MANUFACTURING RESOURCE PLANNING

Manufacturing Resource Planning (MRP II) is essentially a business planning system. It is an integration of information systems across departments. In an enterprise implementing MRP II manufacturing, finance and engineering managers are linked to a company-wide information system. Thus, managers have access to information relating to their functional area of management as well as to information pertaining to other aspects of business. In reality, to reduce cost and provide good customer service, this integration is clearly mandatory. For example, the sales department has to have the production schedule to promise realistic delivery dates to customers, and the finance department needs the shipment schedule to project cash flow.

The concept of integrating information systems across departments is one that is basically common sense. Once integration across departments is achieved and its value experienced, it seems hard to believe that this has not always been the case. However, it is relatively recent. It is only since the 1970s that the integration of business functions and sharing of information across departments are being practiced. Several businesses still exist where business functions are working in isolation from each other, each focusing on their narrowly defined operational area with their own information system.

To fully comprehend and appreciate MRP II, one needs to understand the evolution of manufacturing planning. The questions of what, how much, and when to produce are the three basic questions in manufacturing planning. Over the years, different approaches to answer these questions have been proposed. The latest approach to answering these questions and, in fact, placing the answers in context within the whole business practice is MRP II. Although MRP II is largely borne out of the batch production and assembly environment, it is applicable in almost any facility.

BEFORE MANUFACTURING RESOURCE PLANNING

Until the 1970s the aforementioned three basic questions were typically answered by classic inventory control models. All these methods were based on the concept of stock replenishment where the depletion of each item in inventory is monitored and a replenishment order is released periodically, or when inventory reaches a predetermined level, or a hybrid of the two. Order quantities are determined by considering the tradeoff among related costs, based on the forecast demand and the level of fluctuations in demand. This approach fails to recognize the dependence between the components and end-items. Furthermore, it does not take into consideration the difference in demand characteristics between a manufacturing environment and a distribution environment. While demand in a distribution environment needs to be forecast for each item and does have fluctuations, in a manufacturing environment the demand needs to be forecast only for the end-product and not for the component items, in general. In addition, in a manufacturing environment the questions of what, when, and how much to order cannot be answered independent of production schedule. The production schedule states how much to produce of each product, and based on that the demand for each component item can be calculated since the usage of each item to build the end-product is exactly known.

The difference in the nature of demand in a manufacturing environment brought the development of Material Requirements Planning (MRP) systems, which translate the production schedule for the end-item referred to as the Master Production Schedule (MPS) into time-phased net requirements for each component item. This translation, however, involved large volume of transaction processing and thus warranted computing power. MRP systems found widespread acceptance once computers became available for commercial use starting in the late 1970s. It is not appropriate, however, to view MRP systems in isolation. As previously stated, material planning cannot be viewed in isolation of production and capacity planning. Each is a part of a broader system which is commonly

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referred to as Manufacturing Planning and Control (MPC) system. MPC includes sales and operations planning as well as detailed materials planning and ties up these plans with corresponding levels of capacity planning. A typical illustration of manufacturing resource planning is given in Fig. 1, where the hierarchy of MPC activities with corresponding levels of capacity planning are shown.

MANUFACTURING PLANNING AND CONTROL SYSTEMS

Sales and Operations Planning

Sales and Operations Planning is commonly known in the literature as Aggregate Production Planning and Resource Planning. Figure 1 shows the hierarchy of MPC activities. The highest level is basically concerned with matching capacity to estimated demand in the intermediate future, typically about 12 to 18 months, through the aggregate production plan. As the name implies, the aggregate production plan is usually prepared for product families or product lines as opposed to being prepared for individual end-products. This aggregated plan may be expressed in total labor hours, units, or dollars, or a combination of these. Likewise, time is also aggregated such that the plan is expressed on a monthly or quarterly basis. Typically, the time periods are monthly for the initial 3 to 6 months, and quarterly for periods thereafter. Because of the possible conflicts among the objectives of minimizing costs, keeping adequate inventory levels, and maintaining a stable rate of production, aggregate production planning is a complex task. Several costs such as those of inventory holding, hiring/firing, overtime/undertime, subcontracting, and backordering are considered in its preparation. During the preparation of the production plan, capacity is not considered a "given." This means that capacity may be increased or decreased based on the projected demand and the various costs. This could be through adding/deleting shifts, overtime/undertime, or expansion/closure of facilities. Capacity planning at this level is often referred to as *resource planning*.

The academic literature on aggregate production planning problem contains several different approaches to providing the solution. One approach is modeling it as a mathematical programming problem. Various mathematical programming models such as the transportation method of linear programming (1), linear programming (2,3), mixed-integer programming (4), and goal programming (5) have been applied to solve the problem. In a mathematical formulation, usually the objective is to minimize the total cost subject to demand and capacity constraints, by adjusting the above listed variables. A variation of this approach is the Linear Decision Rule (6) model where the assumption of linear costs (except for the labor cost) is relaxed. In addition to these optimizing methodologies, heuristic search procedures (7,8) and regression of past managerial decisions (9) have also been applied to the problem.

The aggregate production plan guides and constraints the scope of short-term decisions and needs to be disaggregated into detailed production schedules for individual end-products for short-term planning. In other words, the sum of individual end-product short-term production schedules must be consistent with the aggregate production plan. The disaggregation process provides the link between longer-term aggregate plans and shorter-term planning decisions. In the research literature the so-called "hierarchical production planning models" attempt to provide this link. These models utilize not just one but a series of mathematical models. Decisions made at one level constitute the constraints at lower levels where short-term decisions are made (10–17).

