

Thesis
On
MRP FOR MULTILEVEL FLEXIBLE BOM
Submitted in partial fulfilment of the requirement for the award of the
Degree of
Master of Engineering
IN
PRODUCTION & INDUSTRIAL ENGINEERING

Submitted By:

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CERTIFICATE

This is to certify that the work in this thesis report entitled “MRP FOR MULTILEVEL FLEXIBLE BOM” submitted in partial fulfilment of requirement for the award of **Master of Engineering Degree in Production & Industrial engineering** in Mechanical Engineering Department of Thapar University, Patiala, is an authentic record of work carried out by me under the guidance of **Mr A.S. Jawanda, Associate Professor, Mechanical Engineering Department, Thapar University, Patiala.**

The matter embodied in this report has not been submitted in part or full to any university or institute for the award of any degree. The matter in this report is an original compilation by me with referred material from published literature duly acknowledged.

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ABSTRACT

The Bill of material (BOM) along with the demand is used for making the master production schedule. While all aspects of production are considered as variable traditionally the BOM is invariable i.e. the quantity of parts / sub-assemblies for final product are fixed. In master production schedule time of manufacturing is also not variable with an inflexible bill of material. If there are shortages in any of the components / sub-assemblies of the final product then traditionally in MRP the shortage is compensated by ordering extra in future orders of raw materials and final product deliveries may be delayed.

This work presents a method of compensating for the shortage by varying the BOM within tolerant limits. The compensation for a two level BOM from literature is improved to incorporate a compensation for a multilevel BOM. With the help of this when shortage occur in any sub assembly in second level or in any component in a lower level then a new bill of material is formulated with help of a linear programming model. The requirements of final product (like top assembly) stated in the master production schedule are met in given time by the substitution of other components or produce with a decreased number of components which are within tolerant limits. This concept is developed for multi levels but an example of top assembly is taken for three levels for presenting the concept.

Keywords: Material requirement planning, Flexible Bill-of-Materials (BOM), Master production schedule, Linear programming.

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Chapter 1 INTRODUCTION

1.1 MATERIAL REQUIREMENT PLANNING

1.1.1 DEFINITION

Material requirement planning (MRP) was introduced in the 1960s. It is designed and developed to operate within a predictable and stable batch manufacturing environment. MRP is a set of back scheduling techniques that uses inventory record file data, bill of material (BOM) data, and a master production schedule for the calculation of requirements of material.

CHAKRAVARTY and BALAKRISHAN [8] says that “Material requirement planning system needs to adjust production plans in order to counter the adverse effects caused by various unexpected disturbances or production uncertainties such as unexpected demand increases, tool or machine breakdowns, new product introduction, non- arrival of raw materials, and excessive rejects.”

Material requirements planning (MRP) is the planning methodology for the production of a product that is made of multiple components requires significant coordination to ensure that the component parts are available when they are required for production. This is the segment of examining the coordination that how material requirements panning can accomplish.

TARUN NANDA [22] says, “Materials Requirement Planning system (MRP System) is the function of operations management which ensures that all resources needed to produce finished products are available in the requisite quantity at the right time. In other words, MRP system keeps track of all materials, components and sub-assemblies required for the final product and ensure their availability when needed.”

MRP is computerized system for the management of dependent-demand inventory, scheduling replenishment orders, and meeting demand for end items as given in the Master Production Schedule.

As there is occurrence of unexpected shortages in some of the items in the bill of material, so to overcome these shortages this paper proposes the concept of flexibility in bills of material. Generally, the bill of material for products is fixed. There is no fixed

quantity of items in bill of material as ranges of quantities of lower-level items characterize flexibility.

1.1.2 MRP SYSTEM

Figure 1-1 shows the structure of MRP system: [23]

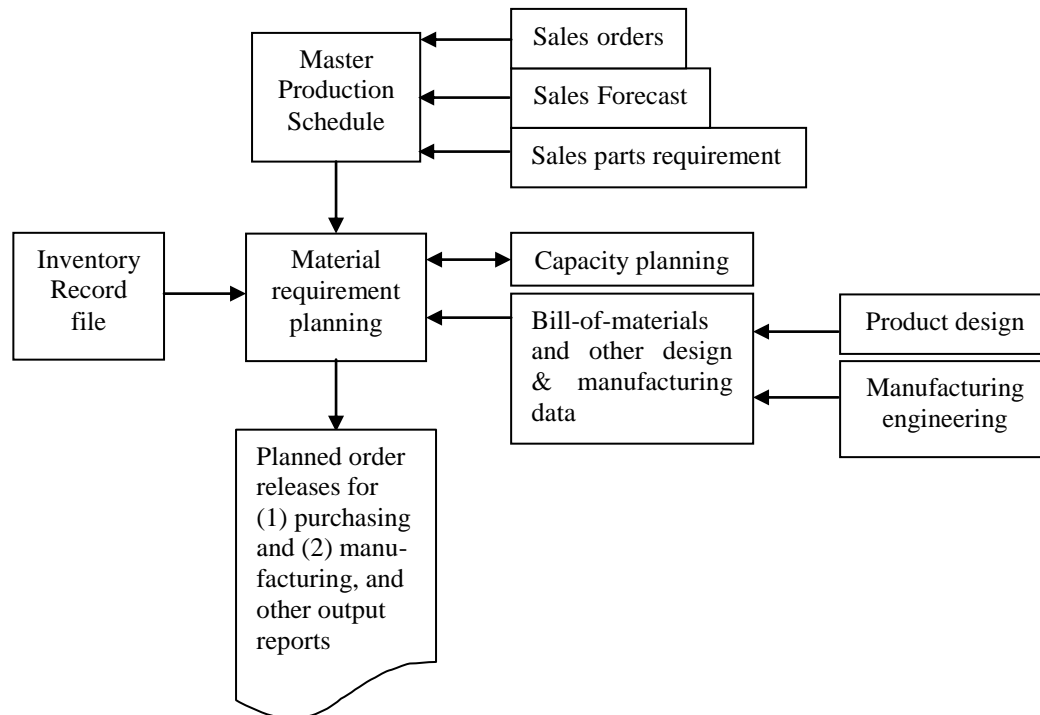


Figure 1-1 Structure of MRP system

1.1.3 EFFECTIVENESS OF MRP SYSTEMS

- MRP system provides a look into the future on an item-by-item basis.
- Under MRP, inventory control is action oriented rather than clerical bookkeeping.
- Order quantities are relating to requirements.
- Inventory investment can be held to a minimum.
- The timing or requirements, coverage and order actions are emphasized.

1.1.3 BENEFITS OF MRP SYSTEM

Following are the Benefits: [22]

- 1) Material Requirement Planning (MRP system) calculates the (dependent) demand of components from the master production schedule (MPS) of their parents and provides a better forecast of component requirements. This helps in ensuring availability of components; parts etc. at the right time, helps in reducing their inventory levels, better utilization of labour and capacity and ultimately better customer service.

- 2) Material Requirement Planning (MRP system) provides information on whether the tentative MPS prepared is practically feasible or needs a revision. Master Production Schedule gives information on how many products of which type have to be made in what period of time, what priority is to be followed etc. MRP takes this information and finds out what materials (to be purchased), what parts, components, subassemblies etc. (to be purchased or manufactured in-house) would be needed in different periods. It compares this entire requirement with available in-house capacity, supplier limitations, and tells whether the given schedule can be met or needs a revision. Only when MPS meets all capacity constraints, supplier constraints, can it be accepted and MRP plays an important role in it.
- 3) MRP system automatically updates the dependent demand and inventory replenishment schedules of components when the production schedule of parent items change. The MRP system alerts the planners whenever action is needed on any component.

Table 1-1 Difference between traditional system and MRP system [13]

TRADITIONAL SYSTEMS	MRP SYSTEMS
Part oriented	Product/component oriented
Independent demand	Dependent demand
Continuous item demand	Discrete demand
Recorder point order signal	Time phased order signal
Forecast of all items	Forecast of end items only
Quantity based	Quantity and time based
Safety stock of all items	Safety stock of end items only

1.1.4 SCOPE OF MRP IN MANUFACTURING

MRP is having scope in many areas of manufacturing: [24]

The basic function of MRP system includes inventory control, bill of material processing and elementary scheduling. MRP helps organizations to maintain low inventory levels. It is used to plan manufacturing, purchasing and delivering activities.

"Manufacturing organizations, whatever their products, face the same daily practical problem - that customers want products to be available in a shorter time than it takes to make them. This means that some level of planning is required."

Companies need to control the types and quantities of materials they purchase, plan, which products are to be produced, and in what quantities and ensure that they are able to meet current and future customer demand, all at the lowest possible cost. Making a bad decision in any of these areas will make the company lose money.

1.1.5 CHARACTERISTICS OF PRODUCTIVE SYSTEMS

- MRP derives demand for subassemblies, components, materials, etc., from the production schedules of parent items.
- MRP offsets replenishment orders (purchase orders) relative to the date when replenishment (purchase) needed.
- Small lot sizes of materials as compared with variability.
- Relatively short and reliable lead times for materials purchased from suppliers.
- Production processes requiring long processing times.

1.1.6 OBJECTIVES OF THE MRP

- **Reduction in Inventory Cost:** By providing the right quantity of materials at right time to meet master production schedule, Material Requirements Planning (MRP) tries to avoid the cost of excessive inventory.
- **Meeting Delivery Schedule:** By minimizing the delays in materials procurement, production decision making, Material Requirements Planning (MRP) helps to avoid delays in production thereby meeting delivery schedules more consistently.
- **Improved Performance:** By stream lining the production operations and minimizing the unplanned interruptions, Material Requirements Planning (MRP) focuses on having all components available at right place in right quantity at right time.
- **Realistic delivery commitments:** By using Material Requirements Planning (MRP), production can give marketing timely information about likely delivery times to prospective customers.

1.1.7 INFORMATION FOR MRP

MRP needs information: [25]

- Demand for all products.
- Lead times for all finished goods, components, parts and raw materials.
- Lot sizing policies for all parts.

- Opening inventory levels.
- Safety stock requirements.
- Any orders previously placed but which haven't arrived yet.

1.1.8 INFORMATION FROM MRP

MRP obtaining information: [25]

- Planned orders: replenishment orders to be released at a future time.
- Order release notice: notices to release planned orders.
- Action notices: notices to expedite, de-expedite, or cancel orders, or to change order quantities or due dates.
- Priority reports: information regarding which orders should be given priority.
- Inventory status information.
- Performance reports such as inactive items, actual lead times, late orders, etc.

1.1.9 TYPES OF DEMAND

There are two types of demand: [22]

- a) Independent demand
- b) Dependent demand

1.1.9 (a) Independent Demand

Independent Demand of a manufacturing organization is the demand whose quantity or value is influenced by market conditions or other factors but does not depend upon demand of other items produced by the organization or held in its inventory. Independent demand is determined through demand forecasting, customer orders etc. The demand of different type of end items (finished products) produced by an organization comprises its independent demand.

