (instead of red in A1 or white in another variant) and the power of E2 is 80 kW (instead of 40 kW in E1 or 60 in another variant):

Attribute	Value
Color	Green
	Red
	White
Power	40
	60
	80

The variant code describing specific variants can be constructed from the attribute name (e.g., “C” for color and “P” for power) and the desired value (e.g., “gr” for green and “40” for 40 kW).

The product structure for this variant is generated only when an order for a particular variant, say “C = gr/P = 80,” is placed. This happens in such a way that all rows exhibiting the variant code “C = gr” or “P = 80” are considered plus all rows that have no entries in the variant-code columns. Parts without a variant code go into all variants.

Figure 2.17 shows the structure table including variant codes. Because the variant parts are not listed as independent entities in the part master data, variant-specific part numbers such as X1, A1, and E1 do not no longer appear.

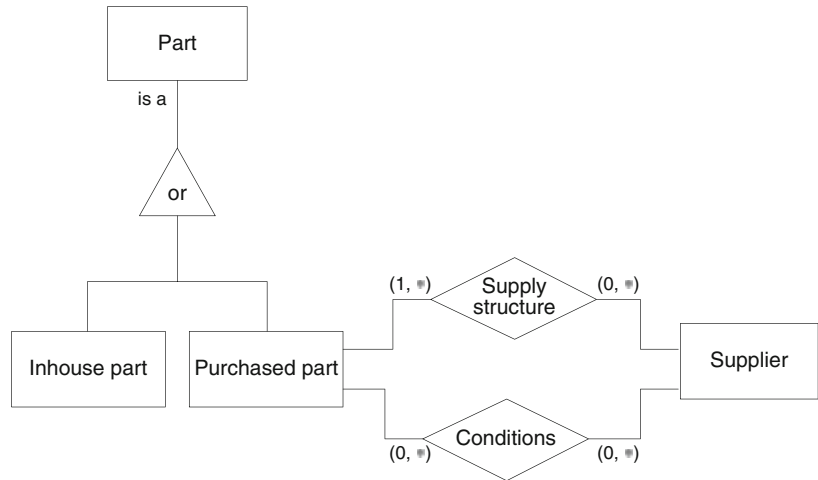
The variant problem is very complex. More advanced solutions employ *rule-based approaches*, especially for automatically generating variant bills of materials. Decision tables and knowledge-based solutions for this purpose have been integrated into ERP systems. For example, *Infor ERP COM* uses a knowledge base in which manufacturing and cost-related knowledge (including plausibilities) are stored. When a bill of materials is to be created, the knowledge base is processed, deriving feasible, cost-effective connections between the parts in question.

The next stage in on-the-fly creation of product structures, beyond dynamic variants, is *product configuration*. In electronic commerce, where customers may put the desired product together online, electronic configurators are especially common. Configuration will be discussed in more detail in Sect. 2.2.2.

2.1.3 More Master Data

While part data and product structure data are at the core of material requirements planning, many additional data structures are needed. These include supplier, customer, and warehouse data.

Fig. 2.18 ERM connecting parts and suppliers



Suppliers Supplier data are used in material requirements planning for procurement and purchase orders. Typical attributes of a supplier include:

- Supplier number
- Supplier name
- Address
- Contact person
- Payment data
- Supplier rating (e.g., percent of deliveries being disputed, quality, and average delay time)
- Liability limit

Suppliers are connected with those parts (materials) that are not produced in-house. In Fig. 2.18, these are the parts represented by the “purchased part” specialization of the entity type “part.” The relationship type “supply structure” connects a purchased part with one or more suppliers.

In a similar way, these two entity types are again connected with the help of the relationship type “conditions.” Attributes of this relationship type are the terms of delivery and payment (e.g., discount and time for payment allowed).

Customers Customer data are required for sales and distribution. Customers have similar attributes as suppliers, for example:

- Customer number
- Customer name
- Address
- Contact person

- Customer rating
- Credit line

Customers and parts (in particular, end products) are related in a similar way as suppliers and parts. Because of these similarities, we will refrain from showing the relationships between these entities again with a separate diagram.

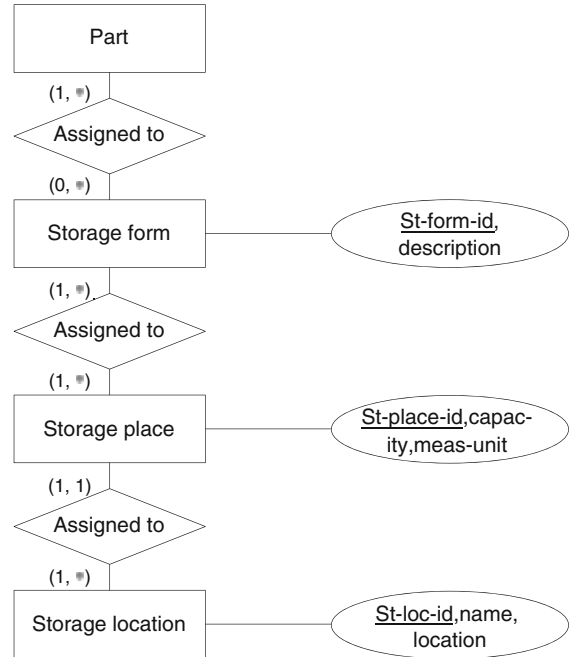
Warehouse Warehousing data structures depend very much on the physical organization of the inventory. Few companies store everything, from raw materials to replacement parts and intermediate products, all the way to the end products, in just one warehouse. Most companies use multiple storage locations and different types of physical storage such as pallet shelves, silos, tanks, and high-bay warehouses. Therefore, different companies in different industries have rather different data models for their warehouse area.

Figure 2.19 assumes that, generally, a given part can be stored in different ways (i.e., different storage forms), for example, on pallets or stacked on a shelf. Storage locations are usually broken up into storage places that allow certain types of storage forms.

2.1.4 Dealing with Missing Data

In describing the MRP master data, we have assumed that either these data already exist or the organization possesses all information

Fig. 2.19 Entity-relationship diagram for warehouse master data



needed to create the data. This assumption is usually satisfied when the organization is similar to the type described in the beginning of the chapter: producing a standard production program in mass or large-series production based on well-defined product structures and well-known demand curves and stocking the products.

Whenever customers are directly involved, the situation can be very different. In *make-to-order production*, the end products are often not predefined, but specified by the customer. For these products, the company will usually not have master data, unless the product has been built in the same way before. In *individual make-to-order production*, and especially in *individual one-time production*, the part and product structure data often have to be created just for the specific customer order.

This does not necessarily mean that every single part going into a customer-specific end product has to be designed from scratch. Make-to-order manufacturers also strive to use standard parts as much as possible, because it is more economical. A typical situation is therefore that the higher levels of a product structure exhibit new (i.e., customer-specific) parts, whereas on the lower levels, standard parts are found. For

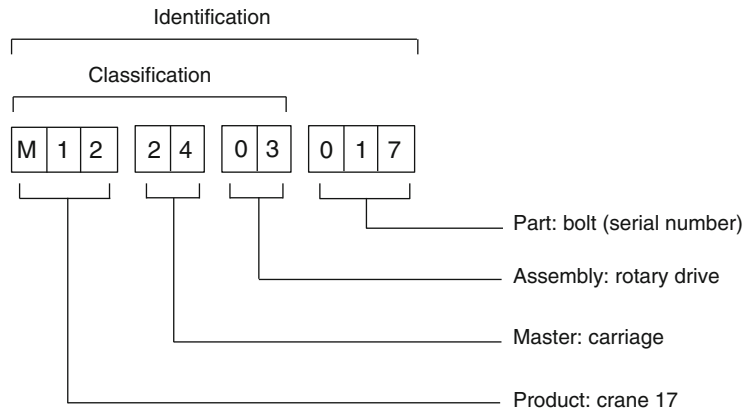
standard parts, master data exist, but for customer-specific parts, this is not the case.

Normally, an ERP system will require the company to create complete master data before any planning based on these data can be done. However, many make-to-order manufacturers are reluctant to make the effort of establishing new parts and product structures because their organization requires elaborate administrative processes for introducing (and approving) new parts.

On the other hand, an ERP system cannot do any planning without the underlying data structures. Therefore, at least some of the data have to be entered in one way or another. The ERP system can support this work effectively by providing adequate assisting features, including:

- Powerful copying and editing functions allowing existing part or product structure data to be copied and modified to suit the present needs
- Temporary parts and product structures which do not have to meet the same requirements as other database objects
- Product structures which reference incomplete part master data
- Planning features that exploit similarity (i.e., planning in analogy to previous similar orders)

Fig. 2.20 Compound number (example)



2.1.5 A Note on “Numbers”

In the previous sections, so-called numbers were employed to identify the parts (materials) in material requirements planning. These numbers are present in the master data, product structures, bills of materials, where-used lists, and in many more places. Likewise, all other objects of enterprise resource planning, such as machines, routings, tools, orders, invoices, and customers, are identified by numbers.

Although we usually speak of “numbers,” these numbers are not meant to be used as numerical values in computations nor are they exclusively composed of numerical digits. In the electric motor example above, the part number was “E10.” The reader will find more examples of numbers (i.e., article numbers) by looking at any sales slip printed by a supermarket’s cash register.