Master Planning and Material Requirements Planning

The next level of planning, shown as Master Production Scheduling in Fig. 1, is the result of disaggregating the aggre-

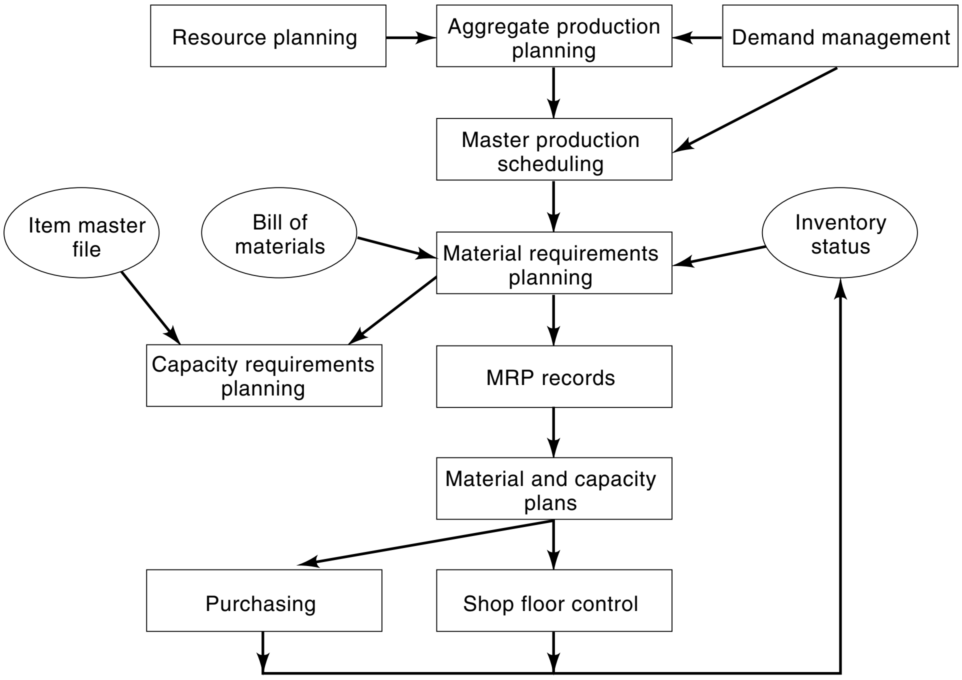


Figure 1. Manufacturing planning and control system schematic.

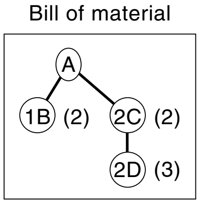
Table 1. Master Production Schedule for Item A

Weeks:	1	2	3	4	5	6
MPS:						100

gate production plan into production schedules for individual end-products. The Master Production Schedule (MPS) is usually expressed on a weekly basis and can be of varying lengths. The planning horizon for the MPS ranges from three months to one year. When several variations of the end-product are offered, the master production schedule is accompanied by a Final Assembly Schedule (FAS). Where FAS is maintained for a specific product configuration, MPS is maintained at the common subassembly level for options.

The master production schedule is a major input to the detailed planning of material requirements. The thrust of material planning is to determine component item requirements based on the master production schedule over the planning horizon. This obviously requires information about which components are needed, how many are needed, how they are assembled to build the end-product, and how much time is needed to obtain each component. This information is given in a product structure file referred to as the Bill of Materials (BOM). BOM is thus another major input for material planning in addition to the MPS. Note, however, that the determination of material requirements cannot be divorced from the information on how many units of each component item is already on hand and how many on order. This information is maintained in the inventory record for each component item. In addition, information on the routing and processing times for manufactured components is maintained in the so-called Item Master File (IMF). The Material Requirements Planning (MRP) system takes these three inputs—MPS, BOM, and inventory records—and calculates the exact time-phased net requirements for all component items. This, in turn, serves as the basis for authorizing the commencement of production for manufactured parts and release of purchase orders for purchased parts. The following simple example serves to illustrate the mechanics of how an MPR system processes the three inputs to obtain the time-phased net requirements for manufactured component items and purchased parts. Table 1 shows the MPS for end-product A. Figure 2 shows the BOM and the inventory record for end-product A, component item C, and purchased parts B and D. Table 2 shows the MRP records for all items.

The BOM shows that end-product A is made by assembling one unit of item B and two units of item C. Each unit of item C is made from two units of item D. Items B and D are purchased parts. Lead times for each item is also presented (in parentheses) in the BOM. The inventory records show the on-hand and on-order quantities and their due dates. The MPS for item A indicates that 100 units of product A is planned to be completed in week 6. Note that the gross requirements for the end-item constitute the MPS.



Inventory records

Item	On hand	On order	
A	20	0	
B	50	0	
C	0	0	
D	0	400	Due in wk. 3

Figure 2. (Left) The Bill of Materials showing all the components of end-item A, their relationships and usage quantities. The lead times for each component are given in parenthesis. (Right) Inventory on Hand and on Order for all items in the Bill of Materials.

Table 2. MRP Records

MRP Record for Item A

Periods	1	2	3	4	5	6
Gross Requirements						100
Scheduled Receipts						
On Hand	20	20	20	20	20	
Net Requirements						80
Planned Order Release					80	

MRP Record for Item B

Periods	1	2	3	4	5	6
Gross Requirements					80	
Scheduled Receipts						
On Hand	50	50	50	50	0	0
Net Requirements					30	
Planned Order Release			30			

MRP Record for Item C

Periods	1	2	3	4	5	6
Gross Requirements					160	
Scheduled Receipts						
On Hand	0	0	0	0	0	0
Net Requirements					160	
Planned Order Release			160			

MRP Record for Item D

Periods	1	2	3	4	5	6
Gross Requirements			320			
Scheduled Receipts			400			
On Hand	0	0	80	80	80	80
Net Requirements						
Planned Order Release						

Since 20 units of item A are on hand, and will remain on hand until week 6, 80 more units are needed in week 6. This information is shown in the MRP record for item A in the rows titled Gross Requirements (100 units in week 6), On Hand (20 units), and Net Requirements (80 units). A work order for 80 units of A, due at the beginning of week 6, needs to be released to the shop floor. Since the lead time is estimated as 1 week for item A, the order needs to be released in week 5. This is reflected in the row titled Planned Order Release. Since assembly of 80 units of A needs to start in week 5, and 1 unit of B and 2 units of C are required to make 1 unit of A, 80 units of B and 160 units of C are needed at the beginning of week 5 before the assembly of A can start. Thus, the planned order release for item A constitutes the gross requirements for its immediate components items B and C.