1.1.9 (b) Dependent Demand

Dependent Demand of a company means the demand the magnitude of which depends upon the demand of other items held in inventory.

1.2 INPUTS FOR MRP SYSTEM

There are three main inputs required for preparing a material requirement planning system (MRP system) [22]. The following are the inputs described as follows:

1. Bill of Material
2. Master Production Schedule
3. Inventory Record Database

1.2.1 BILL OF MATERIAL

A BOM can define products as they are designed (engineering bill of materials), as they are ordered (sales bill of materials), as they are built (manufacturing bill of materials), or as they are maintained (service bill of materials). The different types of BOMs depend on the business need and use for which they are intended. In process industries, the BOM is also known as the formula, recipe, or ingredients list. In electronics, the BOM represents the list of components used on the printed wiring board or printed circuit board. Once the design of the circuit is completed, the BOM list is passed on to the PCB layout engineer as well as component engineer who will procure the components required for the design.

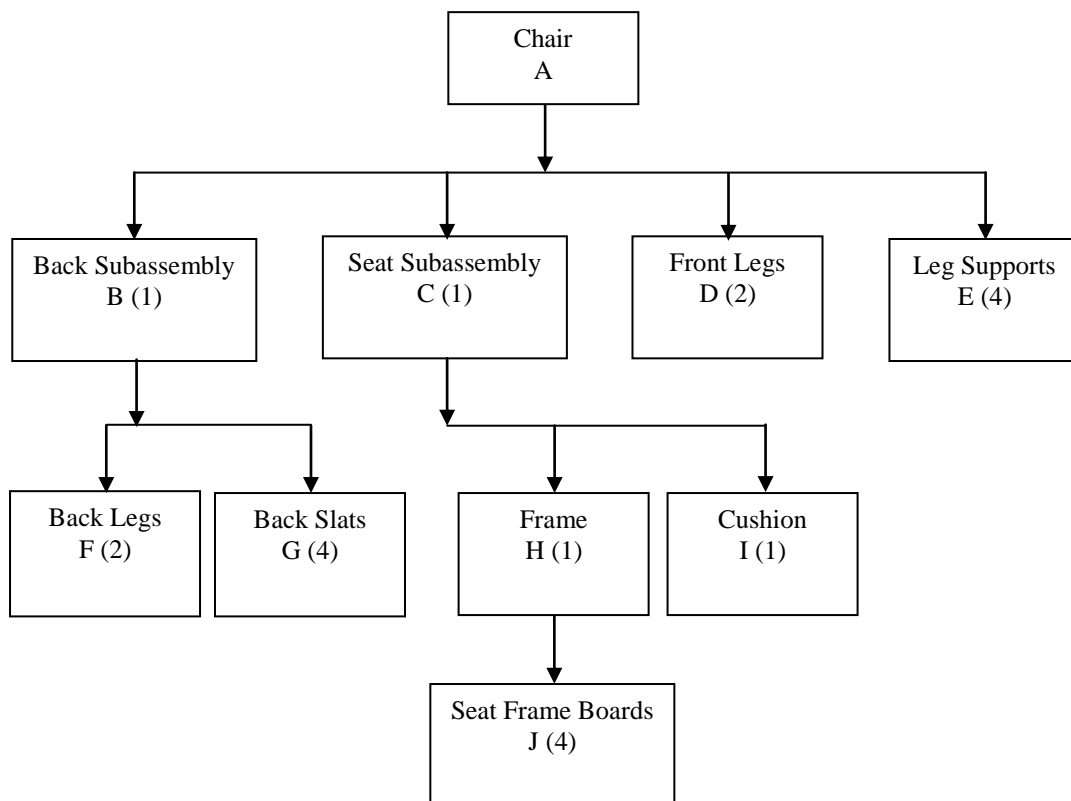


Figure 1-2 Parent-component relation and usage of quantities (BOM) for the chair

The following can be noted about the finished product a (chair) and it's various parts.

A: only a parent and not a component.

B, C and H: Both parent and component. For example, part B is component of finished product A and is parent to parts F and G.

D, E, F, G, I, J are only components.

From the inventory point of view, the following terms are important:

End Item (A): It is the final product (finished goods) sold to the customer. It is a parent and not a component. In accounting statements, inventory of end items is classified as finished goods inventory.

Intermediate Items (B, C, And H): These are items having at least one component and at least one parent. Inventory of these items whether completed or on shop floor is classified as work in progress (WIP). Intermediate items are made from one or more type of components.

Subassembly: It is an intermediate item made by assembling more than one type of components. In the chair example; B, C and H are Intermediate Items. B, C are Subassemblies but H is not. Inventory of subassemblies is classified as WIP.

Purchased items: These items come from the supplier. These have a number of components and one or more parents. Inventory is considered as raw materials.

A BOM can be displayed in the following formats:

- A **single-level BOM** that displays the assembly or sub-assembly with only one level of children. Thus, it displays the components directly needed to make the assembly or sub-assembly.
- An **indented BOM** that displays the highest-level item closest to the left margin and the components used in that item indented more to the right.

Types of Bill of Material

Following are the types of BOM: [26]

i. Standard Bill of material

A standard bill of material is the most common type of bill and lists the mandatory components, the required quantity of each component, and information to control work in process, material planning, and other Oracle Manufacturing functions. Examples include bills for manufacturing assemblies, pick-to-order bills, kit bills, and phantoms.

A configuration bill (a type of standard bill) is a set of option choices made from a model bill that comprise a buildable, sellable product. Configuration items and bills are automatically created from model bills after a customer chooses options on a sales order. Alternatively, you can manually create configuration bills by choosing options directly from a model bill.

ii. Model Bill of material

A model bill of material defines the list of options and option classes you can choose in Oracle Order Entry to order a configuration. A model bill also specifies mandatory components or included items that are required for each configuration of that model. You do not order or build the model itself: you order and build configurations of the model. A model bill can be either assemble-to-order or pick-to-order.

iii. Option class Bill of material

An option class is an item that groups optional components on a bill. An option class is an item that becomes a level in your model bill of material. Option classes can also have mandatory components that apply for all of its options. For example, when you order a computer, the monitor is an option class, and the specific type of monitor you order is an option within that option class. An option class bill can be either assemble-to-order or pick-to-order.

iv. Planning Bill of material

A planning bill of material is a bill of material structure that includes a percentage distribution for its components. The percentages associated with the components on a planning bill of material do not need to add to 100%. You can define alternate and common planning bills, where the bill you reference as a common must be another planning bill. Planning items can be nested within one another

any number of times. When you nest planning items, Oracle Master Scheduling explodes forecasts level by level and applies planning percentages at each level.

v. Engineering Bills of Material

You can define an engineering bill of material as an alternate for a manufacturing bill. The typical use for an alternate engineering bill is to prototype variations from the primary bills that produce the same assembly.

You can specify a list of item catalog descriptive elements for model and option class engineering bills. After you, release the engineering bill to manufacturing, take configuration item, and automatically assigns values to each catalog descriptive element.

Oracle engineering users are allowed to assign manufacturing and engineering items as components to an engineering bill. Bill of Material users can assign only manufacturing items as components to manufacturing bills.

1.2.2 MASTER PRODUCTION SCHEDULE

A Master Production Schedule or MPS is the plan that a company has developed for production, inventory, staffing, etc. It sets the quantity of each end item to be completed in each week of a short-range planning horizon. A Master Production Schedule is the master of all schedules. It is a plan for future production of end items. **MPS INPUTS:** Forecast Demand, Production Costs, Inventory Costs, Customer Orders, Inventory Levels, Supply, Lot Size, Production Lead Time, Capacity **MPS OUTPUT** (production plan): Amounts to be Produced, Staffing Levels, Quantity Available to Promise, and Projected Available Balance.

The Master Production Schedule gives production, planning, purchasing, and top management the information needed to plan and control the manufacturing operation. The application ties overall business planning and forecasting to detail operations through the Master Production Schedule.

The Master Production Schedule will drive detailed material and production requirements in the Material Requirements Planning module.

“Master production schedule” schedules do not include every aspect of production, but only key elements that have proven their control effectively, such as forecast demand,

production costs, inventory costs, lead time, working hours, capacity, inventory levels, available storage, and parts supply

A **master production schedule** may be necessary for organizations to synchronize their operations and become more efficient. An effective MPS ultimately will:

- Give production, planning, purchasing, and management the information to plan and control manufacturing
- The overall business planning and forecasting to detail operations.
- Enable marketing to make legitimate delivery commitments to warehouses and customers
- Increase the efficiency and accuracy of a company's manufacturing.

1.2.3 INVENTORY RECORD DATABASES

The third and final input required to prepare MRP is 'Inventory Record'. Inventory records are prepared from inventory transactions which include receiving the scheduled receipts, adjusting due dates for scheduled receipts, releasing new orders, cancelling orders, withdrawing inventory etc. By recording these transactions, we obtain the inventory record database.

Inventory Record divides the future time horizon into time intervals called 'Time Buckets'. Time buckets can be in hours, days, weeks etc. depending upon planning periods being used in the corresponding MPS.

Inventory Record shows an item's, Lot Size Policy, Lead Time and other time-phased data. The purpose of inventory record is to keep track of inventory levels and component replenishment needs. The time-phased information contained in the inventory record consists of:

- Gross Requirements
- Scheduled Receipts
- Projected On Hand Inventory
- Planned Receipt

Chapter 2 LITERATURE REVIEW

2.1 MATERIAL REQUIREMENTS PLANNING VARIANTS

The material requirement planning systems have been addressed by the methods of dampening the system nervousness. These methods have been reviewed in the literature by Blackburn et al. [1], Murthy and Ma [2], and Yeung et al. [10] Plenert et al. [11] reviews the development of material requirements planning, here they discusses both the successes and failures of material requirements planning and investigates the consequences of these failures and the ways to correct them.

Research by the KADIPASAOGLU and SRIDHARAN [5] shows that safety stock and safety lead-time are two widely used, inventory oriented approaches to cope with system uncertainty. Safety stock generates net requirements to ensure a minimum level of inventory at all times. It absorbs changes at the top level, thus reducing the amount of nervousness transmitted to lower levels.

Koh et al. [18] Safety lead times inflate production lead times at the component level. They are used to cope with time uncertainty such as delivery delays. Safety lead times are always preferable to safety stocks. Similar results for different production configurations (e.g. multi-stage, multi-product manufacturing) are also reported by Buzacott and Shanthikumar [4], Molinder [6] and Krishnamurthy et al. [20].

Hegedus and Hopp [14] state that product level safety stock is a less efficient approach for addressing system nervousness because it increases the inventory level for the entire bill of material rather than specific components.

Freezing the MPS within the planning horizon is a method popularly used in industry. This method implements only a portion of the MPS to reduce the impact of changes in customer demand or demand forecasts. It attempts to provide a balance between schedule instability and cost through the selection of a proper freeze interval. Zhao et al. [3] and [7] presents two methods of freezing MPS, e.g. one is freezing the MPS for material requirements planning systems under demand uncertainty and another one is lot- sizing rules and freezing the MPS in material requirements planning.