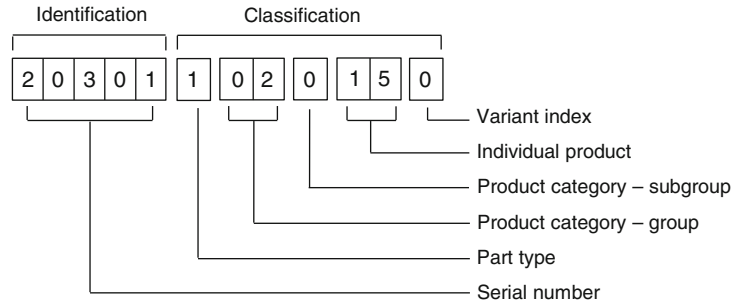
Many numbers contain long sequences of digits, and also letters, dashes, and other nonnumeric characters. The reason for these long strings is that the numbers serve more purposes than just identifying an object. In general, the purpose of a number can be:

- Identification—the number only identifies an object
- Classification—the number shows which category of objects the object belongs to
- Information—the number tells what the object is (so-called mnemonic number)

According to this distinction, different types of numbering systems have been developed and put into practice:

1. *Identification numbers* serve the sole purpose of uniquely identifying an object. The simplest numbering scheme for this is to use serial integer numbers starting with 1. Although textbook examples sometimes use this scheme, it is not typical for real-world applications.
2. *Classification numbers* categorize objects, that is, they are structured in a way that some places of the number are reserved for the category the object belongs to, other places for the subcategory, etc. For example, a numbering scheme may prescribe that the first two places are for the overall category of the part, the next three places for a form identifier, and the next three places for the basic material the part is made of. A part number would then be composed of three components: xx-xxx-xxx (e.g., 10-C12-133). Obviously such a number is generally not unique because there may be more than one part in the same subgroup.
3. *Compound numbers* extend classification numbers by an identifying number within the subgroup in order to make the number unique. Figure 2.20 shows an example. In addition to the classifying components, a serial number is used to uniquely identify the parts within subgroup 03 (rotary drive) of crane 17’s carriage. It should be noted that the identifying part of the number is only unique within the subgroup 03, not within the entire part spectrum.
4. *Parallel numbers* do two things parallel and independently from each other: They classify a part and identify it at the same time. This means that the identifying number is unique

Fig. 2.21 Parallel number (example)



across *all* parts, not only within a group. Figure 2.21 shows an example in which the identifying number is a five-digit serial number and the rest is a classification number. Instead of a classification number, we sometimes find a compound number. This is due to the fact that numbering systems evolve. Often, companies that have been using compound numbers for years and are now going to a parallel numbering system prefer to keep the old numbers and just extend them.

Establishing a numbering system across an entire company is a comprehensive project involving all departments. Part numbers, for example, are needed for production planning, sales, product design, shop-floor control, procurement, cost calculation, invoicing, and many more business areas. These areas have different requirements as to what exactly the part number should express.

Since different interests and opinions on what the numbers should be like collide, it usually takes many years to implement a new system. This is one reason why numbering systems remain in place for a long time. Another reason for this is that the entire organization depends on the system. Experienced consultants recommend keeping a numbering system, once it is installed, for at least 15 or 20 years because of the cost involved with switching. It is very important to build flexibility and adaptability into the design

of the system so that it can cope with changing requirements over the years.

2.2 Master Production Planning

Demand for end products can originate from an abstract sales plan or from concrete customer orders. Therefore, we distinguish between planning for anonymous demand (make-to-stock production) and planning for customer orders (make-to-order production).

2.2.1 Planning for Anonymous Demand

When a company produces goods to be sold on the market to customers who are not known at the time the production is planned, we speak of *anonymous demand*. The quantities to be manufactured depend on a sales plan or on expectations as to what the company will be able to sell in the future.

There are basically two approaches to draw up a master production plan: optimization and forecasting. While optimization is the preferred approach in management science, forecasting is the approach mostly taken in practice.

Optimization Model Creating an optimal *master production plan* (also known as *production program*) usually starts from figures taken from the company's sales plan. A *sales plan* indicates which quantities the company intends to sell within the period(s) under consideration. The sales plan can be compiled on an aggregate level (e.g., product groups) or refined down to the level of individual products. Accordingly, a master production plan may refer to product groups or individual products.

Vast numbers of optimization models for master production planning have been proposed in the literature. Many of them are set up as linear optimization models to be solved with *linear programming (LP)*. They are also known as *LP models*.

The following shows a simple LP model taking market, warehouse, and capacity constraints into account. The objective is to compute the quantities of all products to be produced within the given period (e.g., 1 year) so that the total contribution margin is maximized. To keep the model simple, the planning period is not divided into subperiods (e.g., months). This means that only the total quantity of each product for the entire period is computed, not the distribution across the subperiods.

Objective function

$$Z = \sum_{i=1}^n (p_i - c_i)x_i \text{ max.}$$

Constraints

$$x_i \leq q_1$$

$$x_n \leq q_n$$

$$\sum_{i=1}^n s_i x_i \leq w$$

$$\sum_{i=1}^n r_{i1} x_i \leq a_1$$

$$\sum_{i=1}^n r_{im} x_i \leq a_m,$$

with

Z = objective function (contribution margin)

x_i = quantity of product type i ($i = 1, \dots, n$)

p_i = sales price per unit i

c_i = variable cost per unit i

q_i = maximum quantity of product type i that can be sold

s_i = storage place needed per unit i

w = total warehouse capacity

r_{ij} = required capacity of operating facility j per unit i

a_j = total available capacity of operating facility j ($j = 1, \dots, m$)

Based on this simplified model, a number of extensions have to be made to represent more realistic planning situations. For example, since MRP has a granularity of quarters, months, or weeks, the total planning period has to be split up into subperiods. This introduces a large number of additional variables and constraints. Furthermore, constraints should be considered not only on the selling market side but also on the buying market (procurement) side. A number of additional modifications are necessary to tune the model. Altogether, this means that the model size grows, and the computability decreases.

Forecasting Methods Instead of optimizing the master production program, most ERP systems offer methods to *forecast* the future demand of end products to be produced. This means that the production program is not set up according to an optimality criterion, but by carrying the planning of the past forward into the future. Common forecasting methods include moving averages and exponential smoothing.

The *moving averages* method computes an average of the past n periods to predict what the demand of the product under consideration in the next period will be. Suppose the current period is $k-1$. Let m_j be the demand that actually occurred in period j and v_k the forecast for period k . Then, v_k is the average of the n most recent actual demands, that is, from period $k-n$ to $k-1$:

$$V_k = \frac{1}{n} \sum_{j=k-n}^{k-1} m_j.$$

This method is called “moving” because one period later, the average of actual demands now includes period k , but not $k-n$, that is, it goes from $k-n+1$ to k . Two periods later, the average refers to periods $k-n+2$ to $k+1$, etc.

Even though the moving averages method is extremely simple, it allows for slower or faster adaption to changing demand. If the parameter n is stipulated with a small value, then demand variations are quickly reflected in the forecast. If n is large, fluctuations are leveled, and outliers do not much affect the forecast.

In the following example, actual demand values from 6 past periods are given. Suppose n is 5 and we want to predict the demand for period 10.

Period j	...	4	5	6	7	8	9	10
Demand m_j	...	100	90	118	110	105	97	–

Computing the forecast for this period yields $v_{10} = 104$. If one period later we know that the actual demand in period 10 was 100, we can compute the forecast for the next period, resulting in $v_{11} = 106$.

Exponential smoothing is a method that can be configured to give recent demand fluctuations more weight than earlier ones. The forecast value v_k is easily calculated: It is equal to the previous forecast v_{k-1} plus the weighted deviation of the actual demand m_{k-1} from this forecast:

$$v_k = v_{k-1} + \alpha(m_{k-1} - v_{k-1}).$$

The weighting factor α is the parameter to influence the method’s behavior. α can be stipulated with a value between 0 and 1. If α is close to 1, the forecast will be close to the actual demand in period $k-1$. This means that the forecasting

immediately follows demand fluctuations. The opposite is true for a small α . This can be seen by setting α to 0. In this case, demand changes have no effect at all. The next forecast is the same as the previous one.

Between the two extremes, there is a range of possibilities to take recent demand values into account with great or with little weight ($0 < \alpha < 1$). In this way, the demand curve is smoothed to reflect demand variations either more or less quickly.

The table below illustrates the effect of different α values. Starting with period 6 ($v_5 = 100$), v_6 is 98 if $\alpha = 0.2$ but only 92 if $\alpha = 0.8$. Obviously, the drop in actual demand—forecast v_5 is 100 but actual demand m_5 is only 90—is reflected more immediately when α is larger.

Exponential smoothing as described above causes the forecasts to follow demand variations, but not all extreme movements (except if $\alpha = 1$), with a time lag. This is acceptable if there are ups and downs in the actual demand, but if all demand changes go in one direction, it may be preferable to catch up with the trend faster.

This can be achieved by smoothing not only the demand variations but also the forecast variations. Let

$${}^2v_k = \text{second-order forecast}$$

$${}^1v_k = \text{first-order forecast.}$$

The forecast from second-order exponential smoothing is obtained by first computing the first-order forecast 1v_k as before, then computing the weighted deviation of the previous period’s second-order forecast ${}^2v_{k-1}$ from 1v_k and adding this deviation to ${}^2v_{k-1}$:

$${}^2v_k = {}^2v_{k-1} + \alpha({}^1v_k - {}^2v_{k-1}).$$

Period j	...	4	5	6	7	8	9	10
Actual demand m_j	...	100	90	118	110	105	97	–
Forecast v_k								
For $\alpha = 0.2$		–	100	98	102.0	103.6	103.9	102.5
For $\alpha = 0.8$		–	100	92	112.8	110.6	106.1	98.8

In this way, the demand variations are smoothed twice. As a consequence, the forecasts are adapting faster to the actual demand curve, provided that the trend goes in one direction (i.e., continuously increasing or decreasing).

2.2.2 Planning for Customer Orders

Many companies today produce goods according to specific customer orders instead of according to an abstract production program. The previous section showed how a master production plan based on anonymous demand can be created. Now we will discuss what a customer-oriented manufacturing company has to do to determine their primary requirements.

Companies relying in their planning on customer orders are said to pursue *make-to-order production*. The majority of small and medium-sized manufacturing companies work in a make-to-order style. These companies, unlike make-to-stock manufacturers who produce standard goods to be stocked and sold from the warehouse, produce their goods when customers order them. This often implies that the customer specifies what the goods should be like (i.e., the product specification is provided by the customer).

Make-to-order production is common in the investment goods sector (e.g., machine tools, production facilities, cranes, and elevators). Typical make-to-stock manufacturers are found in the consumer goods sector (e.g., television sets, washing machines, and lamps). However, many consumer goods nowadays are made to order as well (e.g., cars and personal computers).

Primary requirements planning in make-to-order production is quite different from make-to-stock production. Instead of optimizing or forecasting a standard production program, all activities are related to specific customer orders. Typical tasks include scheduling the customer order to obtain a delivery date, designing the product the customer wants, calculating the cost of the product, making a quotation, etc.

Make-to-order production is not a uniform approach but includes a wide range of options.

These options differ in the degree to which the planning, execution, and controlling actually depend on the customer order or are independent of the order.

For example, a customer may request an end product that needs to be designed in a specific way. This does not necessarily mean, however, that all parts going into that end product must be designed from scratch. Instead, the company will try to use as many standard parts as possible to cut costs. In another company, the situation may be different, requiring the company to manufacture not only the end product but also assemblies and individual parts specifically for the customer.