In the MRP records for items B and C, gross requirements are reflected in week 5 as 80 and 160, respectively. There is an on-hand quantity of 50 for B. Hence, the net requirement is only 30 units. Since the purchasing lead time for B is estimated to be 2 weeks, a purchase order for the remaining 30 units needs to be released 2 weeks ahead of the date of need, that is, in week 3, as shown in the MRP record. Similarly, 160 units of C are needed and there is no on-hand quantity. Therefore, a work order needs to be released to the shop to start making 160 units of C in week 3, since the lead time is 2 weeks and the need date is week 5.

The planned release date of the work order for making item C is week 3. Since 2 units of item D are used in each unit of item C, 320 units of item D needs to be withdrawn from stock in week 3 to start making the 160 units of item C. Therefore, again, the planned order release for item C determines the gross requirements of its immediate component D. As shown in the MRP record for item D, the gross requirement for item D is 320 units in week 3. Item D has a 3-week purchasing lead time. Thus, beginning of the current period is too late to release an order for item D. However, an order for item D has apparently been released in the amount of 400 units in the previous planning cycle. It is scheduled to be received in period 3. Since the order has been released in the past, it is an open order referred to as "Scheduled Receipt." This meets the requirement of 320 units in week 3. In addition, 80 units will remain on hand after period 3.

This example serves to demonstrate the two aspects of MRP: (1) netting of requirements for each item over on hand and on order quantities and (2) time phasing order releases by the estimated lead time for each item to meet the net requirements. It also demonstrates the coordination between order release date and order quantities of an item and the gross requirements of its immediate components. This process is referred to as the BOM explosion. Thus, as a result of the BOM explosion the MRP system produces (1) the planned order release schedule for manufactured and purchased items, (2) shop work orders, (3) purchase orders, and (4) reschedule notices, if necessary, for open orders.

The MRP records are processed (i.e., the BOM explosion is performed) on a periodic basis. The periodicity is influenced by the dynamism of the operating environment and by the computer processing power. With the ever-increasing processor speed it has become easier to update MRP records frequently. In the research literature the replanning of the MPS and the consequent BOM explosion (i.e., updating of the MRP records) is modeled via a rolling horizon procedure. Once the MRP records are processed for the planning horizon, it is assumed that the first period's decision is implemented and then the horizon is rolled to the beginning of the next period (or more than one period depending on the replanning frequency). The planning horizon length is fixed. Therefore, new periods' requirements are added at the end of the horizon, and the MRP records are updated based on the new information. Frequent replanning keeps MRP records updated. However, it is not necessarily desirable because it often results in changes in production schedules. Changes in demand and consequently the master production schedule, as well as the addition of the new periods' requirements at the end of the horizon, result in changes in (a) the due dates for open orders and (b) the quantity and timing of planned orders for the end item. Since end-item planned orders constitute the gross requirements for component items, the components' due dates for open orders and planned orders (timing or quantity) also change. This phenomenon is referred to as *system nervousness* and is identified as a major obstacle to the successful implementation of MRP systems (18–21). Several authors have investigated the impact of replanning frequency and the issue of system nervousness (22–26).

Lot-Sizing. An important issue in the BOM explosion is the order size determination. As item net requirements within the planning horizon are determined, order releases are planned to meet these requirements. In the example above, planned order quantities are equal to net requirements. However, ordering policy is not always "order as much as needed in each period." In fact, the order quantity may be quite different than the net requirements, such that a few periods' net requirements may be combined in one order. In that case, as the order is received, some of it goes to stock and is carried until it is consumed in the following periods whose net requirements are included in the order. How many periods' requirements should be combined in one order constitutes the issue of lot-sizing. The lot sizes are usually determined based on the tradeoff between the inventory carrying and ordering costs. Sometimes, the order quantity may be fixed, especially for purchased parts since the supplier may have control over the order quantity due to packaging and shipping requirements or because of quantity discounts, and so on. The lot-sizing procedure used has quite an impact on the system. As net requirements are consolidated into fewer orders, the pattern of gross requirements for components tend to be such that a period with a high requirement is followed by a number of periods with zero requirements. In other words, requirements tend to get more and more "lumped" for lower level items. This results in violent swings in capacity requirements from period to period and, in turn, causes implementation problems. In addition, lot size could amplify the impact of schedule changes and system nervousness.

The academic literature on lot-sizing is very rich. Several approaches have been proposed. One approach assumes that lot-sizing is performed for each item independent of other items and ignores the coordination between multiple levels of BOM. This is referred to as *single-level lot sizing*. Two methods have been proposed to obtain the optimum solution to the single-level lot-sizing problem assuming a finite horizon. One is a dynamic programming-based procedure (27) and the other is an efficient branch and bound procedure (28). Several heuristic procedures have also been developed to achieve the balance between the cost of carrying inventory versus the cost of ordering for the single-level lot-sizing problem (29–34). Some of the well-known heuristic procedures are:

Economic Order Quantity (EOQ). Order quantity is determined using the basic EOQ model with the average demand per period set-up cost and per period unit holding cost.

Periodic Order Quantity (POQ). A variant of EOQ. Order periodicity suggested by the EOQ model is used. Order quantity is equal to the number of periods' requirements within the periodicity.

Fixed Order Quantity (FOQ). Order quantity is a fixed quantity determined by an external constraint or preference.

Part Period Balancing (PPB). The order quantity is determined such that the cost of carrying inventory does not exceed the cost of placing a new order over the periods that the order covers.

Silver and Meal (SM). Cost is minimized over the number of periods that the order covers.

Several studies evaluating the performance of the heuristic procedures under a wide range of operating conditions have been reported in the literature (35–42). Some authors have evaluated the performance of these single-level heuristics, level by level, in a multilevel MRP system (43–49). Results from these studies show that under rolling horizons and demand uncertainty, conditions encountered in practice, none of the lot-sizing procedures provide the optimum solution and that the difference in the performance of lot-sizing rules tend to disappear (41,42).

Another approach to solving the lot-sizing problem is to take into consideration the dependency between the timing and quantity of the parent item order and component item requirements, as reflected in BOM. This is referred to as the *multilevel lot-sizing problem*. Several researchers have developed optimizing (50–56) as well as heuristic procedures (57–68) for the multilevel lot-sizing problem. Some authors also proposed capacitated lot-sizing procedures (68a,b). However, these procedures are not easily applicable to large size problems. The number of items and levels in BOM found in practice are often much too large for these methods to be useful. Furthermore, practical applications of such multilevel procedures have not been reported. The usual practice is to apply single-level heuristic lot-sizing procedures, on a level-by-level basis (69). Among such heuristics, only a few—LFL, EOQ, FOQ, and POQ—are reported as used by practitioners (70). Excellent reviews of lot-sizing research can be found in Refs. 71–73.