KADIPASAOGLU and SRIDHARAN [5] evaluate the effectiveness of three strategies for reducing nervousness: freezing, end-item safety stock, and lot-for-lot. They show that freezing the MPS is the most effective strategy for reducing the schedule instability.

KADIPASAOGLU and SRIDHARAN [5] have been proposed that the forecasting beyond the planning horizon has been used to smooth out the cost error. The effectiveness of this approach depends on the accuracy of the demand forecasts and the level of variability in demand. Zhao and Lee [3] report that forecast errors significantly increase total costs and scheduling instability, and influence the selection of some MPS freezing parameters. This paper investigates the impact of MPS freezing parameters on the total cost, schedule instability and service levels in multilevel MRP systems under demand uncertainty conditions. HO and Ireland [9] examines the impact of forecasting errors on the scheduling instability in a Material Requirements Planning (MRP) operating environment.

Zhao and Lam [7] study examines the impact of lot sizing rule selection on the selection of MPS freezing parameters under rolling time horizons under deterministic demand and a model is built to simulate the master production schedule and material requirements planning operations in a make to order environment.

ENNS S. T [16] investigates the effect of forecast bias and demand uncertainty in a batch production environment. He concludes that it is not advisable to use 'over' forecasting. Minimizing forecasting error and then controlling for time and quantity uncertainty by using appropriate planned lead times and safety stock would appear to be the best approach. Ho C. J [17] states that the lot sizing rule creates the most nervous material requirements planning schedule because it reacts to every schedule change in MRP systems.

Significant studies using other methods to deal with MRP system nervousness have been reported. Alfieri et al. [15] use LP-based heuristics for the capacitated lot-sizing problem. The motivation behind the use of LP based heuristics is that their extension to cope with complicating features (to be expected, for example, when dealing with a master production scheduling problem within a MRP system) is generally easier than with alternative approaches such as Lagrange's relaxation.

Chakravarty and Balakrishan [8] presents a PC based procedure for the real time revision of production and inventory schedules in a capacitated flexible manufacturing cell, so as to counter the impact of production contingencies (defined as unanticipated disturbances that force a revision in the schedule). Clark [19] develops three Mixed Integer

Programming (MIP) models and solution methods to assist in identifying a capacity-feasible MPS in MRP systems.

Du and Wolfe [12] propose an active MRP system. They design a fuzzy logic controller as a front-end tool to translate demand uncertainty into fuzzy sets, which are then processed by the neural network. The fuzzy logic controller is associated with order quantities, safety stock and next ordering period in order to make bucket less and real-time decisions.

Bala Ram et al. [21] states that if time and quantity as stated in MPS is not flexible for final product then flexible BOM may be introduced to compensate for the inflexibility in the MPS. This paper addresses situations where a flexible BOM could be used to deal with unexpected shortages. A flexible BOM may allow a tolerance-like range (variations) in the quantity of lower-levels, which gives the opportunity to execute the original production plan under unexpected component shortages in the BOM of end product, and here all other parameters like lead time, lot size, lower and upper limits are fixed.

2.2 GAPS IN THE LITERATURE

Most of the literature on MRP related research has taken fixed BOMs for products. When any change occurs in any of the input parameters assumed to be fixed or invariable like BOM, lot size, lead time, production plan, planning horizon, price of inputs and logistics, etc. the MRP system adapts the schedule or production plan to make up for the change considering any one or more measured criteria like cost, time, etc. to get an optimum MRP.

One of the researches [21] considers shortages that occur in MRP system with flexible BOM. Many issues need to be address in the future. First, how to apply the proposed idea to BOM with more than two levels i.e. three, four and for multilevel. How to deal with unexpected shortages in lower level sub-assemblies and components in the BOM? Whether to use similar LP model implementation at each level. This will add some complications to the logic and to the LP model. For example, consider a shortage in item A in Figure 2-1. One approach is to use the LP model to find k_1 , k_2 , and k_3 . Since changes from ks_1 , ks_2 and ks_3 to k_1 , k_2 and k_3 respectively, will lead to changes from in the PORL tables of the immediate lower level, then we have a need to solve a new LP model to find the values of k_4 , k_5 , k_6 , k_7 and k_8 . If there are more than three levels, then we must solve a LP model for each intermediate level until the last level or until finding an unfeasible solution.

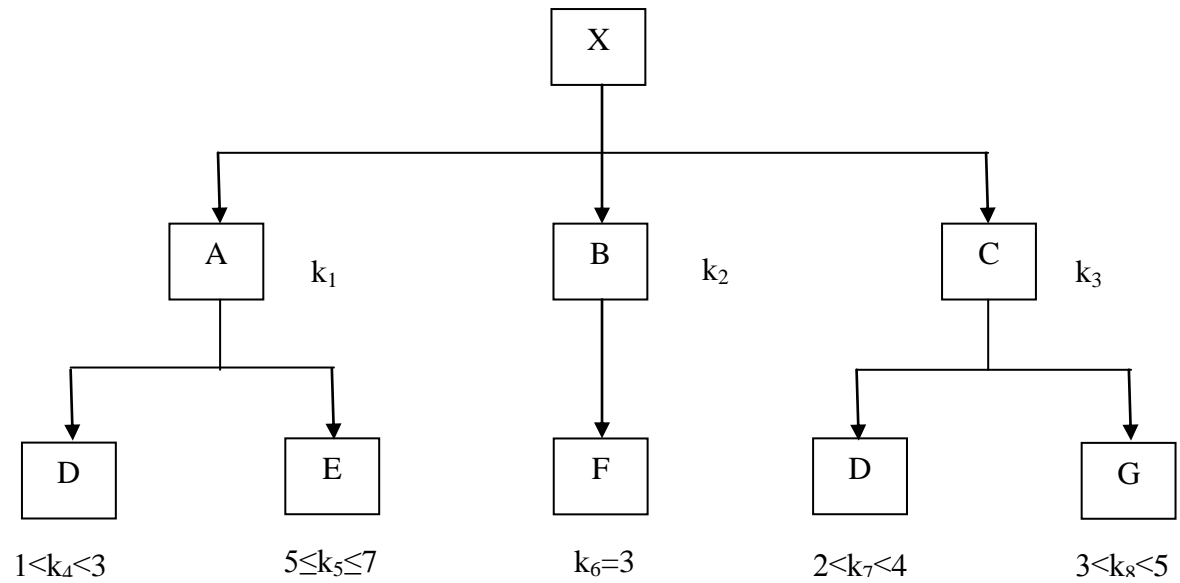


Figure 2-1 An example of complex BOM

However, it should be pointed out that an optimal solution of the LP model at the level of A, B and C items might make the LP model at the level of D, E, F and G items unfeasible. A feasible, rather than optimal, solution on the level of A, B and C items could lead to a feasible solution at the lower level. Therefore, the proposed LP model needs to be modified so that it can take into account all lower levels at the same time, for BOMs with three or more levels.

Another issue is how to use the flexible BOM approach when there are common parts in the BOM. For instance, in the Figure 2-1, if an unexpected shortage occurs for item D which has parent items A and C, then the constraint BOMLP-C3 for item D will be a single constraint involving k_4 and k_7 :

$$(\text{POH}_{t-1}^D + \text{SR}_t^D) \geq (k_4 * \text{PORL}_t^A + k_7 * \text{PORL}_t^C).$$

Chapter 3 PROBLEM DEFINITION

From the gaps in the literature, it is concluded that there is a lot of scope for improvement of the methods available for MRP. One of the methods of MRP for a product with a flexible BOM presented by **BALA RAM** and **M REZA** [21] has been discussed. This uses a linear programming (LP) model for the calculation of parameters required for MRP by considering a single top level (level 1) product, which only uses components from one lower level (level 2). The BOM of the level one assembled product can have a variable proportion of components from the level two, within defined tolerance. This has been applied and presented for an assembly of a ‘Salad’ food item, which has three ingredients of ‘lettuce’, ‘tomato’ and ‘carrot’. It did not consider any other ingredient, which could itself be an assembly of components like a ‘salad dressing sauce’. This would involve a level three or possibly a level 4 component assembly.

This thesis work attempts to address these limitations of two level of BOM considered for the MRP. An iterative approach is tried and tested on an example for solving two suggested improvements.

1. A multi-level BOM with a LP model implementation at each level.
2. Common components/sub-assembly at different levels.

The following representatives BOMs are targeted and tested in Figure 3-1 and Figure 3-2 on one representative example. The implementation has further been generalised and an algorithm developed to make it possible to have a multilevel BOM. This has been presented as a flowchart in the implementation and practically programmed using C language.

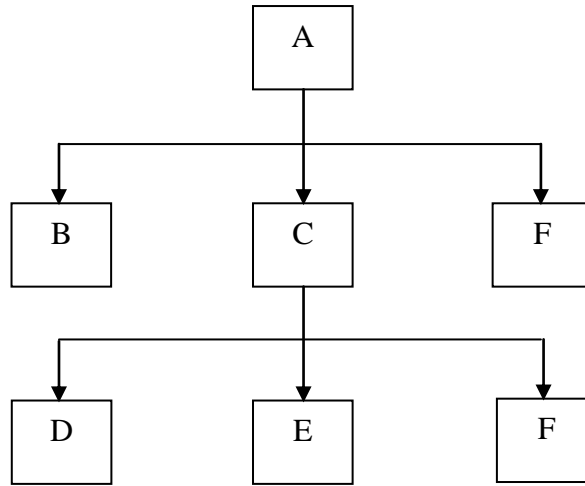


Figure 3-1 Three level BOM with component common at level 2 and 3

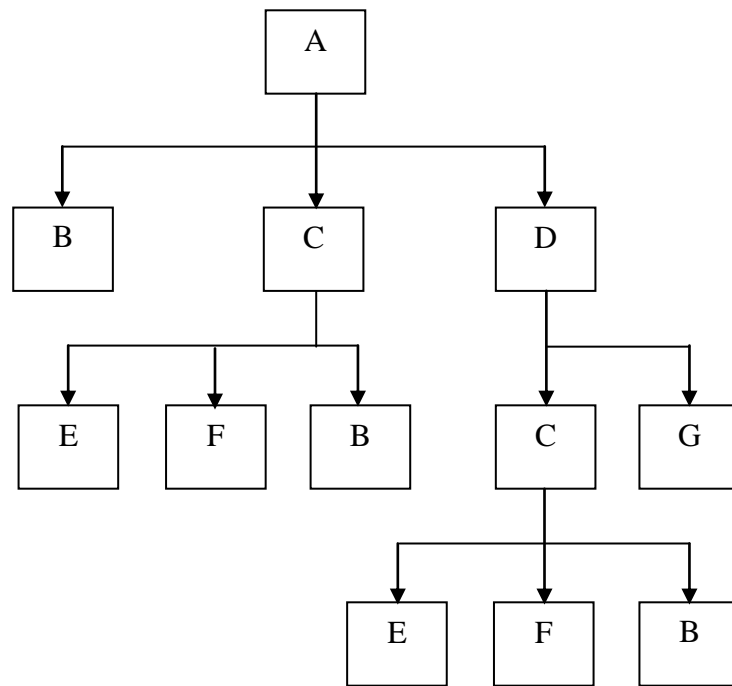


Figure 3-2 Four level BOM with sub assembly common at different level

Chapter 4 IMPLEMENTATION

4.1 TESTING OF TWO LEVEL BILL OF MATERIAL

The two level flexible BOM problem of a ‘Salad’ assembly presented in the paper by BALA RAM and M REZA [21] has been used as a base to test the implementation of the MRP program developed under this thesis. This is then further extending to a multi level BOM problem, which now tested for a three level flexible BOM that is presented in the end of this chapter.