Thus, the spectrum of make-to-order production ranges from production types close to make-to-stock to one-time individual production, including the following levels:

- *Variant production*—customers can order variants of a basic product as discussed in Sect. 2.1.2.
- *Assemble-to-order*—customer-specific products are assembled from standard parts and subassemblies.
- *Subassemble-to-order*—customer-specific end products as well as customer-specific assemblies are made from standard subassemblies and parts.
- *Individual make-to-order*—in principle, all in-house-production parts of a customer-specific product are manufactured to the customer order.
- *Individual-purchase-and-make-to-order*—all parts needed for a customer-specific product (both in-house production and procured parts) are manufactured and purchased to the customer order.
- *Individual one-time production*—this is a special case of the two previous variants, meaning that the product is only produced once in this form as now specified by the customer (e.g., a ship).

Requirements for Make-to-Order Production Make-to-order production gives the customer a prominent role, in contrast to make-to-stock production where customers are not directly involved.

An important objective for the company is to satisfy the customer. Happy customers will return in the future and place more orders, which pays more for the company in the long term than minimizing production cost or maximizing capacity utilization.

Consequently, the goals of make-to-order production focus on *customer satisfaction*. Essential subgoals for production planning are short lead times, strict adherence to deadlines and delivery dates, high product quality, and flexibility regarding customer wishes. Pursuing these subgoals often increases the cost (e.g., overtime work, machine idle times, and air freight). A make-to-order manufacturer will normally accept this increase because the consequences of losing or disappointing the customer are considered to be more severe.

Another requirement in make-to-order production is that the status of all manufacturing orders connected with the customer order is available at all times. When the customer inquires about their orders, the sales employee must be able to find out on click what the current status is. Whenever problems in the plant occur that affect the customer order (e.g., a bottleneck machine breaks down), the sales employee must be immediately informed.

A precondition for employees to be well informed at any time is transparency of the manufacturing processes. This requires, for example, that all connections between manufacturing and purchase orders related to a customer order are explicitly stored. Likewise, all operating facilities involved must be identified. When all connections are available, it is possible to track the consequences of a problem occurring anywhere in the order network and to find out whether the problem will have an impact on the customer order. In other words, an ERP system suitable for make-to-order manufacturers has to create and maintain all connections between the relevant manufacturing entities.

The ERP system should also be able to work with incomplete master data. This problem has already been addressed in Sect. 2.1.4 above. Working with incomplete master data means that the ERP system can still perform material

requirements planning, lead-time scheduling, and capacity planning, even though some of the underlying data structures (e.g., bills of materials and routings) are not complete or even missing. Obviously, the planning results will not be of the same quality and certainty as if they were based on complete data, which is the case in make-to-stock production.

Nevertheless, a make-to-order manufacturer also needs to plan the production, but the conditions under which the planning takes place are different from those a make-to-stock manufacturer is exposed to. Three crucial planning steps are:

- Order calculation
- Order scheduling
- Rough-cut planning

In contrast to make-to-stock production, most make-to-order manufacturers do not have a reliable, cost or profit-based production program from which they can derive the primary requirements. Therefore, they have to go other ways to determine favorable primary requirements that are in line with the company's cost or profit goals.

Two important decisions to make in this process are whether a customer order should be accepted and for what price. In order to be able to negotiate a reasonable selling price, the company needs to know the *cost* of the order.

Accordingly, *order calculation* (precalculation of a customer order) is of utmost importance. Cost calculation is normally based on master data such as parts, bills of materials, routings, and operating facilities (cf. Sect. 3.7.1). If these data are not available, it is difficult or impossible to reliably calculate the cost of a prospective order. Nonconventional approaches have to be applied to obtain even rough cost data (cf. Sect. 3.7.2).

A problem similar to order calculation is *order scheduling*. Scheduling is necessary to be able to agree on a delivery date with the customer. Normally, orders are scheduled using bills of materials and routings, with feasibility of the schedule being established based on capacity data (cf. Sects. 3.3 and 3.4). When these data are not available, other procedures to arrive at a plausible delivery date must be in place.

An important prerequisite for smooth manufacturing conditions in make-to-order production is a good *rough-cut planning*. Since many factors are still unknown, it is not possible to plan the customer orders in detail. Therefore, it is important to at least balance the overall material and capacity situation. If this balance can be established, it is possible later to schedule customer orders without (or with fewer) problems. This is, by the way, one of the fundamental ideas of manufacturing resource planning (MRP II, cf. Sect. 3.2), even though MRP II is targeted more toward make-to-stock than make-to-order production.

Product Specification End products in make-to-order production are typically not standard products but new or at least different products. Because the decisions mentioned above concerning price and time can only be made once the product is “known,” one of the initial steps in the order fulfillment process (cf. Sect. 4.3.2) is to create a specification of the product in the ERP system. This may be done by adopting the customer’s product specification (if they already have one), by creating a specification from scratch and/or by interacting with the customer, in order to derive the specification together.

A product specification is necessary to check the feasibility of the customer’s product idea against the company’s technological capabilities before the customer order is accepted. It is also needed to create order-specific master data such as bills of materials and routings, based on which material and capacity planning can be performed.

One relatively easy way to specify a customer-dependent product is to employ *product variants* as discussed in Sect. 2.1.2. This method, however, is only applicable when the product ordered by the customer is within the given spectrum of variants.

Product configuration goes one step farther than variant management. A *product configurator* is a program that allows a knowledgeable user to put together a product interactively from a set of given components. The program checks which

combinations of assemblies, individual parts, and possibly raw materials are permitted and may recommend especially beneficial combinations.

When complex products are involved, there may be many rules and regulations that have to be considered. Human experts configuring these products are aware of the rules and regulations that may apply. A good product configurator produces results that come close to those of the human experts or in some cases even exceed them.

Product configuration was one of the first domains in which *knowledge-based systems*, especially *expert systems*, were successfully applied. The first configuration systems were developed in the 1980s for putting together computer systems, such as Digital Equipment’s XCON [also known as R1 (McDermott 1981)]. These were followed by a large number of configurators for a variety of products (turbines, elevators, roller blinds, etc.).

Today, configuration systems are very common in *electronic commerce*, allowing customers to select which features of the product they prefer. The configuration program in the background checks whether the selected combination of features is feasible or allows the customer to select only those features that may be combined.

Product configurators can appear as separate systems or be integrated in an ERP system. Typical functionality of an interactive configuration module includes (Hüllenkremer 2003):

- Configuration on the basis of rules
- Immediate notification whether a selection option is permissible
- Automatic explanation of configuration errors
- Suggesting permissible or beneficial alternatives
- Graphic display of the product configuration, allowing the user to directly manipulate the graphic
- Integrated technical computations
- Simultaneous price calculation
- Automatic generation of a quotation (including terms and conditions)
- Internationalization and localization (multilingual settings, different currencies)

- Checking availability and delivery dates with the help of ERP functions
- Automatic preparation and transmission of order data to the ERP system, in case a stand-alone configuration system is used

A product configurator embedded in an ERP system or with interfaces to the ERP system has many advantages. For example, while in the field a sales representative can create and check a product specification together with the customer. Connecting her laptop to the ERP system in the headquarters, she can check immediately whether the configuration is reasonable, how much it costs and when the product will be available. In order to do so, she does not even need specific expertise, because the required knowledge is available in the expert system on her laptop. Based on the configuration result, she can immediately give the customer a quotation and confirm the delivery date.

Product configurators are often connected with *electronic product catalogs*. An electronic product catalog is a digital form of a printed catalog, containing information about products and prices. Today's electronic catalogs offer a wide spectrum of additional functions, for example, advanced searching options. Often the catalog is part of a web shop, which again is connected with an ERP system. In this way, the customer can select products from the product catalog, put them in a shopping cart, and complete the transaction by paying for the products.

If the products are not standard but configurable, the customer is redirected to the product configurator. The product configurator will not only help the customer to put the product together but also calculate the product price depending on the selected options. Afterward, the customer can place the configured product in the shopping cart and proceed to checkout.

2.3 Planning Primary and Secondary Requirements

Primary requirements are derived from the master production plan. Usually, they refer to

end products, but other sellable goods (such as spare parts and assemblies) can also be involved. They are the starting point of material requirements planning.

The core of MRP is planning the *secondary requirements*. Secondary requirements refer to the intermediate products, raw materials, and consumables needed to produce the primary requirements.

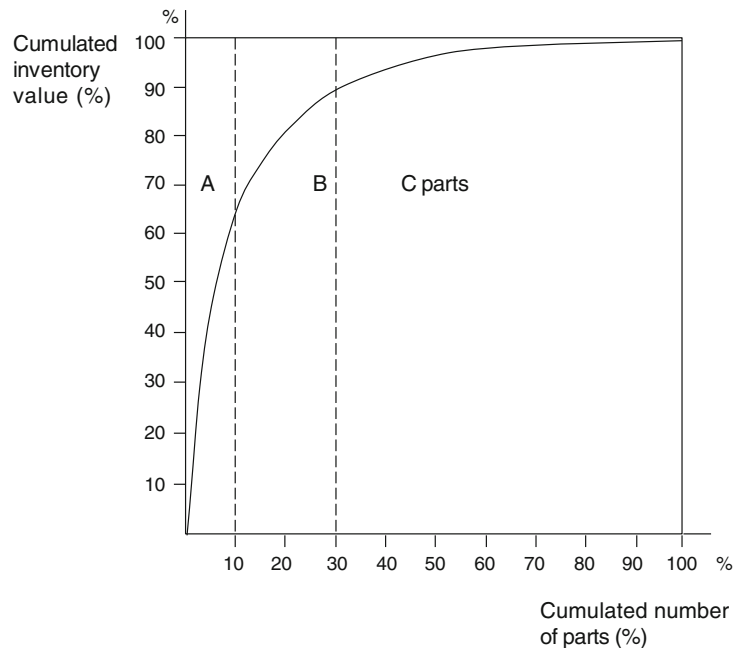
The main task of secondary requirements planning is to compute the quantities of these materials. This task is closely related with a number of other areas such as procurement and inventory management.

Procurement is relevant because a good deal of the parts needed for the end products have to be purchased from suppliers. Procurement takes time, just as in-house production does. This must be taken into account in scheduling the secondary requirements. Procurement will be discussed in Sects. 4.3.1 and 5.3.2.