Safety Stock and Safety Lead Time. Safety stock is inventory that is kept in addition to the item requirements. Safety stocks exist in several different forms and may be needed for several different reasons. Extra inventory of the end-product may be kept as a protection against the uncertainty in demand—that is, forecast errors. At the component level, safety stock may be kept to protect against the uncertainties in the manufacturing process such as process yields. Safety stock of purchased items may be kept to protect against unreliable vendor deliveries. Ideally, there should not be any need for safety stock. However, since both demand and supply are uncertain in many manufacturing environments, safety stocks are commonly used in practice. They can be incorporated into the MRP system by adjusting the net requirements and, thus, the order quantities. Several research studies investigate the use of safety stocks in MRP systems (74–77). One of the reasons for safety stock is to reduce nervousness which results from the uncertainty in demand. However, this is a costly strategy and may not work as intended. Therefore, care should be taken in the determination of safety stock levels (76,77).

Safety lead time is a procedure where the shop or purchase orders are released and scheduled to arrive one or more periods earlier than the actual need date. It is used more against uncertainty in the timing rather than quantity. Both safety stock and safety lead time increase the amount of inventory in the system and inflate capacity requirements. Therefore, the decision to use either one has to be made with a proper understanding of their financial and physical implications on the system (78).

Capacity Planning

While translating the MPS into time-phased requirements for all the items in the BOM, the MRP system is capacity-insensitive. It implicitly assumes that sufficient capacity is available. This makes it necessary to determine the capacity requirements warranted by the MPS as well as by the detailed material plans sequentially, as shown in Fig. 1. First, a rough estimation of capacity requirements is made subsequent to the preparation of the MPS. This is used to ensure the validity of the MPS. Validation of the MPS is important since an unrealistic MPS may create problems in the execution of the production plan. Next, a more detailed determination of capacity requirements is made after the BOM explosion to produce work load profiles for all (or some critical) work centers which serves to confirm the feasibility of the material plan.

Rough Cut Capacity Planning. The viability of the master production schedule is checked by means of rough-cut capacity planning which may be as “rough” as using historical work center work loads or as detailed as using the routing and lead times for the individual products. Techniques available for rough-cut capacity planning include Capacity Planning Using Overall Factors (CPOF), Capacity Bills (CB) and Resource Profiles (RP).

Capacity Planning Using Overall Factors is the least detailed of the three methods. CPOF uses the MPS and historical work loads at work centers as inputs to obtain a rough estimate of capacity requirements at various work centers. Continuing from the above example, assume that one unit of item A requires 1.05 standard labor hours. Also, based on past data, assume that historical percentage of loads (labor hours) in Work Centers (WC) 1, 2, and 3 are 41%, 35%, and 24%, respectively. Based on the CPOF method the total capacity requirements would be (1.05*100) 105 total hours, distributed as (105*0.41) 43.05 hours for WC 1, (105*0.35), 36.75 hours for WC 2, and (105*.24) 25.20 hours for WC 3, all in period 6. The CPOF method is attractive because of its simplicity. However, it would be useful only to the extent the historical work center loads reflect the current requirements. Any change in the product mix or in the processing requirements due to product or process design change may easily outdate the historical figures and, thus, should be taken into consideration prior to the use of the CPOF method. Furthermore, this method shows the capacity requirements in the same MPS time periods where the end-product requirements are located—that is, this method does not time-phase capacity requirements by the estimated component lead times.

In addition to the MPS, CB requires BOM information, shop floor routings, and operation standard times for each item at each work center. From the BOM file, it retrieves the information concerning which components, and how many of each (usages), are needed to build the end-product. The component usages are multiplied by the MPS quantity to determine the total component requirements to build the MPS. Each component requirement is then multiplied by per unit operation standard times for each work center indicated on its shop floor routing. The capacity requirements are summarized by work center.

In CB, BOM information, routing, and operation standard times replace the historical work center load percentages used in CPOF. Therefore, any changes in the product mix, product, or process design (reflected in operation standard times and routings) will be incorporated in the determination of capacity requirements. This makes the CB method more attractive for those environments where such changes may occur frequently.

CB, like CPOF, shows work center capacity requirements (accumulated from all items in BOM) in the same MPS time period where the end-product requirements are located. This may not be an issue for those cases where the manufacturing lead time is short relative to the time bucket used in the MPS. However, when manufacturing lead time extends over multiple MPS periods, aggregating the capacity requirements into the same period may be far from reflecting the real capacity requirements. The Resource Profiles method uses the same information from the BOM, shop floor routings, and operation standard times as does the CB method. In addition, RP time-phases the capacity requirements by component lead times. The resulting output shows work center loads spread over the total manufacturing lead time, for each work center reflected in those time periods when the work is actually expected to be performed. Thus, RP is the most sophisticated of the three rough-cut capacity planning techniques described here.

Rough-cut capacity planning techniques are used to validate the MPS. If capacity requirements exceed available capacity, either the MPS or the capacity availability has to be altered. Thus, the preparation of MPS and its validation by checking capacity availability is an iterative process, where ultimately the correspondence between the MPS and capacity availability is to be achieved.

Capacity Requirements Planning. The next level of capacity planning is performed subsequent to the detailed planning of material requirements. MRP explosion provides the netting of gross requirements over on-hand and on-order quantities and reflects the actual lot-sizes for each component in the planned orders. Also, any additional requirements for components not included in the MPS (e.g., service parts) are also included in the calculations. The time-phased material plans produced by the MRP system are translated into detailed capacity requirements through Capacity Requirements Planning (CRP).

CRP uses the information on shop floor routings and operation time standards (setup and processing times) like sophisticated rough-cut procedures. However, instead of determining capacity requirements based on MPS quantities, CRP translates planned order quantities, reflecting actual lot sizes time-phased during the MRP process, into labor/machine hours. These hours are added to the labor/machine hours translated from open order quantities (work-in-process). This produces time-phased load profiles for work centers over the planning horizon. Calculating detailed capacity requirements enables the validation of material plans by checking for feasibility. Again, the correspondence between hours required and hours available needs to be achieved for successful execution of the plans at the shop floor.