Comparison of the results and the variations are discussed below.

NOTE: The results presented in tables have been tested by solving the example LP manually and the program developed in C and compared with the reported results. Only where these are different from the reported ones in the literature they are written in the table after the ‘/’ marked with ‘*’.

Flexible Bill of Material (BOM)

In this example, the menu item is taken as “Garden Salad” with three no. of ingredients. The preferred combination of items to make one unit of salad is five units of lettuce, four units of tomatoes, and three units of carrots. At times, there is the possibility of a shortage of one or more items due to unforeseen failures in the production process. Figure 4-1 introduces an alternative recipe allowing some flexibility in the proportions of the combination. The flexibility allows the items to compensate for one another in the case of a shortage.

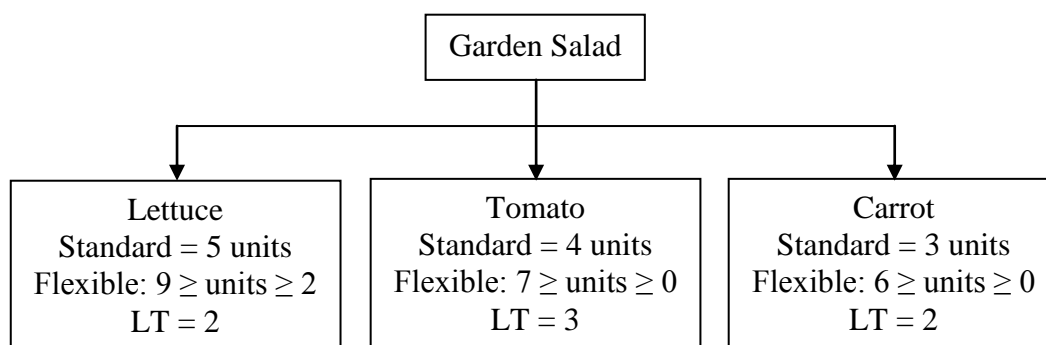


Figure 4-1 A flexible BOM for salad [21]

The MPS for the example is shown in Table 4-1. Period 4 and period 6 is when some unexpected problems occur (discussion below), which requires replenishing using the

flexible BOM approach. It is for this reason that the MPS for the seven-period planning horizon is shown in periods 1, 4 and 6.

Table 4-1 Master production schedule for periods 1-12 [21]

(a) Master production schedule for periods 1-7									
	Independent demand	1	2	3	4	5	6	7	
Planning horizon: Seven periods	Salad	5	8	7	4	6	9	3	
(b) Master production schedule for periods 4-10									
Name: Salad	Independent demand	4	5	6	7	8	9	10	
Planning horizon: Seven periods	Salad	4	6	9	3	5	8	7	
(c) Master production schedule for periods 6-12									
Name: Salad	Independent demand	6	7	8	9	10	11	12	
Planning horizon: Seven periods	Salad	9	3	5	8	7	4	6	

Planned Order Release (PORL) tables for periods 1 through 7 (Table 4-2) using the original BOM (5, 4, and 3) are generated. In this example, assume that the scheduled orders come in period 4. In Table 4-2, the net requirement for lettuce in period 4 is 11 units. In order to meet this requirement, an order of 11 units for lettuce has to be placed in period 2, since the lead-time for lettuce is two periods; this order is shown in period 4 of Table 4-2 as a PORL for lettuce.

Table 4-2 Planned orders release table for periods 1-7

Salad									Lettuce								
Period		1	2	3	4	5	6	7	Period		1	2	3	4	5	6	7
GR		5	8	7	4	6	9	3	GR		25	40	35	20	30	45	15
SR		0	0	0	0	0	0	0	SR		0	0	0	0	0	0	0
POH		0	0	0	0	0	0	0	POH	65	40	0	0	0	0	0	0
NR		5	8	7	4	6	9	3	NR		0	0	35	11	30	42	13
POR		5	8	7	4	6	9	3	POR		0	0	44	11	33	44	22
PORL	0	5	8	7	4	6	9	3	PORL	0	44	11	33	44	22	0	0
Tomato									Carrot								
Period		1	2	3	4	5	6	7	Period		1	2	3	4	5	6	7
GR		20	32	28	16	24	36	12	GR		15	24	21	12	18	27	9
SR		0	0	0	0	0	0	0	SR		0	0	0	0	0	0	0
POH	80	60	28	0	0	0	0	0	POH	39	24	0	0	0	0	0	0
NR		0	0	0	16	22	31	7	NR		0	0	21	12	16	22	3
POR		0	0	0	18	27	36	9	POR		0	0	21	14	21	28	7
PORL	0	18	27	36	9	0	0	0	PORL	0	21	14	21	28	7	0	0

GR (gross requirements) SR (scheduled receipts) POH (projected on-hand) NR (net requirements) POR (planned order receipts) PORL (planned order releases) lot method is fixed order quantity for salad=1, lot method is fixed order quantity for lettuce=11, lot method is fixed order quantity for tomato=9, lot method is fixed order quantity for carrot=7.

Values obtained by implementation in Table 4-2 are the same as reference literature.

When period 4 arrives it is finding that due to the breakdown of harvesting equipment, the actual order received for lettuce is 7 units instead of 11 units. This is shown in Table 4-3 as a schedule receipt for the lettuce in period 4. Consequently, there is a NR of 4 units for the lettuce in period 4 and this means that the requirement stated in the MPS cannot be met in period 4. However, the flexibility of the BOM for salad could permit the MPS to be met in period 4 using a different proportion of ingredients. The LP problem (BOMLP) can be formulated for this situation and shown in Figure 4-2.

Table 4-3 Planned order release table for periods 4-10

Salad									Lettuce								
Period		4	5	6	7	8	9	10	Period		4	5	6	7	8	9	10
GR		4	6	9	3	5	8	7	GR		20	30	45	15	25	40	35
SR		0	0	0	0	0	0	0	SR		7	33	0	0	0	0	0
POH		0	0	0	0	0	0	0	POH	9	0	3	0	0	0	0	0
NR		4	6	9	3	5	8	7	NR		4	0	35/42*	6/13*	20/16*	38/34*	29/25*
POR		4	6	9	3	5	8	7	POR		0	0	44	11/22*	22	44	33
PORL	0	4	6	9	3	5	8	7	PORL	0	44	11/22*	22	44	33	0	0
Tomato									Carrot								
Period		4	5	6	7	8	9	10	Period		4	5	6	7	8	9	10
GR		16	24	36	12	20	32	28	GR		12	18	27	9	15	24	21
SR		18	27	36	0	0	0	0	SR		14	21	0	0	0	0	0
POH	0	2	5	5	0	0	0	0	POH	0	2	5	0	0	0	0	0
NR		0	0	0	7	18	32	24	NR		0	0	22	3	11	21	21
POR		0	0	0	9	18	36	27	POR		0	0	28	7	14	21	21
PORL	0	9	18	36	27	0	0	0	PORL	0	28	7	14	21	21	0	0

GR (gross requirements) SR (scheduled receipts) POH (projected on-hand) NR (net requirements) POR (planned order receipts) PORL (planned order releases) lot method is fixed order quantity for salad=1, lot method is fixed order quantity for lettuce=11, lot method is fixed order quantity for tomato=9, lot method is fixed order quantity for carrot=7.

The values obtained by implementation in Table 4-3 are not the same as the reference literature. Values from reference are written in the table along with accurate values, after the '/', obtained by our implemented program marked by "*".

Discussion of the difference in the results:

The values of net requirements (NR) of lettuce written in the reference are not correct because NR is the difference of GR and POH inventory e.g. NR (sixth period) = 45-3 i.e. 42. The same way net requirement in all other periods gets modified. The value of net requirement in 7th period is 13, then the order release in 5th period should be of 22, because it is a multiple of lot size, which is 11). The value of POR in 7th period also changes to 22, because the lead time for lettuce is 2.

On solving the LP problem, the k_i values for period 4 are $k_1=4$, $k_2=4.5$ and $k_3=3.5$. The k_i values will change the gross requirements for the items due to the shortage of lettuce.

The gross requirement for the lettuce is reduced to 16 from 20, which can now be reached by 9 units on-hand and 7 units of scheduled receipt.

BOMLP-OBJ: Minimize: $\Delta^+_1 + \Delta^+_2 + \Delta^+_3$		
Subject to:		
1.	BOMLP-C1: $k_1 + k_2 + k_3 = 12$	
2.	C2: $k_1 - \Delta^+_1 + \Delta^-_1 = 5$	
3.	$k_2 - \Delta^+_2 + \Delta^-_2 = 4$	
4.	$k_3 - \Delta^+_3 + \Delta^-_3 = 3$	
5.	C3: $-(k_1 * 4) + (9+7) \geq 0$	$\rightarrow k_1 \leq 4$
6.	$-(k_2 * 4) + (0+18) \geq 0$	$\rightarrow k_2 \leq 4.5$
7.	$-(k_3 * 4) + (0+14) \geq 0$	$\rightarrow k_3 \leq 3.5$
8.	C4: $2 \leq k_1 \leq 9$	
9.	$0 \leq k_2 \leq 7$	
10.	$0 \leq k_3 \leq 6$	

Figure 4-2 Linear programming model for shortage shown in period 4 of Table 4-4

For shortage of lettuce in period four (4) $k_1 = 4$, $k_2 = 4.5$, and $k_3 = 3.5$, are the values obtained by implementation in Figure 4-2, are the same as reference literature.

The gross requirements for the tomato and carrot are changed to compensate for the shortage of lettuce and they are increased to 18 from 16 for tomato, and to 14 from 12 for carrot. Compensation for this period was possible because positive inventory was carried on-hand. Since period 4 is the current period, the PORL tables are extended to period 10, the entire planning horizon, in order to determine if there will be any more shortage due to that in period 4 (Table 4-5). For periods 5 through 10, the standard quantity of items (ksi) is used because the goal is always to use the default BOM whenever possible. Note that, for periods 5 through 10 in Table 4-5 the gross requirement for lettuce, tomato, and carrot are obtained by multiplying the PORL in each period by 5, 4, and 3, respectively, the values 5, 4, and 3 are values of standard size (ksi) of lettuce, tomato and carrot. In this case, no more shortages occur after period 4.