Inventory Management Inventory management goes hand in hand with requirements planning because quantities available on stock obviously do not have to be manufactured. Computing the *available stock* depends on what types of stock are kept and how refined the inventory management system is. Typical categories of inventory to be considered include the following:

- *Physical inventory*—the quantity of a part that is actually in the warehouse today
- *Shop-floor stock*—the quantity of a part waiting to be processed in the workshop(s)
- *Reserved stock*—the quantity of a part that is reserved for a customer/manufacturing order and thus not available for planning
- *Open order quantity*—the quantity of a part that has already been ordered from the factory (production orders) or from suppliers (purchase orders)
- *Reorder level*—the quantity of a part that causes a new order to be issued when the stock falls below this quantity (taking into account that the reordering takes time)
- *Safety stock*—the minimum quantity of a part the stock should not fall short of for safety reasons

Fig. 2.22 Typical result of an ABC analysis



ABC Analysis The number of parts materials management has to deal with can be very large. The examples given in Sect. 1.5 exhibited figures up to 350,000 parts.

Not all parts are equally important. Some parts represent high values, causing substantial inventory and capital costs. Other parts are cheap, leading to rather insignificant inventory cost. From a business point of view, this means that excess inventory should be avoided as far as expensive parts are concerned but could be tolerated when the parts are cheap.

An approach to discriminate between important and less important parts is called *ABC analysis*. This name indicates that categories A, B, and C are used to classify all parts managed in the company, depending on their value. In order to do so, the inventory value of each part within a given period has to be determined. Then the parts can be arranged according to their value.

The result of arranging the parts is often plotted in the form of a so-called *Lorenz curve* as shown in Fig. 2.22. When doing an ABC analysis, many organizations realize that:

- A small percentage of their total part numbers (e.g., 10 %) account for a substantial share of

the total inventory value (e.g., 65 %)—these are the *A parts*.

- Another ca. 20 % of the parts account for approximately 25 % of the value—these are the *B parts*.
- The largest percentage of parts (e.g., 70 %) accounts for only a small share of the total value (e.g., 10 %)—these are the *C parts*.

Since the A parts are expensive, causing high cost, it is essential that the requirements of these parts are carefully planned, using precise methods in order to avoid unnecessary inventory and shortage costs. Shortage cost would occur when not enough parts are available, leading to a disruption of the production process.

On the other hand, the C parts are less critical. Additional inventory to provide for safety buffers is acceptable because the additional inventory cost is low. Therefore, C parts can be planned with less precision using simpler methods.

For *secondary requirements planning*, two basic approaches exist, differing with regard to computation time and accuracy of the results. These approaches are:

- Consumption-driven (stochastic) planning
- Demand-driven (deterministic) planning

Consumption-driven planning is fairly simple but not exact, whereas requirements-driven planning is exact, but requires a lot of computing effort. Taking these characteristics into account, many companies choose to employ the two approaches as follows:

- A parts are planned in a requirements-driven way.
- B parts are also planned requirements driven or partly requirements and partly consumption driven.
- C parts are planned consumption driven.

2.3.1 Consumption-Driven Planning

Consumption-driven planning involves estimating the secondary requirements based on past consumption rates, whereas requirements-driven planning calculates the exact amounts using the bills of materials.

The same methods used to forecast end-product sales can be used to predict future material requirements: moving averages, exponential smoothing, etc. If the forecast value applies to an entire period (e.g., a quarter) and consumption is constant per unit of time, a *consumption rate* can be calculated by dividing the forecast value by the length of the period. This quotient is also known as the *withdrawal rate*.

After the forecasted requirements have been determined, two other issues need to be addressed:

1. When should a purchase order be placed (for purchased parts) or a production order be initiated (for in-house production)?
2. How much should be ordered or produced?

Both questions are interrelated. Shorter time intervals between orders lead to smaller order sizes and vice versa. In practice, the *order date* is often determined by using the reorder point R . When the inventory falls below this level, an order for a certain quantity (usually named Q) is initiated. In inventory theory, this is referred to as an (R, Q) policy (“reorder point/order-quantity policy”).

Another order policy is the (s, S) policy, also known as *periodic review policy*. In this policy,

two numbers, s and S , are used. When the inventory is less than or equal to s , the difference between a predefined maximum order quantity S and the inventory on hand is ordered (Nahmias 2008, p. 263).

When using an (R, Q) policy, it is important to set the reorder point high enough so that the safety stock is preserved until the new order arrives. The most important factor in determining the reorder point is the *replenishment time*. It includes (Mertens 2009, p. 76):

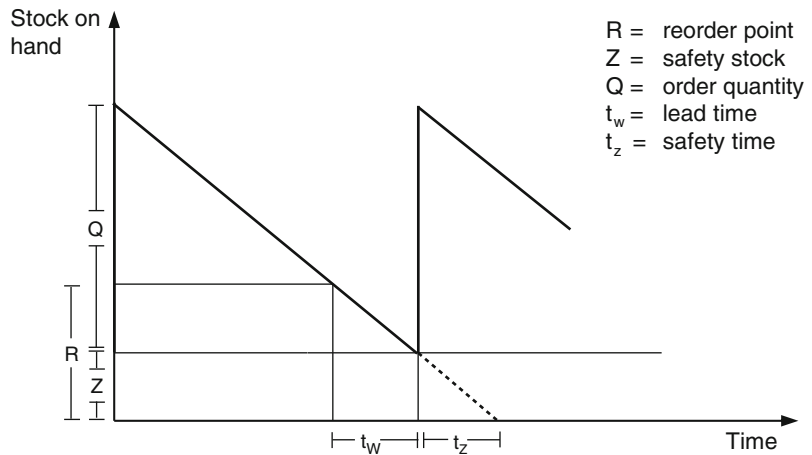
- Preparation time (preparation of a purchase order or production order)
- Delivery time (for purchased parts) or lead time (for in-house production)
- Storing time (time from goods received to goods available for consumption)

The relationship between these times is depicted in Fig. 2.23, assuming a linear decrease in inventory. If t_w represents the replenishment time, then an order must be placed when the stock level reaches R . The period of time t_z serves as a buffer. Assuming the same constant withdrawal rate, the production process will not be affected by delivery delays shorter than t_z .

The reorder point can be saved with the parts’ inventory or master data in the database, as long as the withdrawal rate is more or less constant. When a withdrawal is booked, the remaining stock is compared with the reorder level. If the remaining stock is below the reorder level, an order is initiated. When there is a great deal of fluctuation in the consumption, the reorder level should not be maintained as a constant but determined period by period to avoid unnecessary stock or shortages.

The risk of running short of inventory can to some extent be countered with *safety stock*. It is important to set the safety stock at an appropriate level. A large safety stock means better protection from risk but leads to high inventory cost. A small safety stock means less inventory cost but a higher risk that missing material will disrupt the manufacturing process. How much safety stock is appropriate must therefore be determined by balancing the cost of inventory and the willingness to take risks.

Fig. 2.23 Inventory level with constant withdrawal rate



Calculating Order Quantities In addition to reorder levels and order dates, the quantities to be ordered from suppliers (procurement) or from production planning (in-house manufacturing) have to be calculated. The term *order quantity* stands both for the size of a purchase order and the size of a manufacturing order. In the context of inventory theory, manufacturing orders are usually called production lots, and the quantity is referred to as the *lot size*.

We will mostly be using the terms *order* and *order quantity* to refer to both purchase orders and manufacturing orders. Both cases are similar in that an order is placed—either with a supplier or with the company’s production department.

Although purchase orders refer to external procurement and production lots to in-house production, in principal, the same methods can be used. In both cases, conflicting cost relationships are in play, and a decision maker must try to size the purchase order or the production lot in a way that keeps the cost at a minimum. With externally procured parts, this quantity is called the “optimal order quantity” (or “economic order quantity”), whereas for in-house produced parts, the term “optimal lot size” (or “economic lot size”) is used in the literature. A *lot* (or production lot) is the amount of parts that are produced together.

In the past, many models and methods have been proposed to calculate the optimal lot size. An evaluation of 30 inventory and lot-sizing models based upon comprehensive simulation

experiments can be found in Knolmayer (1985). The 1960s in particular experienced a boom in lot-size research.

In practice, however, only a handful of the research findings have been implemented. Real manufacturing processes are extremely complicated and very difficult to represent in mathematical models and calculations. Only few approaches have made their way into today’s ERP systems, namely:

- Fixed period requirements
- Economic order quantity (economic lot size)
- Moving reorder quantity
- Part-period algorithm

Fixed Period Requirements This method is not concerned with calculating any optimal quantities. Instead, the order quantity is set to a fixed value. This value can be saved in the part master data.

Economic Order Quantity The best-known method for calculating an optimal order quantity goes back to the beginning of the twentieth century. It was made popular by several authors—K Andler, FW Harris, and RH Wilson. It is also known as the *root formula*.

This method assumes that the requirements of a planning period (e.g., 1 year) are known and constant over time. During the planning period, the requirements are the same for each time unit (e.g., a day). Parts are withdrawn from the warehouse at a constant rate. The goal of the method

is to minimize the sum of the fixed and variable (i.e., quantity dependent) costs within the planning period. *Variable cost* is the cost depending on the size of the order, most of which is inventory cost. *Fixed cost* is independent from the order quantity. For in-house production, this is primarily the setup cost.

Under the preconditions of this model, the optimal order quantity is computed by minimizing a cost function. Let

K_1 = the total quantity dependent cost

K_r = the total fixed cost in the planning period

k_1 = variable (quantity dependent) cost per unit and period

k_r = fixed cost per order

a = frequency of placing an order within the planning period

T = length of the planning period

y = total demand in the planning period

x = order quantity

Then the total fixed cost is

$$K_r = ak_r$$

or, because $a = y/x$,

$$K_r = y/xk_r.$$

Assuming a constant stock withdrawal rate, the average stock is $x/2$, and thus, the total variable cost amounts to

$$K_1 = x/2k_1T.$$

Depending on the order quantity x , the total decision relevant cost K is

$$K(x) = K_r + K_1 = y/xk_r + x/2k_1T.$$

The minimum of this function, differentiated by x , is

$$x = \sqrt{\frac{2k_r y}{k_1 T}}.$$

x is the *optimal order quantity* (or “optimal lot size,” “economic order quantity,” and “economic lot size”). In order to meet the demand, x must be ordered a times within the planning period. From $a = y/x$ follows

$$a = \sqrt{\frac{yk_1 T}{2k_r}}.$$

Although x is called an “optimal” order quantity, this optimum can be achieved only under restrictive premises, including the following:

- No capacity restrictions are in place regarding the delivery (of externally procured parts), production (of in-house produced parts), and inventory capacities.
- The demand for the entire planning period is known.
- The demand is the same for all periods. The withdrawal rate is constant for all periods.
- The cost price (or the production cost, resp.) per unit is given and independent of the quantity.
- In the case of in-house production, the product is not connected with other parts on higher or lower manufacturing levels, or if so, these connections can be disregarded.