Capacity insensitivity of the MRP approach has been an early source of criticism. An alternative to the infinite loading of CRP is finite loading. Finite loading also uses the planned orders as input. However, it also requires the orders to be prioritized—that is, placed in the sequence in which they will be processed (79). After prioritizing, it loads the orders to work centers until available capacity is reached. Because of its reflection of the relationship between capacity and scheduling, it is viewed more as a shop scheduling technique (80).

Shop Floor Control

The lowest level in the hierarchical MPC model presented in Fig. 1 is concerned with the execution of plans. Note that MRP output only specifies the release of orders for component item production. Each work order is comprised of several individual processing steps often performed at various work centers/machines. When the work order is released to the shop floor, the material needed to make the parts is withdrawn from the stock room and moved to the work center or machine where the first operation is to be performed. Typically, there may be a large number of work orders often competing for the same set of resources. Therefore, in each work center/machine there needs to be a mechanism to schedule the competing work orders. Operations scheduling is a major element of a manufacturing planning and control system due to its impact on customer service, in terms of on-time delivery performance.

Various scheduling rules exist for prioritizing jobs at each machine. These rules may be as simple as first come first served or based on some other more complicated criterion. Numerous rules have been developed and discussed in the literature (81–84). Some of the well-known rules are:

Shortest Operations First, also known as the Shortest Processing Time (SPT) rule. The jobs are prioritized in the ascending order of the processing times at the current work center.

Earliest Due Date (EDD) rule. Jobs are prioritized in the ascending order of their due dates.

Operations Due Date (OPNDD). Jobs are prioritized in the ascending order of their due dates for the current operation.

Critical Rule (CR). The ratio of time until due date to lead time remaining (in the current and subsequent operations until the completion of the job) is used to prioritize jobs. The job with the smallest CR is the most urgent and is thus given the highest priority.

Total Slack (TS). The difference between time until due date and lead time remaining is used to prioritize jobs. The job with the smallest slack is given the highest priority.

Slack per Remaining Operations (S/RO). The ratio of total slack to the number of operations is used to prioritize jobs. The job with the smallest S/RO is given the highest priority.

The effectiveness of scheduling rules differs based on the performance criterion used such as flow time (time from the arrival of the order until its completion), earliness, tardiness, inventory, number of tardy jobs, shop utilization, and so on. Research shows that SPT tends to minimize average flow time; due-date-based rules tend to perform well in terms of due date related criteria. The literature on scheduling is extensive. Several job shop (85) and flow shop (86) simulations compare the performance of dispatching rules under various operating conditions (87). In these simulations, usually scheduling of a machine is done using a specified dispatching rule, regardless of the scheduling in other work centers. Simultaneous scheduling of all machines is very difficult to model and is rarely done in job-shop settings. Recently, methods such as tabu search, genetic algorithms, and simulated annealing have also been applied to the scheduling problem (88).

Much of the existing literature focuses on problems in which all jobs are assumed available for processing at the beginning of the horizon. It also advocates schedules in which no machine is ever kept idle in the presence of waiting jobs. However, in a typical job shop (e.g., tool room, die shop, small component manufacturing shop) jobs arrive continuously. Thus, superior schedules may involve deliberately keeping a machine idle, in the presence of waiting jobs, in order to process an anticipated "hot" job that is yet to arrive. In addition to dynamic environments, deliberate idle times may also be necessary when both early and tardy completion of jobs is undesirable, or when there are multiple machines. For a review of the literature dealing with the issue of schedules with deliberate machine idle times, an interested reader may refer to Refs. 89–91.

Plossl and Wight (92) distinguish between loading and scheduling. Load is the amount of work waiting in the shop (or at the machine) to be performed and can be computed as the amount of total work. Load can be controlled by monitoring the work input into the shop. Shop loading is said to be balanced when the flow of work into the shop equals the output from the shop. By adjusting the input, one is able to control the amount of work backlog, machine utilization, and the shop throughput. Several authors have studied the issue of controlling the release of jobs to the shop by means of order review/release policies. In general, the results appear to be mixed in that it is not clear if and when such policies are effective in improving the overall system performance (93–99). It appears that controlling the release of orders to balance the load between the machines (100,101) may be a superior approach when compared to basing the order release and control decision on other objectives. See Ref. 102 for a framework for a manufacturing system where an order review/release policy is implemented.

Implementation of MRP Systems

Successful MRP system implementation requires more than just the information system. One of the major success factors is management commitment. First, a commitment needs to be made to provide accurate information that is input to the system. This requires cleaning and integrating the databases and their continuous maintenance as well as timely data entry. Companies successfully implementing MRP systems deal with accurate BOM, MPS, inventory, and lead time data in making inventory and scheduling decisions. Second, a commitment is needed to train the people who will use the system. These are prerequisites to successful MRP system implementation. Providing the prerequisites clearly have costs, and the extent of costs depend on the initial condition of the company. Therefore, a commitment of resources is also needed. Challenges in the implementation of MRP II systems include period-size resolution (short-term planning), data transaction intensity (and resulting accuracy challenges), iterative capacity planning versus finite), and non-intuitive knowledge requirements (extensive training), among the more general. A thorough discussion of these challenges can be found in (80).

Successful MRP system implementation brings several benefits. MRP systems bring a good match between demand and supply by making the need date for items coincide with their due date. Because of the closer match between demand and supply, finished goods inventories are reduced. Improving planning of priorities and scheduling reduces work-in-process, and improving timing for vendor deliveries reduces raw material inventories. Altogether, inventory turnover increases and obsolescence decreases (103,104).

In general, the extent of benefits derived from the system depends on how a company uses the MRP system. Users of MRP systems are classified into four classes: Class A to D. Those companies using it to its fullest capacity (with full support of the top management) for priority planning and capacity planning, with a realistic and stable MPS, are referred to as "Class A" users. At the other end of the spectrum there are Class D users for whom the MRP system exists only in data processing and does not reflect the physical realities of the organization. For a detailed discussion of the MRP users classification see Ref. 103.