Table 4-5 Fully adjusted Planned Order release table for periods 4-10

Salad									Lettuce								
Period		4	5	6	7	8	9	10	Period		4	5	6	7	8	9	10
GR		4	5/6*	6/9*	7/3*	8/5*	9/8*	10/7*	GR		16	30	45	15	25	40	35
SR		0	0	0	0	0	0	0	SR		7	33	0	0	0	0	0
POH		0	0	0	0	0	0	0	POH	9	0	3	0	0	0	0	0
NR		4	6	9	3	5	8	7	NR		0	0	42	13	16	34	25
POR		4	6	9	3	5	8	7	POR		0	0	44	22	22	44	33
PORL	0	4	6	9	3	5	8	7	PORL	0	44	22	22	44	33	0	0
Tomato									Carrot								
Period		4	5	6	7	8	9	10	Period		4	5	6	7	8	9	10
GR		18	24	36	12	20	32	28	GR		14	18	27	9	15	24	21
SR		18	27	36	0	0	0	0	SR		14	21	0	0	0	0	0
POH	0	0	3	3	0	0	0	0	POH	0	0	3	0	0	0	0	0
NR		0	0	0	9	20	25	26	NR		0	0	24	5	13	23	16
POR		0	0	0	9	27	27	27	POR		0	0	28	7	14	28	21
PORL	0	9	27	27	27	0	0	0	PORL	0	28	7	14	28	21	0	0

GR (gross requirements) SR (scheduled receipts) POH (projected on-hand) NR (net requirements) POR (planned order receipts) PORL (planned order releases) lot method is fixed order quantity for salad=1, lot method is fixed order quantity for lettuce=11, lot method is fixed order quantity for tomato=9, lot method is fixed order quantity for carrot=7.

The values of the gross requirement of salad obtained by implementation in the Table 4-5 are not the same as the reference literature. Values from the reference are written in the above table along with accurate values, after the '/', obtained by our implemented program marked by "*".

Discussion of the difference in the results:

The gross requirements of salad is not correct because the GR of lettuce, tomato and carrot is obtained by the multiplication of their standard quantity with the GR of salad e.g. the standard size of these three ingredients is 5, 4 and 3 and the gross requirements in 5th period are 30, 24 and 18. These gross requirements are the multiple of 6 not 5 with standard quantities. Hence, the gross requirement of Salad in all other periods gets modified.

The shortage in period 4 could be dealt with by adjusting or compensating the proportions in the BOM. This did not lead to further shortages in periods 5 through 10. It is assumed that an order of 36 units of tomatoes released in period 3 was to arrive in period 6. However, only 28.5 units were received instead of 36 units. The procedure used for

period 4 is repeated for period 6 to address this shortage. The BOMLP formation for this problem is shown in Figure 4-3 (Table 4-6). By solving the LP model, the k_i values for the problem are $k_1=5.22$, $k_2=3.5$ and $k_3=3.28$ (shown in Figure 4-3).

These values are implemented in PORL tables and the planning horizon is extended to period 12 Table 4-8 and Table 4-10. Table 4-8 shows that, by implementing the new values of k_i in the model, the problem in period 6 is resolved but a shortage of tomatoes occurs again in period 7. In addition, a shortage of carrots also occurs in period 7. The BOMLP to deal with these shortages in period 7 is formulated and shown in Figure 4-4, and the k_i values are $k_1=6.18$, $k_2=3$ and $k_3=2.82$

Table 4-6 Planned Order release table for periods 6-12

Salad								Lettuce									
Period		6	7	8	9	10	11	12	Period		6	7	8	9	10	11	12
GR		9	3	5	8	7	4	6	GR		45	15	25	40	35	20	30
SR		0	0	0	0	0	0	0	SR		44	22	0	0	0	0	0
POH		0	0	0	0	0	0	0	POH	3	2	9	0	0	0	0	0
NR		9	3	5	8	7	4	6	NR		0	0	16	34	25	12	20
POR		9	3	5	8	7	4	6	POR		0	0	22	44	33	22	22
PORL	0	9	3	5	8	7	4	6	PORL	0	22	44	33	22	22	0	0
Tomato								Carrot									
Period		6	7	8	9	10	11	12	Period		6	7	8	9	10	11	12
GR		36	12	20	32	28	16	24	GR		27	9	15	24	21	12	18
SR		28.5	9	27	0	0	0	0	SR		28	7	0	0	0	0	0
POH	3	0	0	7	0	0	0	0	POH	3	4	2	0	0	0	0	0
NR		4.5	0	0	23.5/25*	24.5/26*	13.5/15*	19.5/21*	NR		0	0	13	23	16	7	18
POR		0	0	0	27	27	18	27	POR		0	0	14	28	21	7	21
PORL	0	0/27*	27	27/18*	18/27*	27/0*	0	0	PORL	0	14	28	21	7	21	0	0

GR (gross requirements) SR (scheduled receipts) POH (projected on-hand) NR (net requirements) POR (planned order receipts) PORL (planned order releases) lot method is fixed order quantity for salad=1, lot method is fixed order quantity for lettuce=11, lot method is fixed order quantity for tomato=9, lot method is fixed order quantity for carrot=7.

The values obtained by implemented program in the Table 4-6 are not the same as reference literature. Values from the Reference are written in the above table along with accurate values, after the '/', obtained by our implemented program marked by "*".

Discussion of the difference in the results:

In this Table 4-6 also the similar case as discussed for net requirement of lettuce in Table 4-3, the values of NR of tomato written in the reference are not correct perhaps may be the method of calculation of NR is not correct. So, follow the same procedure for the

modification of the values of NR. The values of PORL are correct but these are shifted towards right, so move these values towards left because the lead time of tomato is 3.

BOMLP-OBJ: Minimize: $\Delta_1^+ + \Delta_2^+ + \Delta_3^+$		
Subject to:		
1.	BOMLP-C1: $k_1 + k_2 + k_3 = 12$	
2.	C2: $k_1 - \Delta_1^+ + \Delta_1^- = 5$	
3.	$k_2 - \Delta_2^+ + \Delta_2^- = 4$	
4.	$k_3 - \Delta_3^+ + \Delta_3^- = 3$	
5.	C3: $-(k_1 * 9) + (3+44) \geq 0$	$\rightarrow k_1 \leq 5.22$
6.	$-(k_2 * 9) + (3+28.5) \geq 0$	$\rightarrow k_2 \leq 3.5$
7.	$-(k_3 * 9) + (3+28) \geq 0$	$\rightarrow k_3 \leq 3.44$
8.	C4: $2 \leq k_1 \leq 9$	
9.	$0 \leq k_2 \leq 7$	
10.	$0 \leq k_3 \leq 6$	

Figure 4-3 Linear programming model for shortage shown in period 6 of Table 4-7

For the shortage of tomato in sixth period, the new values of BOM obtained by implementation are $k_1 = 5.22$, $k_2 = 3.5$ and $k_3 = 3.44$ the same values as in the reference literature, but the value of $k_3 = 3.27$ is used for the compensation.

Table 4-8 Partially adjusted Planned Order release table for periods 6-12

Salad								Lettuce									
Period		6	7	8	9	10	11	12	Period		6	7	8	9	10	11	12
GR		9	3	5	8	7	4	6	GR		47	15	25	40	35	20	30
SR		0	0	0	0	0	0	0	SR		44	22	0	0	0	0	0
POH		0	0	0	0	0	0	0	POH	3	0.02/0*	7.02/7*	0	0	0	0	0
NR		9	3	5	8	7	4	6	NR		0	0	18	36	27	14	22
POR		9	3	5	8	7	4	6	POR		0	0	22	44	33	22	22
PORL	0	9	3	5	8	7	4	6	PORL	0	22	44	33	22	22	0	0
Tomato								Carrot									
Period		6	7	8	9	10	11	12	Period		6	7	8	9	10	11	12
GR		31.5	12	20	32	28	16	24	GR		29.5	8.46	15	24	21	12	18
SR		28.5	9	27	0	0	0	0	SR		28	7	0	0	0	0	0
POH	3	0	0	7	0	0	0	0	POH	3	1.48/1.5*	0.02/0*	0	0	0	0	0
NR		0	3	0	19/25*	20/26*	9/15*	24/21*	NR		0	0	15	18	18	8.98/9*	13
POR		0	0	0	27	27	9/18*	27	POR		0	0	21	21	21	14	14
PORL	0	0/27*	27	27/18*	9/27*	27/0*	0	0	PORL	0	21	21	21	14	14	0	0

GR (gross requirements) SR (scheduled receipts) POH (projected on-hand) NR (net requirements) POR (planned order receipts) PORL (planned order releases) lot method is fixed order quantity for salad=1, lot method is fixed order quantity for lettuce=11, lot method is fixed order quantity for tomato=9, lot method is fixed order quantity for carrot=7.

The values obtained by implementation in the Table 4-8 are not the same as the reference literature. Values from the reference are written in the above table along with accurate values, after the '/', obtained by our implemented program marked by "*".

Discussion of the differences in the result:

In Table 4-8 there is also same problem as in Table 4-6 so do the same modification as discussed above for tomato. The value of (tomato's) POR in 11th and PORL in 8th period is 18 because the net requirement of tomato in 11th period is 15. As the lot size and lead-time of tomato is 9 and 3 respectively. The projected on hand inventory of lettuce and carrot in 6th and 7th period is modified e.g. POH (sixth period) = (44+3-47) =0. The right value net requirement of carrot in 11th period is 9 as the GR is 12 and on-hand inventory in last period is 3.

BOMLP-OBJ: Minimize: $\Delta_1^+ + \Delta_2^+ + \Delta_3^+$	
Subject to:	
1.	BOMLP-C1: $k_1 + k_2 + k_3 = 12$
2.	C2: $k_1 - \Delta_1^+ + \Delta_1^- = 5$
3.	$k_2 - \Delta_2^+ + \Delta_2^- = 4$
4.	$k_3 - \Delta_3^+ + \Delta_3^- = 3$
5.	C3: $-(k_1 * 3) + (0.22/0^* + 22) \geq 0 \rightarrow k_1 \leq 7.34/7.33^*$
6.	$-(k_2 * 3) + (0+9) \geq 0 \rightarrow k_2 \leq 3$
7.	$-(k_3 * 3) + (1.48/1.5^* + 7) \geq 0 \rightarrow k_3 \leq 2.82/2.83^*$
8.	C4: $2 \leq k_1 \leq 9$
9.	$0 \leq k_2 \leq 7$
10.	$0 \leq k_3 \leq 6$

Figure 4-4 Linear programming model for shortage shown in period 6 of Table 4-9

For shortage of tomato and carrot in 7th period, the values of new BOM $k_1 = 7.34$, $k_2 = 3$ and $k_3 = 2.82$ are approximately same as the reference literature but having fault by very quantity which is written above after the ‘/’, obtained by our implemented program marked by “*”.