Although in practice these premises are seldom met, the root formula is still acknowledged in inventory theory and remains one of the options available in most ERP systems.

Moving Reorder Quantity Unlike the economic order quantity, the moving reorder-quantity (MRQ) method does not assume that the demand is the same for all (sub) periods across the entire planning horizon. Instead, different demand values per period are considered.

The MRQ method approximates the minimum of the total cost per unit. For a single demand y_j to be met in period j , which is procured or produced in period i ($i \leq j$), the *inventory cost* for storing the quantity y_j amounts to

$$k_1 y_j (j - i).$$

Combining the demands of the periods i to t ($i \leq t$) into one order results in inventory cost of

$$k_1 \sum_{j=i}^t y_j(j-i).$$

The total cost of periods i to t , K_{it} , is then

$$k_{it} = k_r + k_1 \sum_{j=i}^t y_j(j-i).$$

and the cost per unit is

$$k_{it} = \frac{k_{it}}{\sum_{j=i}^t y_j}.$$

The moving reorder-quantity method proceeds step by step, adding up period demands one by one until k_{it} has reached its minimum. In other words, we are looking for that value of t for which

$$k_{it} < k_{it+1}$$

if one more demand (y_{t+1}) were added. Once the value of t has been determined, the optimal order quantity is

$$x = \sum_{j=i}^t y_j.$$

The moving reorder-quantity method is suitable in practice when the demands of all periods and the cost coefficients k_r and k_1 are known. It does, however, have the disadvantage that minimizing the cost per unit is not necessarily the same as minimizing the total cost of a planning period.

Part-Period Algorithm The part-period algorithm attempts to minimize the cost per order (DeMatteis 1968). It builds on a property of the classical economic order-quantity model, namely, that in the optimum, the inventory cost K_1 and the fixed cost K_r are equal. This can be

seen by setting the first derivative of the cost function

$$K(x) = y/x \cdot k_r + x/2 \cdot k_1 T$$

to zero, resulting in

$$y/x \cdot k_r = x/2 \cdot k_1 T.$$

The left side of the equation has the fixed cost K_r , while the right side has the inventory cost K_1 .

The part-period algorithm applies this property to a situation where the demand is not continuous, as in the economic lot-size model, but discrete (i.e., individual period demands). In the part-period algorithm, the optimum is approximately reached when an order's inventory cost equals its fixed cost:

$$k_1 \sum_{j=i}^t y_j(j-i) = k_r$$

A transformation of this equation to

$$\sum_{j=i}^t y_j(j-i) = \frac{k_r}{k_1}$$

shows that both sides have the dimension "quantity multiplied by periods" (or "number of parts multiplied by number of periods"), hence the name of this method.

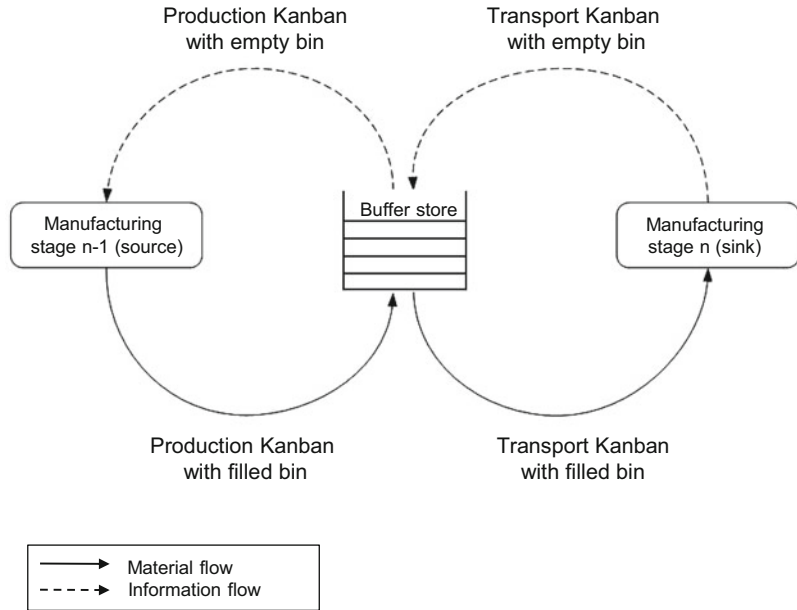
Just as in the moving reorder-quantity method, the algorithm proceeds by successively adding period demands y_t and examining whether or not the left side is still less than the right. Once

$$k_1 \sum_{j=i}^{t+1} y_j(j-i) > k_r,$$

the optimum has been passed. Hence, the optimal order quantity is

$$x = \sum_{j=i}^t y_j.$$

Fig. 2.24 Kanban control cycle (Loos 2011)



To conclude this subsection on optimal order quantities, it is worth noting that the “optimum” is not very sensitive to changes. For example, it does not make much difference whether the fixed and quantity-dependent costs are exactly the same or not. Specifically, increasing the quantity has less effect on the cost than decreasing it. In the economic order-quantity model, the cost increases only by 8 % when the order size increases by 50 % or decreases by one third. For the iterative methods (moving reorder-quantity and part-period methods), this means that it may be acceptable to just add another demand in order to reduce the risk of shortages.

In many companies, optimization of the order sizes is not of central importance, because the costs that can be influenced make up only a relatively small percent of the total production cost.

Excursus: Kanban A special form of consumption-driven requirements planning is based on the *Kanban* principle. Kanban is a Japanese word for a signboard or a card used to indicate something. The Kanban principle stands for a just-in-time form of decentralized control where the consumption of material drives the

replenishment of inventory from the source that provides the material.

Applied to production planning and control, the Kanban principle is used to harmonize the flow of parts between two subsequent manufacturing stages and the production of parts. When demand is recognized in stage n , supply from stage $n-1$ is requested. This is accomplished by using *Kanban cards*.

Figure 2.24 illustrates the basic idea with the help of two manufacturing stages communicating through Kanban cards and transport bins. Two types of cards are used in this system: production Kanbans and transport Kanbans.

A *production Kanban* is attached to a bin containing material that is brought from stage $n-1$ to the buffer store located in front of stage n . The transporter leaves the production Kanban behind in the buffer store.

When stage n needs material for its operations, a bin with a *transport Kanban* attached is taken from the buffer store and brought to the manufacturing site. When the buffer is depleted or when a certain number of production Kanbans have accumulated in the buffer store, the Kanbans are returned to stage $n-1$, thereby initiating the production of more parts to eventually fill up the buffer store.

In case stage $n-1$ runs short of parts needed for the production, demand is communicated to stage $n-2$, using the production Kanbans in the buffer store in the front of stage $n-1$. This continues all the way to the raw-material stage. In this fashion, the entire manufacturing chain, from the last stage to the first, is organized according to the “pull principle,” demanding supply when it is actually needed.

Conventional MRP and MRP II planning, on the other hand, relies on the “push principle,” meaning that supply is provided to stage n by stage $n-1$ according to previously planned demand and not to actual demand.

Kanban was originally developed by Toyota as a manual approach to lean production (Ohno and Bodek 1988). Meanwhile, electronic versions have been implemented in a number of ERP systems, sometimes called “e-Kanban.” Instead of paper cards, they employ electronic media using barcodes or RFID tags (cf. Sect. 11.4.1).

Kanban works best when the flow of production is smooth and uninterrupted, as can be the case in series or mass production. Kanban is actually a means of fine-tuning smooth production. Conditions under which the Kanban approach has proved to be beneficial include the following (Takeda 2006, pp. 185–189):

- Standardized production program, using standard parts as much as possible in order to realize continuous consumption
- Production organization according to the material flow
- Effective transportation system, short transport times
- Small lots (lot size is in fact the amount of parts that fit into one or more bins)
- High availability of operating facilities, short changeover times
- Low defect rate through immediate quality assurance at the workplace

Kanban systems exist in different versions and are used for different purposes. Some applications utilize more or fewer types of Kanbans instead of the two described above. This is the case when external suppliers are included. The most successful applications of Kanban have

been reported from supply chains of the Japanese automotive industry.

2.3.2 Requirements-Driven Planning

While consumption-driven planning focuses on assumptions and estimates, requirements-driven planning is based on certainty. Therefore, it is also called *deterministic planning*. As long as the primary requirements are as expected, the secondary requirements can be calculated exactly. For this purpose, product structures (bills of materials) are employed to determine the quantities of subordinate parts needed to produce the primary requirements.

Using bills of materials to determine the secondary requirements is also known as *bill of materials explosion*. Programs exploding bills of materials are called *bill of materials processors (BOM processors)*. A BOM processor is a core component of any MRP system.

Whereas consumption-driven planning treats each part separately, requirements-driven planning must take into account how the parts are related with each other. Because of the hierarchical relationships within the product structures, decisions made on a higher level affect the lower levels as well.

When in Fig. 2.25, for example, the lot size of assembly A is doubled, the secondary requirements for parts that go into this assembly (D and E) are also doubled. On the other hand, if assembly C is still stocked, less of C needs to be produced and also less of all other parts that go directly or indirectly into C (i.e., G, H, I, and J).

This example clearly shows that in requirements-driven planning, calculating gross and net requirements and building lot sizes are closely connected. Principally, each of the following tasks must be completed for every part, before the next part is dealt with:

1. Gross requirements planning
2. Net requirements planning
3. Order-size planning
4. Dependent requirements planning

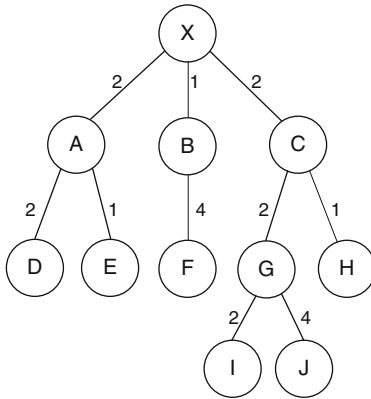


Fig. 2.25 Product structure (example)

5. Forward shifting

When dealing with a leaf of a product structure tree, the last two tasks are omitted.

Gross Requirements Planning For *end products* and sellable intermediate products, planning the gross requirements starts from the primary requirements as determined in primary requirements planning (cf. Sect. 2.3.1). For *dependent parts*, the starting point is the secondary requirements derived from higher-level nodes of the product hierarchy. In addition to these quantities, other components may be added, for example, requirements for replacement parts and estimates based on seasonal consumption patterns.

Net Requirements Planning To determine the net requirements, *available stock* must be subtracted from the gross requirements. Parts planned according to the requirements-driven approach may still be stocked, for example, when inventory orders were included in the plan (i.e., internal orders filling gaps in the capacity utilization), when the gross requirements include consumption-driven components, or when unneeded buffers are left over (e.g., for a previous order, more than the actually needed quantity was produced).