Several empirical studies dealing with the practical issues surrounding efficient and effective implementation of MPC systems, in particular MRP-based systems, have appeared in the literature. See, for example, Refs. 105–107. Kochhar and McGarrie (107) report seven case studies and face-to-face meetings with senior managers and identify key characteristics for the selection and implementation of MPC systems. They conclude that (1) the operating environment significantly impacts the choice of the system and (2) the existing framework for an objective assessment of the need for individual control system functions is largely inadequate in serving the needs of managers. This result demonstrates the need for a modular design and a decentralized architecture for MPC systems, thus providing individual companies the maximum flexibility in tailoring the system to meet their needs within a common framework. Such an architecture and design, in our view, should automatically preserve the best features in all variants of the system and, thus, be able to guarantee efficiency and effectiveness (108).

Problems with MRP

There are a number of fundamental flaws in the MRP-based approach to production planning and control. Central weakness is MRP's modus operandi of sequential, independent processing of information. The approach attempts to "divide and conquer" by first planning material at one level and then utilization of manpower and machines at another level. The result is production plans which are often found to be infeasible at a point too late in the process to afford the system the opportunity to recover. Second, MRP-based systems do not provide a well-designed formal feedback procedure instead depend on ad hoc, off-line, and manual procedures. When a problem occurs on the shop floor, or raw material is delayed, there is no well-defined methodology for the system to recover. Thus, the firm depends on and actively promotes safety buffers, leading to increased chances for missing strategic marketing opportunities.

A third flaw concerns the use of planned lead times. Planned lead times are management parameters which are provided prior to the planning process and represent the amount of time budgeted for orders to flow through the factory. This can result in a tremendous amount of waste in terms of work-in-process inventory. For example, consider four single operation jobs A, B, C, and D with processing time requirements 5, 4, 7, 9 and all four due at time 25. Under an MRP system, the planned lead time is prespecified and fixed. Let the planned lead time for each of these jobs be 25. Thus, the material for all four would be made available at time 0 by the MRP system. Suppose, the jobs are processed in the order A-B-C-D. Since we know from Little's law that inventory is proportional to flow time, we shall focus on flow time as the performance measure. It is easy to verify that the average flow time for the given sequence is 25, assuming early delivery is not permitted, consistent with the just-in-time manufacturing philosophy. Suppose the material arrival dates for the four jobs are planned to coincide with their planned start dates. Then, the average flow time would be 17.5. This translates into a saving of 30% in inventory costs. Note that this is only possible if a complete schedule can be constructed and the information is used to plan material procurement and delivery. See Ref. 109 for a detailed report of how substantial reduction in inventory costs can be obtained by first constructing a complete schedule and then using the schedule information to plan material.

The fourth problem with MRP systems is that often schedules are extremely nervous, which, in turn, leads to increased costs, reduced productivity, low morale, and lower customer service leads (110). The following numerical example demonstrates the problem of nervousness in detail. Figure 3 shows the BOM. Table 3 shows the MRP records in subsequent planning cycles. The BOM includes two components below the end-item level: One unit of end-item A comprises one unit of component B and two units of component C.

The planning horizon is assumed to be 12 periods long, and the lead time is three periods for each item. End-item lot size is determined by using the periodic order quantity (POQ) method, with a periodicity of four periods. A lot-for-lot regime is employed for lot-sizing the component requirements. The MRP records for the first planning cycle, which covers periods 1 through 12, appear in Table 3a. The beginning inventory is 163 units for end-item A, 27 units for component B, and 54 units for component C. An order for 341 units of item A is scheduled to be received in period 2, and orders for 304 units of item B and 608 units of item C are scheduled to be received in period 3.

In period 1, the demand forecast for item A is 75 units, and the projected inventory balance (i.e., inventory on-hand) at the end of the period is 88 units (Table 3a). An order for 348 units of item A is planned for release in period 3 to cover the demand forecast in periods 6 through 9. Therefore, at the beginning of period 1, *expedited orders* are released for 17 units of item B and 34 units of item C, both of which are due at the beginning of period 3. The actual demand for item A in period 1 is 106 units, as opposed to the 75 units forecast. Consequently, the actual inventory balance at the end of period 1 is 57 units, instead of the anticipated 88 units. The effect of this sudden spike in demand is evident in the MRP records presented in Table 3b.

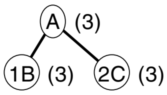


Figure 3. The Bill of Materials showing all the components of end-item A, their relationships and usage quantities. The lead times for each component are given in parenthesis.

At the beginning of period 2, demand forecast for period 13 becomes available and is added to the horizon. Since only 57 units of item A are on hand and 341 units are scheduled to be received in period 2, the total will not be sufficient to cover the anticipated demand during periods 2 through 5. Therefore, an *unplanned* order for 314 units of item A is released in period 2, and it is due in period 5. Consequently, the previously planned order for 348 units of A in period 3 is *canceled*. In turn, the due dates of open orders for items B and C are *expedited* from period 3 to period 2 (Table 3b). Furthermore, the expedited component orders released in period 1 are *rescheduled to later periods* to avoid inventory buildup.

Note that the cumulative lead time for end-item A is six periods. Between planning cycles 1 and 2, the following changes occurred in item A's schedule: (1) An unplanned order for 314 units is released in period 2, necessitating an emergency setup; (2) new planned orders are made for 335 units in period 6 and 110 units in period 10; and (3) the previous plans for producing 348 units in period 3 and 270 units in period 7 are canceled. Together, these changes cause a ripple effect, leading to a complete revision of the material plans for items B and C: Open orders for 304 units of items B and 608 units of item C are expedited from period 3 to period 2, and open orders for 17 units of item B and 34 units of item C are postponed from period 3 to period 6. Also, the new plan calls for order releases in periods 3 and 7 for both items whereas the previous plan did not. Likewise, planned orders in period 4 are canceled.

These types of changes to the material plan directly impact the capacity plan. In particular, changes within the cumulative lead time (periods 2 through 6) may not be feasible. The new and unplanned order for 314 units of product A and the expedited orders for the components (for 304 units of B and 608 units of C) may necessitate overtime and, thus, lead to an increase in cost. Such changes may also cause other jobs to become tardy. For a detailed discussion of the issue of nervousness see Ref. 111.