Table 4-10 Fully adjusted Planned Order release table for periods 6-12

Salad								Lettuce								
Period	6	7	8	9	10	11	12	Period	6	7	8	9	10	11	12	
GR	9	3	5	8	7	4	6	GR	47	18.5	25	40	35	20	30	
SR	0	0	0	0	0	0	0	SR	44	22	0	0	0	0	0	
POH	0	0	0	0	0	0	0	POH	3	0.02/0*	3.48/3.5*	0	0	0	0	
NR	9	3	5	8	7	4	6	NR	0	0	21.5	39.5	30.5	17.5	25.5	
POR	9	3	5	8	7	4	6	POR	0	0	22	44	33	22	33	
PORL	0	9	3	5	8	7	4	PORL	0	22	44	33	22	33	0	0
Tomato								Carrot								
Period	6	7	8	9	10	11	12	Period	6	7	8	9	10	11	12	
GR	31.5	9	20	32	28	16	24	GR	29.5	9/8.5	15	24	21	12	18	
SR	28.5	9	27	0	0	0	0	SR	28	7	0	0	0	0	0	
POH	3	0	0	7	0	0	0	POH	3	1.48/1.5*	0	0	0	0	0	
NR	0	0	0	25	26	15	21	NR	0	0.52/0*	8.52/15*	18.5/18*	18.5/18*	9.52/9*	13.5/13*	
POR	0	0	0	27	27	18	27	POR	0	7/0*	14/21*	21	21	14	14	
PORL	0	0/27*	27	27/18*	18/27*	27/0*	0	PORL	0	14/21*	21	21	14	14	0	0

GR (gross requirements) SR (scheduled receipts) POH (projected on-hand) NR (net requirements) POR (planned order receipts) PORL (planned order releases) lot method is fixed order quantity for salad=1, lot method is fixed order quantity for lettuce=11, lot method is fixed order quantity for tomato=9, lot method is fixed order quantity for carrot=7.

The values obtained by implementation in the Table 4-10 are not the same as the reference literature. Values from the reference are written in the above table along with accurate values, after the '/', obtained by our implemented program marked by "*".

Discussion of the difference in the results:

In this Table 4-10 there are many inaccuracies seen in reference literature. Follow the same procedures as discussed above for the modification of incorrect values.

Conclusion of testing on two levels:

It is concluded that the program implementation using C has been successfully tested for two level flexible BOM and can be used as a base for the extension of work to a multi-level flexible BOM.

The proposed work consists of implementation of multilevel BOM and starting implementation of two levels from end last lower levels. In this way, implementation of intermediate levels (means implementation of two levels repeatedly) is carrying on for the compensation of BOM to overcome the shortage of a certain sub-assembly / component in specific period which comes due to some breakdowns or unwanted reasons. Following is the Figure 4-5 showing different levels with common components. The components with different BOM, are used commonly in other levels also to make compensation with sub-assemblies. This compensation of BOM of components having the effect on their on-hand inventory rather than the BOM of components in different levels is not same.

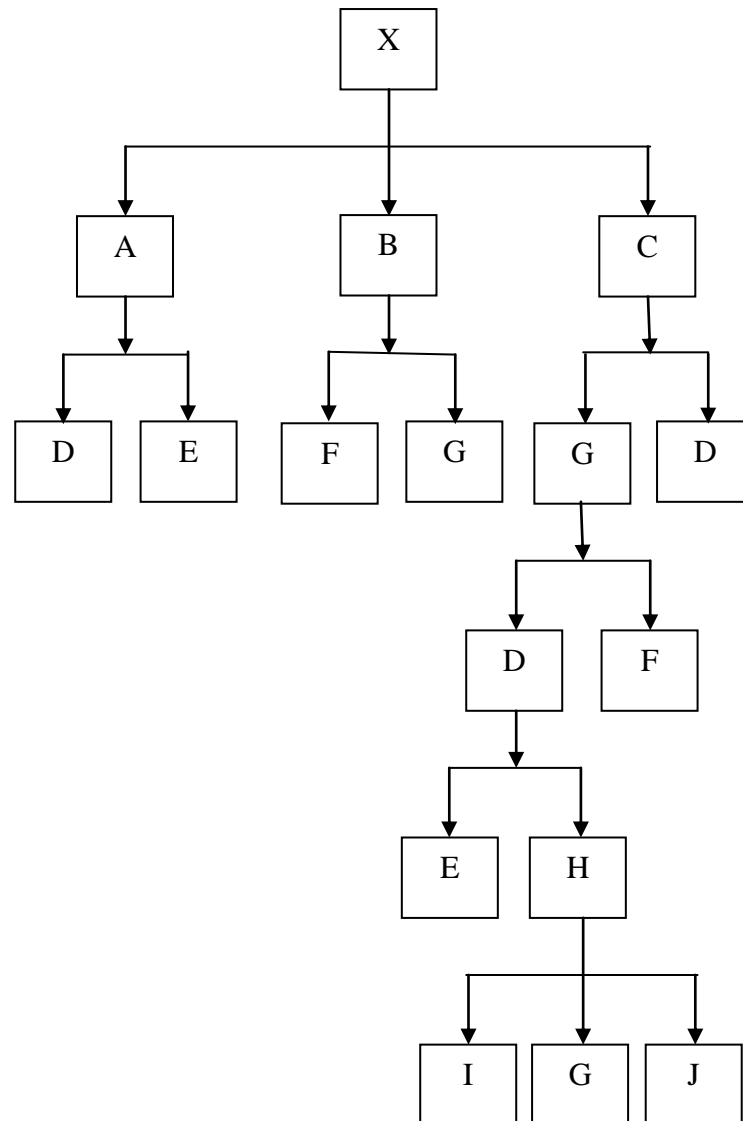


Figure 4-5 Implementation of Multi-level flexible BOM

4.2MRP FOR A MULTI-LEVEL FLEXIBLE BOM

In order to address flexible BOMs, a new moderate approach must be used in the BOM process. The procedure is shown in the flow chart presented in Figure 4-6. The steps in the flowchart are discussed below.

Step S1. Here from start of material requirement planning, take “n” no. of component / sub-assemblies of top most assembly.

Step S2. A standard bill of material (BOM) is assumed for sub-assemblies that are being planned for production. This bill of material is taken as a default BOM and the objective is to be as close to it as possible. For example, the BOM could be a list of items that make up a certain top assembly. In addition, the parameters of bill of material, which prescribe the ranges (lower limit and upper limit) on its flexibility, must be specified. The

parameters are cki, lli and uli, which are defined in Step S8. Within the assumption of default BOM, lead-time (lt), lot size (ls) is also assumed.

Step S3. Now, take (enter) gross requirement (“GR”) of top assembly for “x” no. of periods.

Step S4. For the standard value of bill of material (default BOM), Planned Order Release (PORL) tables are computed for the planning horizon as in normal material requirement planning (MRP). It is also assumed that Projected On-Hand inventory at the beginning and all Scheduled Receipts are known.

Decision D1. In any specific period (called the current period), the Planned Order Receipt (PORP) for the period is compared with the corresponding PORL. There are two possibilities:

- 1. PORP equals or exceeds the corresponding PORL. In that case, the procedure for that period is complete and then stop, the standard bill of material (default BOM) and the normal computations are adequate for purpose.**
- 2. PORP is less than the corresponding PORL. In this case, the procedure will be routed to another decision point (D2).**

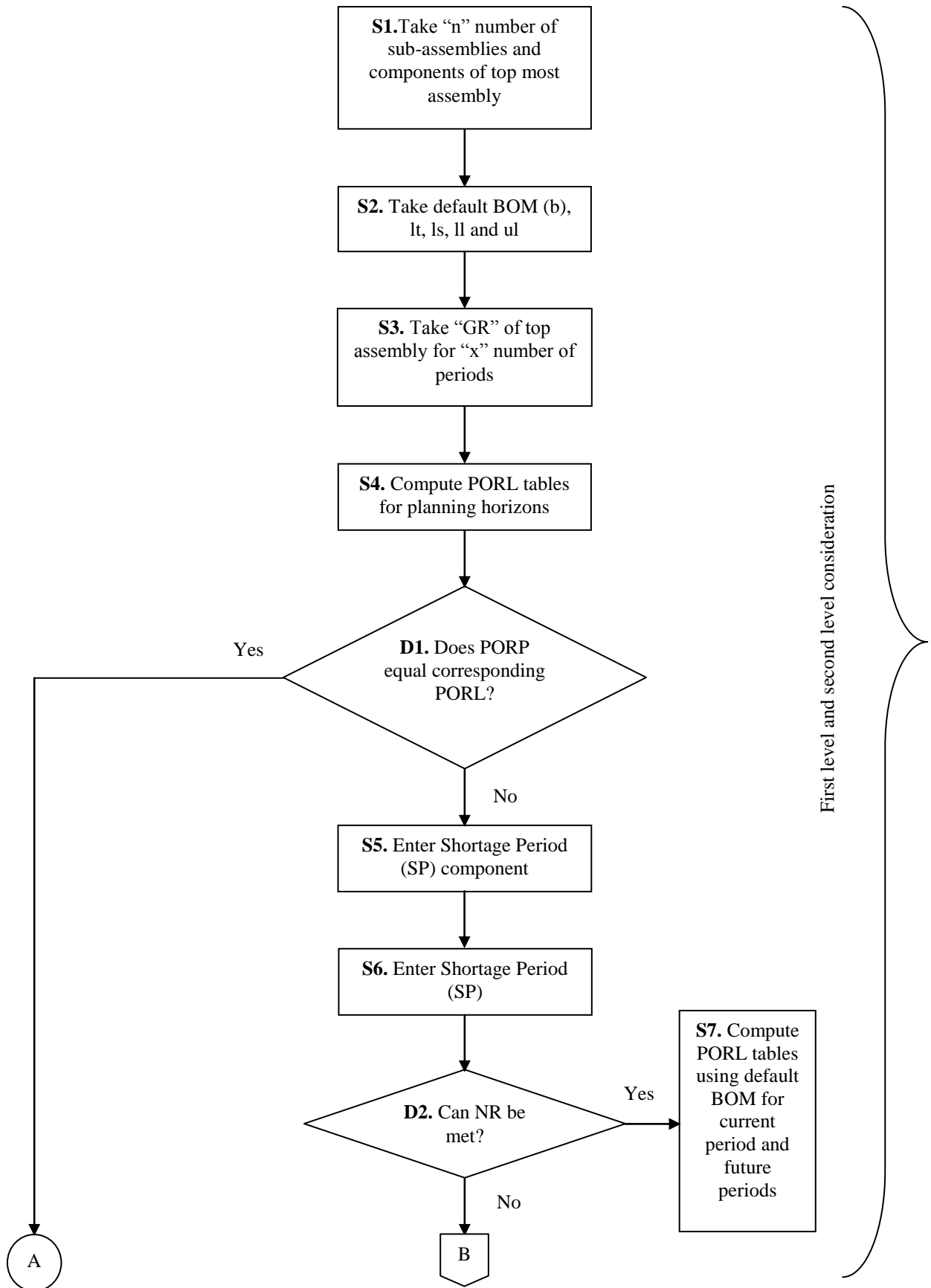
Step S5. Now enter any sub assembly in which shortage occurs.