Depending on how differentiated the warehousing structure is, safety stock, shop-floor stock, reservations, and open purchase orders may be taken into consideration. If waste is

anticipated, the net requirements must be multiplied by the expected waste factor.

A detailed scheme for planning gross and net requirements is shown in Fig. 2.26 (Mertens 2009, p. 133). It contains sample data for the above-mentioned factors, divided into periods.

Order-Size Planning When the net requirements for a certain number of periods are known, they can either be directly used for planning the requirements on the next level or they can be bundled into *production lots*. In Fig. 2.26, the net requirements from periods 2, 3, and 4 have been combined into one lot (2,208 units) and the net requirements from periods 5 and 6 into another lot (1,887 units).

Order quantities may also be computed for externally procured parts. However, the steps following order-size planning—derived requirements planning and forward shifting—are obviously not applicable to purchased parts. Instead, purchase orders are created and order placement is initiated.

For lot-size planning, basically the same methods as described above are used. From a theoretical standpoint, this is problematic because the presumptions on which the “optimality” of a lot size is based are largely not met. In particular, computing lot sizes without considering the connections with other parts can cause problems later on. The quantity of a lot on a given level of a product structure affects the planning of all parts on the lower levels. This problem will be explored in more detail with the help of Figs. 2.27 and 2.28 below.

Dependent Requirements Planning This process step starts from the production lots computed in step 3. Using the product structures of the parts involved, it derives dependent (or secondary) requirements. Multiplying the lot size with the quantity coefficients results in the quantities of those parts directly needed for the current part.

As an example, let us assume that the planning shown in Fig. 2.26 was for assembly C

Fig. 2.26 Gross and net requirements planning [Mertens 2009, p. 133]

Period		1	2	3	4	5	6
Total dependent requirements for one assembly (from BOM explosion)		700	550	1300	800	900	700
+ Consumption-driven demand		270	400	300	140	340	250
+ Independent requirements (replacements)		130	200	100	60	160	50
= Gross requirements		1100	1150	1700	1000	1400	1000
Warehouse stock	3000						
- Safety stock	300						
- Reserved stock ^{a)}	900						
= Available stock	1800	1800	700		300	600	
Open production-order quantity	900						
- Forecasted rejections	90						
- Inflow from recycling			50			100	
= Available stock from production order	810			450	360		
= Net requirements	-	400	1250	340	700	1000	
+ Additional requirements for scrap (10%, factor 0.11)		-	44	137	37	77	110
= Extended net requirements	-	444	1387	377	777	1110	
Lot sizing		-	2208	-	-	1887	-

^{a)} This reserved stock is released to available stock in periods 4 and 5.

Exact requirements for further planning/explosion

Fig. 2.27 Derived requirements and forward shifting with lot sizes

Period	1	2	3	4	5	6
Net requirements C (after lot-size planning)	-	2208	-	-	1887	-
Dependent requirements G	-	4416	-	-	3774	-
After forward shifting	4416	-	-	3774	-	-
Dependent requirements H	-	2208	-	-	1887	-
After forward shifting	2208	-	-	1887	-	-

Fig. 2.28 Derived requirements and forward shifting without lot sizes

Period	1	2	3	4	5	6
Net requirements C (no lot sizing)	-	444	1387	377	777	1110
Dependent requirements G	-	888	2774	754	1554	2220
After forward shifting	888	2774	754	1554	2220	-
Dependent requirements H	-	444	1387	377	770	1110
After forward shifting	444	1387	377	777	1110	-

of Fig. 2.25. Figure 2.27 continues the planning process, illustrating the dependent requirements for parts G and H.

Forward Shifting Although the focus of MRP is on planning quantities, the temporal structure of the production process is not completely disregarded. Taking into account that executing a production order takes a certain amount of time, the derived requirements needed for the order must be completed earlier by just that amount of time. This time is called a *forward shift* or *lead-time offset*. If, for example, the size of lot C is such that it takes 14 days to manufacture the lot, then all parts that go into C (H and G) must be available 14 days earlier than C, that is, the lead-time offset is 14 days.

The purpose of forward shifting is to give the material requirements plan a rough temporal structure. This, however, is not straightforward, because the actual manufacturing dates depend on decisions that are made later in the planning process. Therefore, rough estimates based on experience have to be used instead, depending on what information is available, how certain the expectations are, and how much computational effort is reasonable. Typical approaches are:

- The lead time is actually calculated, using the setup, transition, and processing times stored in the routing and operating facility data. This time is then used to shift the derived requirements forward (i.e., toward the present).
- The same forward shift is applied across the board for all parts of one manufacturing level. The lead-time offset can be determined, for example, from the average offset that was actually observed in the past.
- The same forward shift (e.g., one or two periods) is applied to all parts and all manufacturing levels.

The first approach is without question the most accurate, provided that the lead-time components can be predicted with sufficient certainty. Unfortunately, calculating a forward shift is often not feasible, because it

would basically require a complete lead-time and capacity-scheduling run. Therefore, many manufacturing companies use the same time span as lead-time offset for all parts of the same manufacturing level or even across all levels. The schema of Fig. 2.27 showed an example of a standard lead-time offset of one period.

When all steps of requirements-driven planning for the part under consideration have been completed, the same steps are applied to the next part, as long as the part is not a leaf of a product structure tree. In this way, roughly scheduled derived requirements are created for all parts. In one of the next rounds, for example, the tasks of gross and net requirements planning, lot-size planning, dependent requirements planning, and forward shifting will be executed for assembly G.

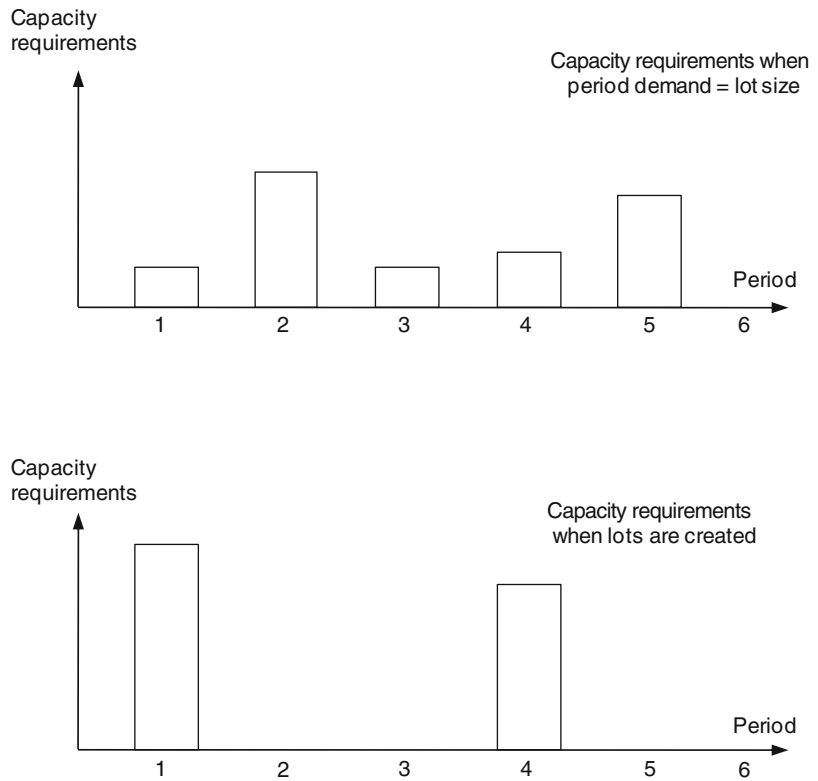
Impact of Lot-Size Planning When individual requirements on a higher level are bundled into lots, this changes the requirements and time planning of all lower parts, directly or indirectly.

To demonstrate the effect of lot sizing, we will take up the planning scheme shown in Fig. 2.26. If each period's requirement is produced as a separate lot (i.e., no specific lot sizing), the derived quantities and dates for parts G and H are as in Fig. 2.28, assuming a forward shift of one period. If, however, lots are planned, requirements for lower-level parts going into the current part move up in time. The required quantities are higher in some periods and nonexistent in others. This effect was illustrated in Fig. 2.27.

Another effect of lot-size planning is that assumptions are made regarding the availability of the operating facilities at the implied manufacturing dates. Not only the facilities needed for the current part but also those needed for the subordinate parts have to be available on the right dates so that the production can be completed on time.

To illustrate this effect, let us assume that part H needs only one machine and the capacity requirements are approximately proportional to the quantity. In this case, the allocation of

Fig. 2.29 Consequences of lot-size planning for capacity requirements



capacity requirements is as shown in Fig. 2.29. On the other hand, when lot sizes are planned, the capacity demand is significantly higher in periods 1 and 4. This means that the higher-level part C can only be produced as planned if the increased capacity necessary for part H is available in periods 1 and 4.

From a theoretical point of view, the connections between lot-size planning and capacity requirements have to be taken into account for all of the parts. Otherwise, any attempt to optimize the production plan will at best end up in a suboptimum.

In practice, however, *feasibility* of the production plan has usually received more attention than optimization. Therefore, material requirements planning focuses only on the quantities, relying on the implicit assumption that the required capacity will be available when the production has to be completed. This assumption, however, is only justified when the production program is basically stable, the demand curves are well known and more or less uniform,

and the midterm available capacity is about equal to the required capacity.