As mentioned earlier, uncertainties about supply and/or demand and dynamic lot-sizing combined with rolling planning are major causes of nervousness in schedules. Many strategies have been recommended to dampen nervousness, including freezing a portion of the master production schedule (112–120), time-fencing (80), using lot-sizing procedures selectively (121), forecasting beyond the planning horizon (122), incorporating the cost of changing the schedule into the lot-sizing process (123–125), using lot-for-lot ordering below level 0 (120), and using buffer stock at the end-item level (76,77,120,121). Freezing the MPS appears to be the most effective method for reducing nervousness (119). However, research is still ongoing to find ways to compensate for the likely reduction in service level when the MPS is frozen (126).

MPC in Different Environments

The MPC system design, especially the activities in levels 2, 3, and 4, to a great extent depend on the nature of demand that a company is facing. Three principal environments where the approaches to MPC system design will differ are defined as Make-to-Stock, Make-to-Order, and Assemble-to-Order.

Table 3. MRP Records in Subsequent Planning Cycles

a. MRP Records in the Beginning of the First Planning Cycle

Item A

Periods	1	2	3	4	5	6	7	8	9	10	11	12
Gross Requirements	75	146	87	92	95	70	111	111	65	99	85	86
Scheduled Receipts		341										
On Hand	88	283	196	104	9							
Planned Order Release			348				270					

Item B

Periods	1	2	3	4	5	6	7	8	9	10	11	12
Gross Requirements			348				270					
Scheduled Receipts			304									
On Hand	27	27										
Planned Order Release	17			270								

Item C

Periods	1	2	3	4	5	6	7	8	9	10	11	12
Gross Requirements			696				540					
Scheduled Receipts			608									
On Hand	54	54										
Planned Order Release	34			540								

b. MRP Records in the Beginning of the Second Planning Cycle

Item A

Periods	2	3	4	5	6	7	8	9	10	11	12	13
Gross Requirements	146	87	92	95	70	111	111	65	99	85	86	110
Scheduled Receipts	341											
On Hand	252	165	73									
Planned Order Release	314				335				110			

Item B

Periods	2	3	4	5	6	7	8	9	10	11	12	13
Gross Requirements	314				335				110			
Scheduled Receipts	304				17							
On Hand	17	17	17	17								
Planned Order Release		301				110						

Item C

Periods	2	3	4	5	6	7	8	9	10	11	12	13
Gross Requirements	628				670				220			
Scheduled Receipts	608				34							
On Hand	34	34	34	34								
Planned Order Release		602				220						

Make-to-Order. When a company builds its products according to customer specifications, then MPS is expressed in terms of each customer order. Capacity requirements are based on the current backlog of customer orders. Bills of material are specific to each customer order; and since each order is unique, manufacturing lead time has a large degree of uncertainty.

Assemble-to-Order. When the products offered by the company have large variety, then it is not practical to stock each and every possible end-product. However, customers may expect delivery faster than the time it would take to manufacture the product after the order is received. Therefore, the MPS is maintained in terms of major subassemblies (options) level. When a customer order is received, the final assembly is made according to the desired end-item configuration. The specific customer orders are maintained in the Final Assembly Schedules. In the assemble-to-order environment, Planning Bill of Material represent the major product options. Figure 4 shows the Planning Bill of material for a fictitious automobile.

Figure 4 shows that 40% of the cars made are Model A, 30% are Model B, 25% are Model C, and 5% are the Limited Model. Seventy-five percent of all cars have automatic transmission, and 25% have stick shift transmission. Engines can be V6 (75%) or V8 (25%). Also, cars can have two-wheel drive (60% of all cars) or four-wheel drive (40% of all cars). With these options there are $4 * 2 * 2 * 2 = 32$ end-product configurations. Instead of building all possible configurations to stock, MPS is kept at the options level; that is, there are 13 MPS (1 for common items) and up to 32 FAS where only

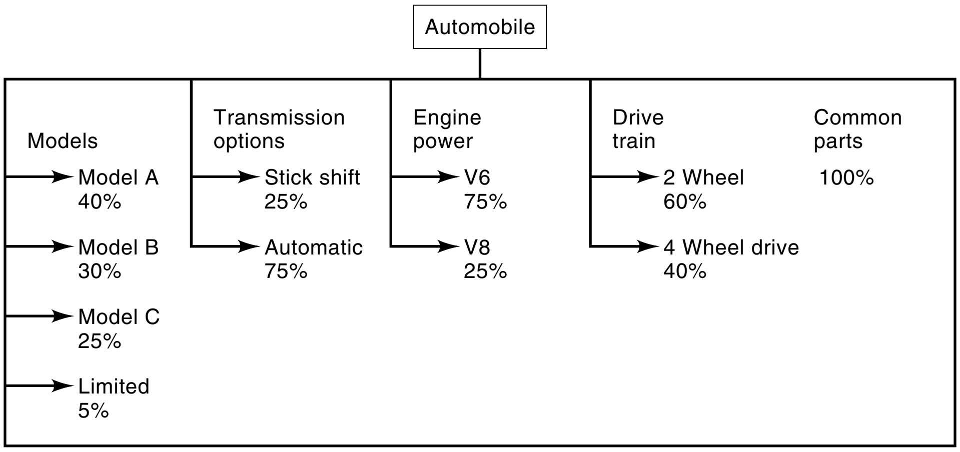


Figure 4. The Planning Bill of Material for the automobile showing the options available in building the end-item: Model, Transmission, Engine Power, Drive Train.

the record of actual customer orders are maintained. Keeping the MPS at options level reduces the delivery lead time and facilitates the forecasting of demand. The major uncertainty is in the product mix. The total of options can be more than 100% to buffer the uncertainty in the product mix.