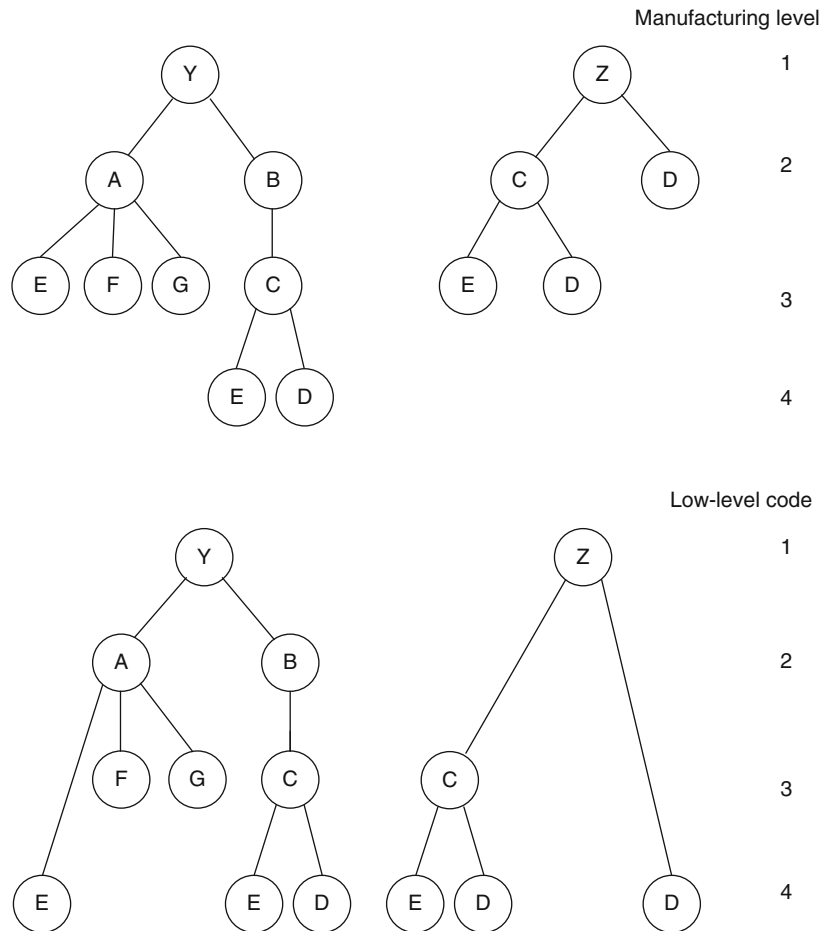
Although not without problems, this is also the underlying assumption of the planning approaches supported by MRP, MRP II, and ERP systems. Only in the field of supply chain management (SCM) have interdependencies between different parts, quantities, and capacities been explicitly taken up and are being considered in the planning approaches.

Manufacturing Levels vs. Low-Level Codes

Requirements-driven material planning can be performed in basically two different ways: by manufacturing levels or by low-level codes. The first way is most common when dealing with a single product structure, for example, in make-to-order production. The second way is typical when all products of a standardized end-product program are included, for example, in mass or series production.

Proceeding by manufacturing levels means that one product structure tree at a time is

Fig. 2.30 Product structures by manufacturing levels and low-level codes



traversed, branch-by-branch, part-by-part, and from top to bottom. If a part appears more than once in the tree (or in different trees), it is dealt with several times. In Fig. 2.30 (upper section), this is the case for parts C, D, and E.

Calculating net requirements involves subtracting available stock in the course of the process. Since higher-level parts are considered first, the existing stock is assigned to the higher manufacturing levels. This may cause net requirements to appear for the same part on a lower level.

However, the temporal structure of the production process is such that the lower-level parts have to be available *before* the higher-level parts. As a consequence, production of a part that occurs both on a lower and a higher level will be initiated to fill the lower-level requirements, although at the time stock is still available. This

stock, however, was reserved to fill the higher-level requirements at a later point in time.

To avoid such misassignments of available stock, so-called *low-level codes* were introduced. In this approach, the product structures are reorganized across all trees in such a way that each part occurs only on one level. Graphically speaking, the trees are stretched vertically so that each node reaches the lowest manufacturing level that the part has in any branch of any of the trees. This level is called the low-level code of the part. In the lower section of Fig. 2.30, parts D and E receive the low-level code 4 and part C the code 4.

Requirements-driven planning by low-level codes starts with the first part on the highest level (code 1), executing:

- Gross requirements planning
- Net requirements planning

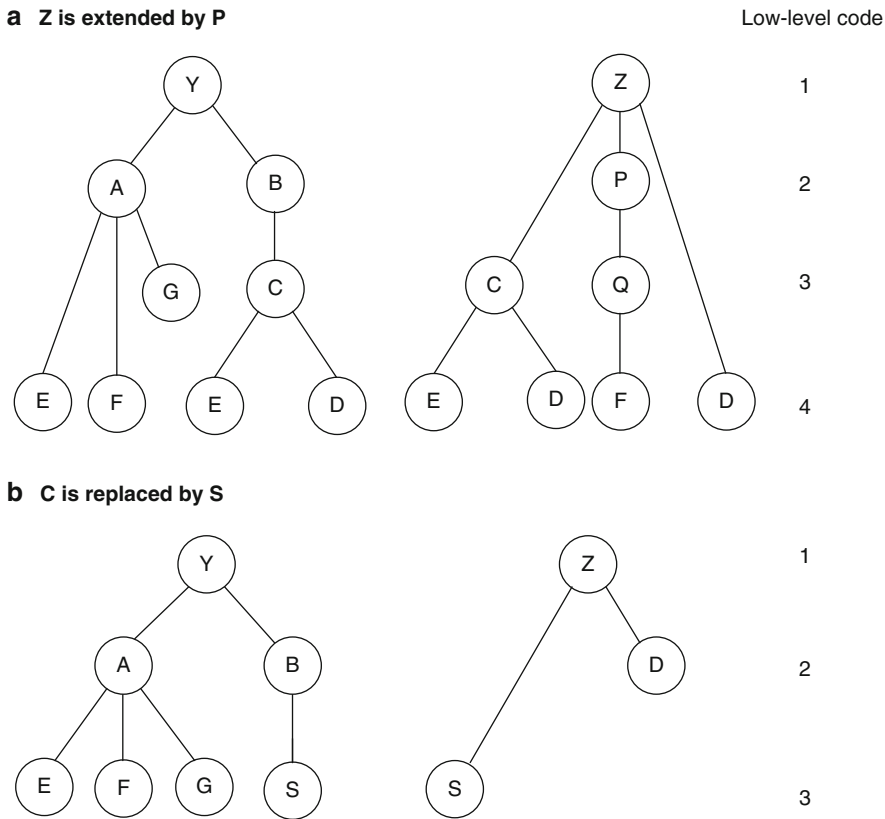


Fig. 2.31 Induced changes of low-level codes

- Lot-size planning
- Deriving requirements for subordinate parts
- Forward shifting

for this part. Then it continues with the next part of level 1, then with the next to the next part of level 1, etc. When all parts of level 1 have been dealt with, the process goes to the next level, treating all parts with low-level code 2 as above, then to the next level, etc.

In this process, requirements for subordinate parts occurring on several levels and/or in several product structures are gradually collected and accumulated, as the process touches the respective nodes in those structures. Requirements planning for a derived part (i.e., gross and net requirements planning, lot sizing, etc.) does not start until the part’s low-level code has been reached in the process. When all parts on all levels have been dealt with, the total requirements for all parts are available in the database.

Using low-level codes, the parts shown in Fig. 2.30 would be processed in the following sequence:

- Level 1: Y, Z
- Level 2: A, B
- Level 3: C, F, G
- Level 4: D, E

Low-level codes help to avoid mistakes in requirements-driven planning such as inadequate allocation of stock, but they also have *disadvantages*. Worth mentioning is the administration effort. Creating the codes across hundreds of thousands or millions of parts is an extremely time-consuming task, although simple from an algorithmic point of view. Basically, it involves traversing all product structure trees and for each part, storing the lowest manufacturing level ever reached in the part master record.

More problematic than the one-time creation is the *maintenance effort*. Every time a new part

is entered into the database, its low-level code must be determined, but what is worse, the codes of all other parts in the database must be reevaluated. The reason is that the codes may need to be changed due to the product structure of the new part. The same applies when an existing part is deleted from the database.

Figure 2.31 illustrates the two scenarios. The top section of the figure shows the case that end product Z is augmented by part P. Part F goes into part Q, which goes into P. Part F was already contained in the product structure of end product Y (with low-level code 3). Introducing P changes the low-level code of F to 4 because in Z's product structure, F is on a lower manufacturing level than in Y's.

The lower section of the figure shows a scenario in which assembly C is no longer produced in-house but replaced with a purchased part S. Since C is not there anymore, D and E are not needed either (for C) but are still needed for Z and A, respectively. They move up according to Y's and Z's product structures, and their low-level codes are now equal to the manufacturing levels.

2.3.3 MRP in Make-to-Order Production

An essential characteristic of make-to-order production is that the product is specific to the customer. This means that important master data such as product structures may not be available and have to be created for the order. Furthermore, customer-specific products are not produced to stock but only when the customer places an order. This is actually an expensive strategy in comparison to mass or series production. The company cannot benefit from cost savings that go along with larger batches if they produce only customer-specific parts. Likewise, it is difficult to meet short delivery dates if for all parts, planning can only start when a customer order is placed.

For these reasons, make-to-order manufacturers strive to use not only customer-specific parts but also standard parts where possible. Since standard parts are typically included in

more than one product, they can be planned independently from specific customer orders and produced in larger batches, which saves time and cost.

Planning Levels Different *planning levels* can be introduced to handle customer-specific parts and standard parts. Zimmermann called these levels the *expectation-oriented* planning level and the *customer-order-oriented* planning level (Zimmermann 1989, pp. 74–76).

Figure 2.32 illustrates this distinction with the help of two product structures representing the customer-specific products Y and Z. The company has decided to use the standard parts C, E, and F whenever possible, but A, B, D, and G are parts that must be manufactured just for the customer order.

As the figure shows, planning for the parts Y, Z, A, B, D, and G will be done when a customer order arrives, while planning for the parts C, E, and F can be done whenever suitable, for example, following a consumption-driven approach as described in Sect. 2.3.1. The dashed line between the two planning levels is called the *stock-keeping level*.

Inventory management in make-to-order production has to meet more challenges than in make-to-stock production. The reason is that consumption is not as smooth as in make-to-stock production where the planning can be based on a known, possibly constant withdrawal rate. In make-to-order production, the future customer orders are not known, and hence, derived requirements can at best only be estimated. Consequently, higher inventory levels including safety buffers have to be kept, causing additional inventory cost.

Alternatively, the company may try to keep the inventory (for standard parts) at a reasonably low level and purchase peak demand from suppliers or competitors. In some industries, for example, suppliers exist that have specialized in express delivery of certain materials at substantially increased prices (e.g., special materials which otherwise have long delivery times). If such an option is available, the company may consider a trade-off between increasing the inventory level (i.e., high inventory cost) and

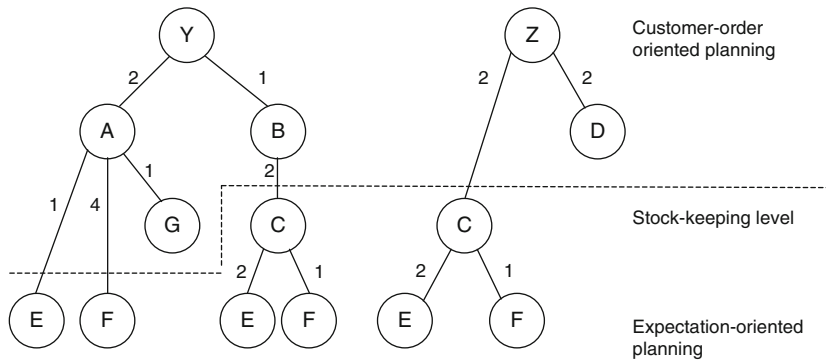


Fig. 2.32 Expectation and customer-order-oriented planning

express delivery when demand peaks arise (i.e., high delivery cost).