Make-to-Stock. When the company is building standard products that the customers buy off-the-shelf, then the schedule is based on the forecast demand. Items are built to stock, and demand is satisfied instantaneously from stock. In this environment, MPS is stated in terms of end-products. Customer order promising is based on available-to-promise quantity. The available-to-promise values are calculated for the end-product for those periods where there is an order quantity (these order quantities constitute the MPS). For the first period, available-to-promise is the on-hand plus first-period order quantity (if any) minus the sum of all customer orders until the next period where there is an order quantity. For later periods, available-to-promise is the order quantity minus all customer orders in that and subsequent periods until the next period where there is an order. Since MPS is based on forecast information, customer orders consume the forecast. The forecast errors are monitored, and forecasts and the MPS are updated if needed. The available-to-promise logic facilitates the effective coordination between marketing/sales and production functions. The concept of available-to-promise is demonstrated in the example shown in Table 4.

Note that the MPS row shows production of 40 units of the end-product in weeks 1, 3, and 5. In period 1 the sum of the on-hand quantity and the MPS order quantity is 50. In periods 1 and 2 (until period 3 where there is the next MPS order quantity) the total of customer orders is 25. Therefore, up to a total of 25 units are available-to-promise within periods 1 or 2. In periods 3 and 4, the sum of customer orders is 26. Thus, 16 units are still available-to-promise within periods 3 or 4. In periods 5 and 6, there are no actual customer orders. So the MPS quantity of 40 units in period 5 can be used to promise to customers in period 5 or 6.

Table 4. Order Promising for the End-Product

Periods	1	2	3	4	5	6
Forecast	20	20	20	20	20	20
Customer Orders	18	7	22	4		
On Hand	30	10	28	8	28	8
Available-to-Promise	25		14		40	
MPS Order Quantity	40		40		40	

In environments where the production process involves repetitive manufacturing and flow systems such as assembly lines, the production schedule is typically based on a rate of production and is stable over some period of time. Thus, material planning becomes much less sophisticated. Since item routing on the shop floor is determined by the flow of the line, and components need not wait or go in and out of stock between subsequent operations, tracking material on the shop floor is not needed. This reduces the number of levels in the BOM as well as the number of transactions on the shop floor. Lead times becomes shorter, and material flow on the shop floor can easily be controlled by kanbans. In this kind of environment, Just-in-Time manufacturing techniques can be applied to manage the shop floor operations. The design of the MPC system is thus determined by the market characteristics that the company is facing. See Ref. 80 for a detailed discussion of different MPC environments.

MANUFACTURING RESOURCE PLANNING (MRP II)

It is easy to see that manufacturing planning and control activities are closely related to the activities of other functional areas such as marketing and sales, product/process engineering and design, purchasing, and materials management. The quality of the major inputs to manufacturing planning—namely, the MPS, BOM, and inventory record information—is not determined solely by manufacturing. These inputs are prepared, shared, and updated by other functions within the organization as well. For example, consider the following.

While marketing creates the demand, manufacturing is responsible for producing the parts and products necessary to meet the demand. Therefore, any marketing activity that may influence future demand needs to be confirmed by manufacturing. Thus, as a statement of planned production, MPS provides the basis for making delivery promises via the ATP logic. It is valuable for coordinating the activities of sales and production departments. Any change or update by sales needs to be approved by manufacturing and vice versa.

Changes in BOM impacts product routings and lead times which are used in material and capacity planning. Proper material and capacity planning, therefore, warrants close coordination between manufacturing and engineering so as to maintain valid bills of materials. Any changes in the BOM will have to be agreed upon by both engineering and manufacturing to assure (1) the feasibility of tolerances and (2) the impact of product revisions and new product introductions (where marketing also is involved) on the shop floor system.

Likewise, accounting/finance functions should also use the same data as manufacturing, for making revenue and cost projections. MPS converted to dollars depicts the revenue stream, purchase orders converted to dollars represent the cost of materials, and shop floor activities represented in work orders converted to dollars reflect the labor and overhead costs. In other words, production schedule converted to dollars reflects the cash flow schedule. Discrepancy in the information used by manufacturing and finance/accounting should not be acceptable.

Traditionally, however, each function within an organization had its own way of doing things, with unique databases. Furthermore, communication among the various functional areas has not always been perfect. However, such separation of the activities across functions is artificial. In any business, all activities are interrelated and constitute the whole rather than a collection of different functions. Therefore, the next logical step was to combine the manufacturing activities with those of finance, marketing, purchasing, and engineering through a common database. This recognition led to the evolution of MRP to what is called Manufacturing Resource Planning or MRP II (127).

It is easy to realize that since there is one physical system in operation in a company, there is no justification for having more than one information system representing different dimensions of this physical system. The information system should also be unique and reflect the actual physical system. Thus, MRP systems evolved into MRP II when a common database became available for use by all functions, and any change or update by one functional area would immediately become visible to the rest of the organization.

In addition to integrating the various functional areas within the business, MRP II systems also provide a “what if” capability. It can be used to simulate what would happen if various decisions were implemented, without changing the actual database. This makes it possible to see, for example, the impact on capacity and material requirements of changing the schedule and the impact on customer responsiveness of product design/engineering changes leading to BOM changes.

CONCLUSION

A vast majority of small and large manufacturing companies, around the world, have made significant and substantial investment in MRP II systems and, hence, continue to use MRP II-based systems for manufacturing planning and control (128). A recent survey of U.S. companies covering a wide spectrum of manufacturing industries (ranging from machine tools, automobile components, furniture, plastics, and medical equipment to computers and defense electronics) shows that MRP is the most widely used system (56% of the firms reported using an MRP system) for manufacturing planning and control (129). Furthermore, the American Production and Inventory Control Society (APICS) has listed “improved MRP” systems as one of the top 10 topics of concern to their 80,000 plus members in 1995. Just one MRP system software, MAPICS, has an installed base of an estimated 13000 sites worldwide (130). Recent evidence indicates that there are more than 100 MRP II software products available in the market (131). The dominance of MRP-II systems is further substantiated by a recently completed survey conducted by Advanced Manufacturing Research, Inc. The results suggest that the size of the market for MRP-based production planning and control software in 1993 alone has been over US $2 billion. Thus, it is clear that MRP systems not only continue to dominate the manufacturing planning and control (MPC) in practice but may continue to do so for several years to come (132,133).

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MANUFACTURING SYSTEMS, AUTOMATIC. See AUTOMATION.

MANUFACTURING TECHNOLOGY. See COMPUTER INTEGRATED MANUFACTURING.

MANUFACTURING WITH LASERS. See LASER DESKTOP MACHINING.

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