As mentioned in Sect. 2.2.2, make-to-order production requires that the status of a customer order, and of all dependent orders, can be retrieved at any time. This is possible when the connections between the orders are explicitly stored and maintained in the database. If standard parts are involved, it is quite likely that secondary requirements resulting from different end-product orders are combined into the same production lot. If the part is on an intermediate manufacturing level, requirements for parts on the next lower level, derived from the current part (and from other parts), may again be aggregated into lots, etc.

Suppose an operating facility needed for any of the lower-level parts in Fig. 2.32 breaks down. In order to check which customer orders might be affected, the production manager needs to know the connections from the machine to the manufacturing orders involved and from there to the end-product customer orders. While the former connections are available in the manufacturing orders (or the routings), the latter ones have to be explicitly created and maintained.

Figure 2.33 contains a general scheme, showing connections on two levels between individual requirements, production orders (lots), and derived requirements. w , x , y , and z are part numbers. In order to keep the figure simple, only the “downward” connections are shown completely: from the level n requirements \rightarrow level n orders \rightarrow level $n + 1$ requirements \rightarrow level $n + 1$ orders.

In the opposite direction, only some of the connections have been explicitly included in the figure. For example, an arrow connects one of the three y requirements with the first w order on level n . Had all connections been drawn, three arrows would be pointing upward from the y requirements to the same order. Instead, the letter p is used to indicate that the requirement record contains an upward pointer.

Reservations and Availability Checks In make-to-order production, *reservation* of stock plays a more prominent role than in make-to-stock production. The reason is that completing a customer order on time has very high priority. In order to be able to complete an order as planned and confirmed, material (just as other resources) has to be definitely available when it is needed.

Early checking to ensure the availability, followed by a reservation, is typical for many make-to-order manufacturers. In some cases, for example, when an important customer is involved, the reservation may already be booked when an inquiry is received or when the company sends a quotation to the customer.

This is particularly important when purchased parts with long delivery times or in-house parts with long lead times are involved. By the time a customer order has been received, it may be too late to place a purchase or manufacturing order for this part. The delivery or lead time may be longer than the time the customer is willing to wait for delivery of the order. Therefore, a purchase order might already be placed after the

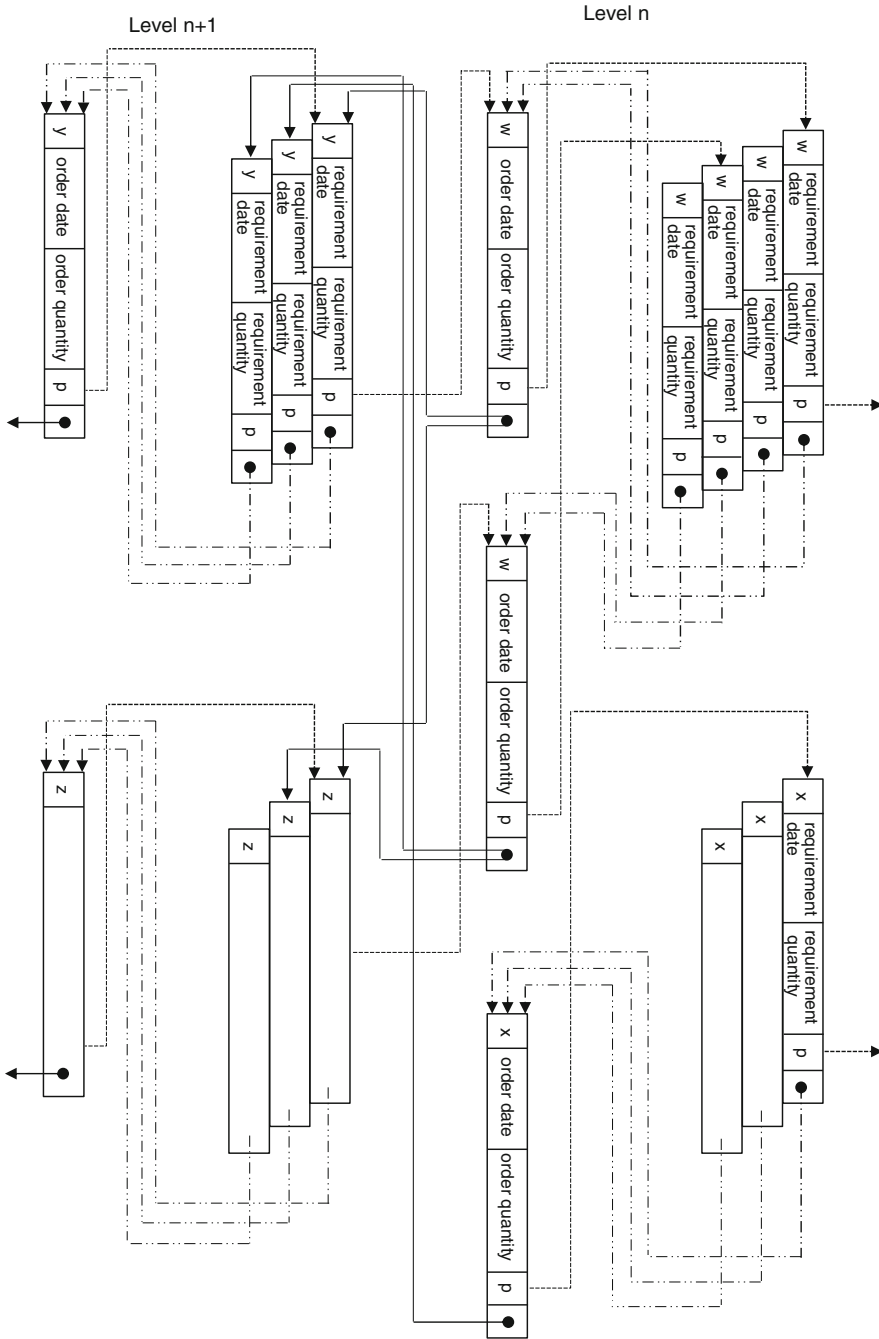


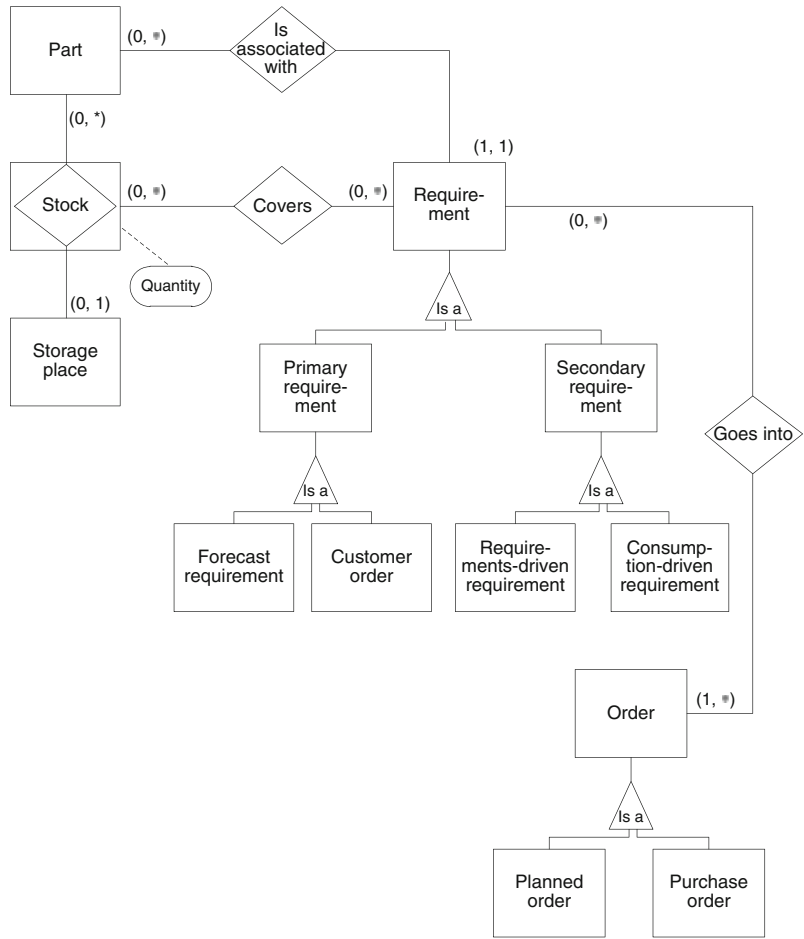
Fig. 2.33 Connections between individual requirements and orders

customer’s first inquiry, even if there is a risk that a customer order will not come through.

Advanced approaches for availability checking have been developed in the field of supply

chain management (SCM) and included in ERP systems. They are often summarized under the name *ATP* (“available to promise”). ATP and other methods will be discussed in Sect. 10.1.5.

Fig. 2.34 Entity-relationship diagram for key MRP entities



2.4 Outcome of Material Requirements Planning

The main task of material requirements planning is to determine the secondary requirements. Starting from the primary requirements that result from end-product program planning, the required quantities of all subordinate parts are calculated. Inexpensive parts are usually planned based on previous consumption and forecasting, whereas more expensive parts are planned with higher accuracy, using the bills of materials.

One major outcome of MRP is *planned orders* (also called planned manufacturing or production orders) representing either the requirements of individual periods or the requirements of several

periods bundled into production lots. These planned orders are later used to create *manufacturing orders* (also called production orders), which are given to the company's manufacturing department.

Another major outcome is *purchase orders* for externally procured parts (also called procurement orders). Like planned orders, they may be based on individual period requirements or on requirements of several periods bundled into an "optimal" order quantity.

To summarize the connections between the key terms of material requirements planning, an entity-relationship diagram is presented in Fig. 2.34. This diagram is highly simplified, showing only the main entity types and their relationships.

Parts are associated with *inventory* data and with *requirements*. Requirements can be primary

or secondary requirements. *Primary* requirements come from forecasts or from customer orders. *Secondary* requirements are computed as either consumption driven or requirements driven.

To be satisfied, requirements on all levels finally have to go into orders, which can be *planned orders* (for in-house production) or *purchase orders* (for external procurement).



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