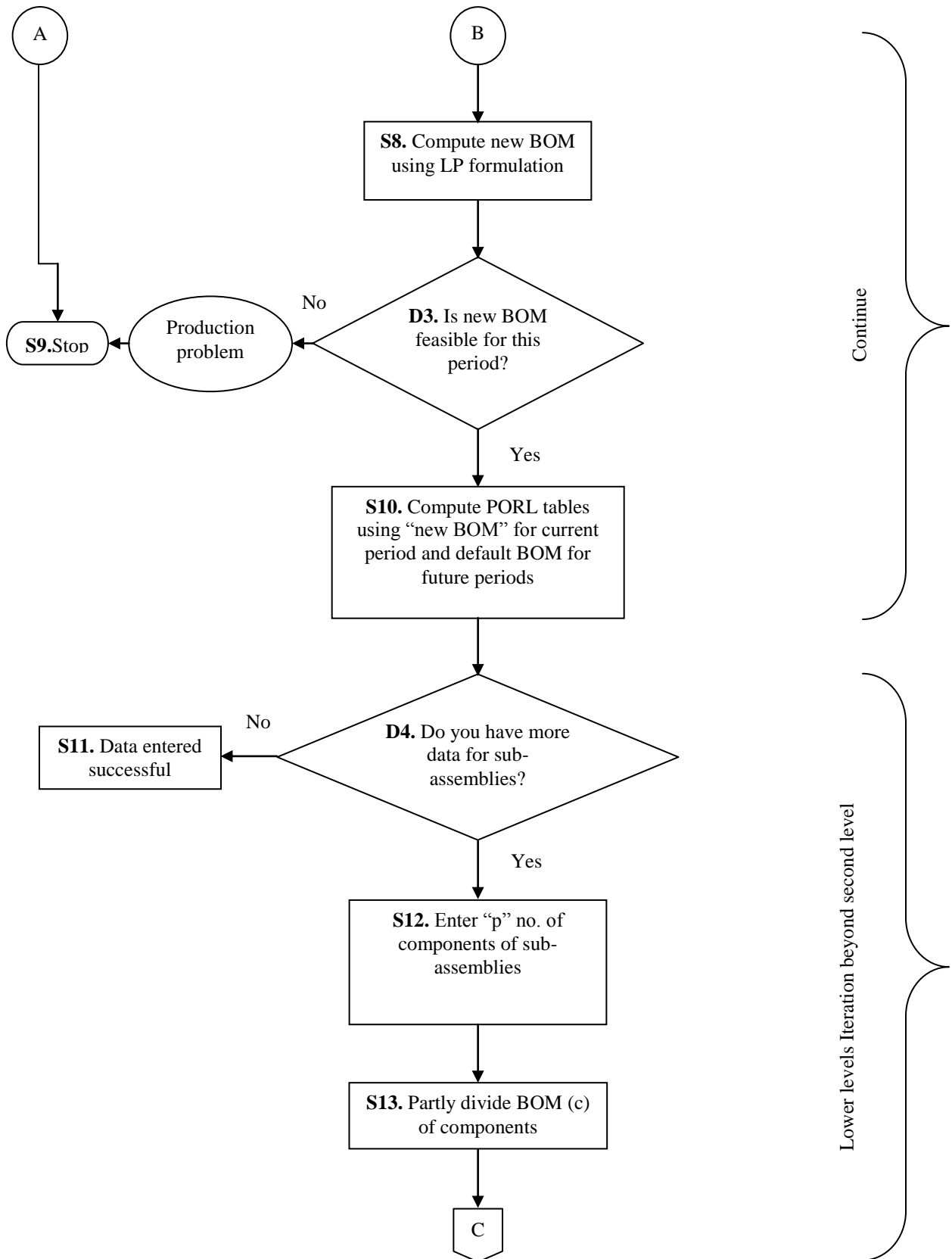
Step S6. Enter any period of any sub assembly in which shortage comes. Shortage in units occur when scheduled receipt is not same to the PORL or units (planned on hand inventory + scheduled receipt) is less than gross requirement of that specific period which is released in lots as according to the net requirement of any specific period.

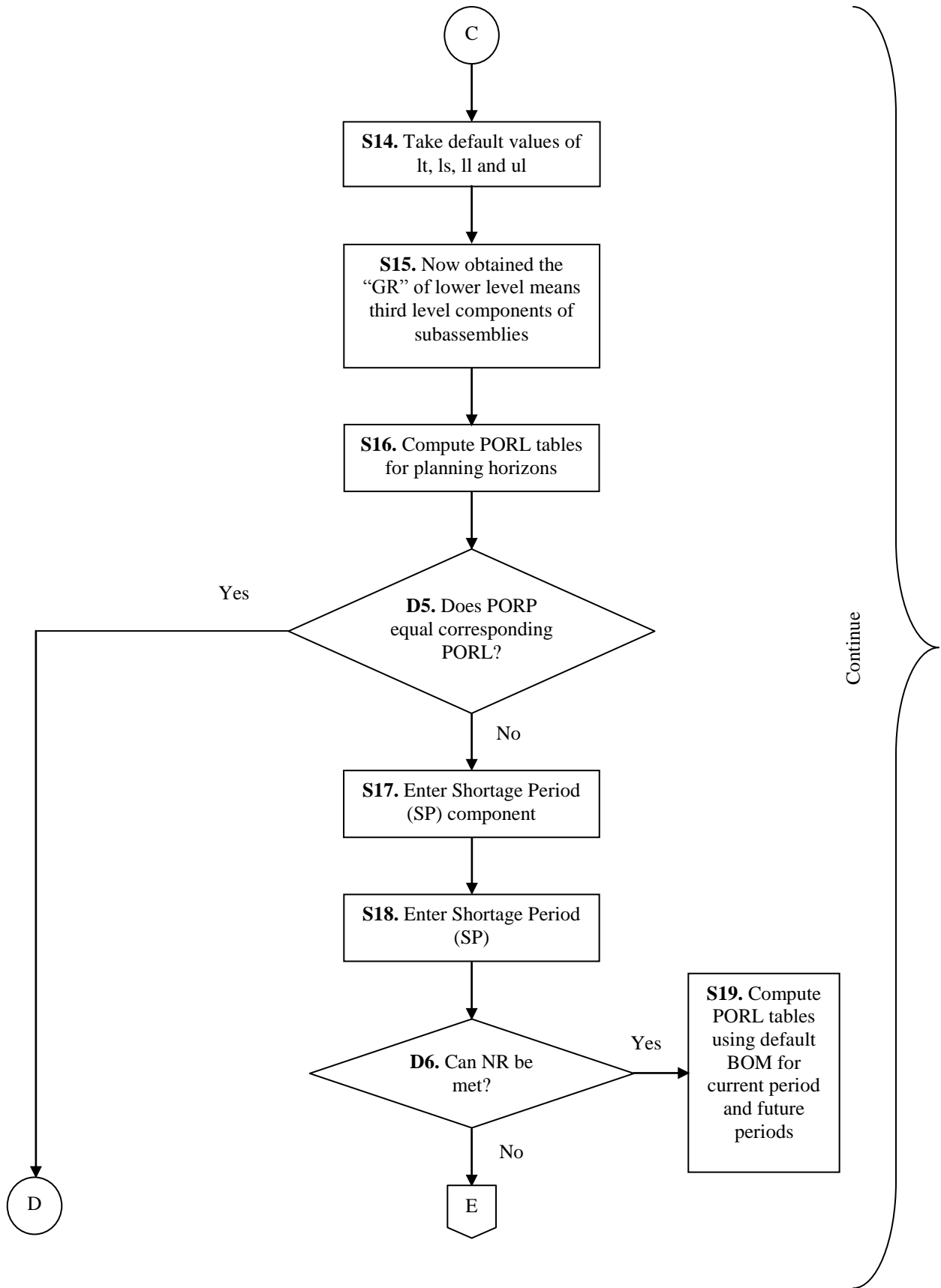
Decision D2. Based on the lead-time, determine the situation that the net requirement (NR) will be met or not. Then, there are two possibilities:

- 1. If net requirement (NR) will be met. This will lead or flow the procedure to S7 in order to update the PORL tables. The PORL tables obtained without any shortage.**
- 2. Otherwise, if net requirement (NR) will not be met. This will lead or flow the procedure to S8, which is described below.**

Step S7. Planned order release (PORL) tables will be computed using the same standard size of bill of material (default BOM) for the current and future periods. Since projected on-hand inventory is used to compensate for the shortage. In this way, PORL tables have been updated.







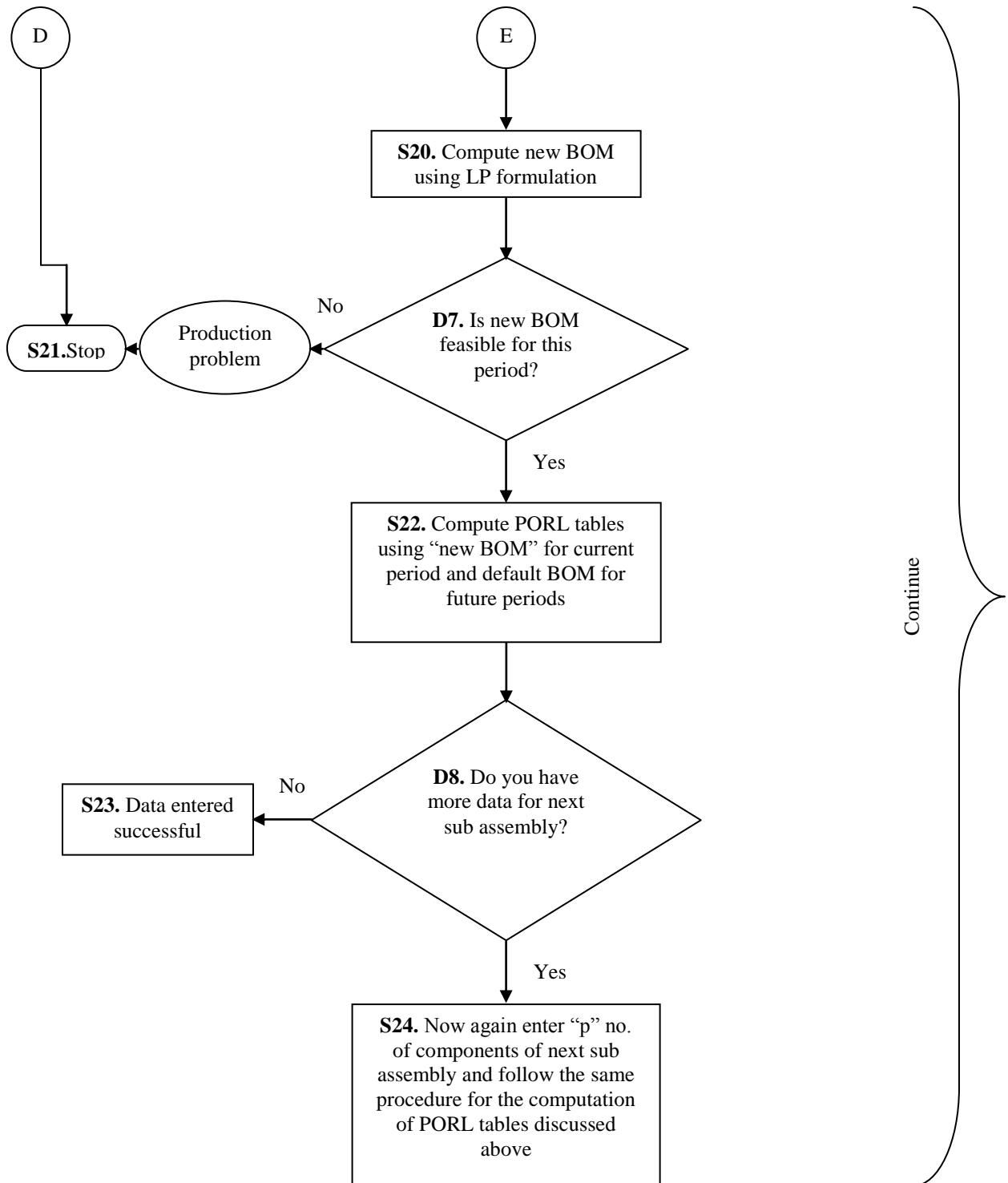


Figure 4-6 Multilevel flow chart of the model

Step S8. A “new BOM” is defined by solving LP model. We need following notations (stated in the context of the top assembly example) to formulate the LP:

- b(BOM)** Standard size (BOM) of sub assemblies “i” in one unit of top assembly
- ck_i** Adjusted quantity of sub assemblies “i” in one unit of top assembly
- dp_i, dn_i** Positive and negative deviation of ck_i relative to b
- dp_i=ck_i –b** if ck_i ≥ b
- dp_i=b – ck_i** if ck_i < b
- PORL_t** Planned Order Release for sub assembly in period t
- POH_tⁱ** Projected on Hand inventory of sub assembly “i” in period t
- SR_tⁱ** Scheduled Receipt of sub assembly “ i” in period t
- ll_i** Lower limit of adjusted quantity of sub assemblies
- ul_i** Upper limit of adjusted quantity of sub assemblies
- “n”** Number of sub-assemblies at the second level of BOM.

The LP will have the following objective function and constraints.

Objective. Minimize the deviation of adjusted bill of material from the standard BOM or

$$\text{Minimize } dp_i + dn_i \quad \text{for } i = 1, 2, 3, \dots, n \quad (\text{BOMLP-OBJ}).$$

Constraint C1. The adjusted quantity (in units) of the lower level sub assemblies that make up one unit of the end top assembly must be the same as in the standard BOM or

$$\sum ck_i = \sum b \quad \text{for } i = 1, 2, 3 \dots n \quad (\text{BOMLP-C1}).$$

Constraint C2. The sum of positive and negative deviations of the quantity of each lower level sub assemblies from the standard should equal the total deviations or

$$ck_i - b = dp_i - dn_i \quad \text{for } i = 1, 2, 3 \dots n$$

or

$$ck_i - dp_i + dn_i = b \quad \text{for } i = 1, 2, 3 \dots n \quad (\text{BOMLP-C2}).$$

Constraint C3. The sum of the current period projected on-hand inventory and scheduled receipt should not be less than the derived demand for each sub assembly based on the planned order release for the top assembly in the current period or

$$(\text{POH}_{t-1}^i + \text{SR}_t^i) \geq (ck_i * \text{PORL}_t) \quad \text{for } i = 1, 2, 3 \dots n \quad (\text{BOMLP-C3}).$$

Constraint C4. The adjusted quantity (ck_i) must be between the lower limit and the upper limit of sub assembly “i” in one unit of top assembly or

$$ll_i < ck_i < ul_i \quad \text{for } i = 1, 2, 3 \dots n \quad (\text{BOMLP-C4}).$$

We will refer to the above LP formulation as BOMLP. BOM is solved to find values for ck_i for each sub assembly “i”.

Decision D3. In this step, try to verify “new BOM” that whether the LP model has displaying readings to a feasible solution for the current period. There are also two possibilities that are to be followed:

1. **If there is no feasible solution after using “new BOM” for the current period, Then there are some production problem. Due to that reason the procedure will stop, the ranges or limits of adjusted quantities provided in the flexible BOM are not feasible for the current period, In this case, the next step is S9.**
2. **If “new BOM” computed with LP model (i.e. the adjusted quantities of bill of material) is feasible. Then, update PORL tables with “new BOM”. Here the next step is S10.**

Decision D4. Here moving further to third level means the lower level of sub assemblies (i.e. “p” no. of components of each sub assembly). In this case (in third level) one component is common for each sub assembly and also common for top-assembly. The common component of sub assemblies is also the sub assembly of top assembly. All components in each case exit with different bill of material.

Now asking the question, “Do you have more data for components (lower level of sub assemblies means for third level)? Therefore, there are two possibilities that are as follows:

1. **If answer is “no” then statement come on screen that data entered is successful, next step is S11.**
2. **If “Yes” then enter “p” no. of components. This type of entries takes place in step S12.**

Step S13. So by following this way, partly divide BOM of sub assembly into components according to the requirement. One of component, which is common in all sub assemblies of top assembly, has different BOM (c) in each case. The parameters are cki , lli , uli , which are also defined in step S20.

Step S14. For the continuation of same procedure of material requirement planning (i.e. computation of PORL tables), lead-time (lt), lot size (ls), lower limit (ll), and upper limit (ul) for each component in all the cases in the third level is also assumed.

Step S15. As the bill of material (c) of third level components is partly divided, hence the gross requirement “GR” (units) of components is obtained.

Step S16. For the partly divided BOM (c), Planned Order Release (PORL) tables are computed for the planning horizon as in normal MRP. It is assumed that Projected On-Hand at the beginning and all Scheduled Receipts are known.

Decision D5. In any specific period (called the current period), the Planned Order Receipt (PORP) for the period is compared with the corresponding PORL. There are two possibilities:

- 1. Planned order receipt (PORP) equals or exceeds the corresponding PORL. In this case, the procedure for this period is complete and stop, the default BOM and the normal computations are sufficient.**
- 2. PORP is less than the corresponding PORL. In this case, the procedure will be routed to another decision point (D6).**

Step S17. Now enter any component in which shortage occurs.

Step S18. Enter any period of that selected component in which shortage comes. Shortage in units occurs when scheduled receipt is not same to the PORL or units (planned on hand inventory + scheduled receipt) is less than gross requirement of that specific period which is released in lots as according to the net requirement of any specific period.

Decision D6. Based on lead-time, determine the situation for which net requirement (NR) can be met. There are two possibilities:

- 1. One situation is that the NR can be met. This will lead or flow the procedure to S19 in order to update the PORL tables.**
- 2. Another one is NR cannot be met. This will lead or flow the procedure to S20, which is prescribed below.**

Step S19. PORL tables will be computed using the partly divided BOM (c) for the current and future periods. Since some of the projected on-hand inventory is used to compensate for the shortage. In this way, PORL tables have been updated.

Step S20. A “new BOM” is defined by solving LP model. We need following notations (stated in the context of the sub assembly example) to formulate the LP:

- c** Partly divided standard(BOM) of components “j” in one unit of sub assembly
- ck_j** Adjusted quantity of components “j” in one unit of sub assembly
- dp_j, dn_j** Positive and negative deviation of ck_j relative to b
- dp_j=ck_j – c** if ck_j ≥ c
- dp_j=c – ck_j** if ck_j < c
- PORL_t** Planned Order Release for components in period t
- POH_t^j** Projected on Hand inventory of components “j” in period t
- SR_t^j** Scheduled Receipt of components “j” in period t
- ck_j** Adjusted quantity of components
- ll_j** Lower limit of adjusted quantity of components.
- ul_j** Upper limit of adjusted quantity of components.
- “p”** Number of components at the third level of BOM.

The LP will have the following objective function and constraints.

Objective. Minimize the deviation of adjusted quantity for bill material from the standard BOM or

$$\text{Minimize } dp_j + dn_j \quad \text{for } j = 1, 2, 3 \dots n \quad (\text{BOMLP-OBJ}).$$

Constraint C1. The adjusted quantity (in units) of the lower level components that make up one unit of the end sub assembly must be the same as in the standard BOM or

$$\sum ck_j = \sum c \quad \text{for } j = 1, 2, 3 \dots n \quad (\text{BOMLP-C1}).$$

Constraint C2. The sum of positive and negative deviations of the adjusted quantity of each lower level components from the standard should equal the total deviations or

$$ck_j - c = dp_j - dn_j \quad \text{for } j = 1, 2, 3 \dots n$$

or

$$ck_j - dp_j + dn_j = c \quad \text{for } j = 1, 2, 3 \dots n \quad (\text{BOMLP-C2}).$$

Constraint C3. The sum of the current period projected on-hand inventory and scheduled receipt should not be less than the derived demand for each component based on the planned order release for the subassembly in the current period or

$$(POH_t^j + SR_t^j) \geq (ck_j * PORL_t) \quad \text{for } j = 1, 2, 3 \dots n \quad (\text{BOMLP-C3}).$$

Constraint C4. The quantity ck_i must be between the lower limit and the upper limit of components “j” in one unit of sub assembly or

$$ll_j < ck_j < ul_j \quad \text{for } j = 1, 2, 3 \dots n \quad (\text{BOMLP-C4}).$$

We will refer to the above LP formulation as BOMLP. BOM is solved to find values for ck_j for each component “j”.

Decision D7. In this step, try to verify “new BOM” that whether the LP model has displaying readings to a feasible solution for the current period. There are also two possibilities that are to be followed:

- 1. If there is no feasible solution after using “new BOM” for the current period, then there are some production problems. Due to that reason the procedure will stop, the ranges or limits of adjusted quantities provided in the flexible BOM are not feasible for the current period, In this case, the next step is S21.**
- 2. If “new BOM” computed with LP model (i.e. the adjusted quantities of bill of material) is feasible. Then, update PORL tables with “new BOM”. Here the next step is S22.**

Decision D8. After the completion of computation of PORL tables for first sub assembly, again asking the same question for next sub-assembly “Do you have more data for next sub-assembly”. In this above discussed case having two possibilities:

- 1. If answer is “no” then statement come on screen that data entered is successful, next step is S23.**
- 2. If “Yes” then enters again “p” no. of components and follow the same procedure of computation of PORL tables of sub assembly with the use of LP model for finding the “new BOM” of specific period in which shortage occur due to some unwanted reason or can say manufacturing equipment breakdowns. In this way the PORL tables of “p” no. of components in the lower levels of “n” no. of sub-assemblies computation takes place with the same procedure discussed above.**

4.3EXAMPLE OF THREE LEVEL FLEXIBLE BOM

The concept of a flexible BOM is motivated for multilevel top assembly with common component or parts in each level with different BOM. Now, there is an explanation of three level flexible BOM having three sub-assemblies and two components in second level and components in third level which are common with subassemblies and components. Following is the Figure 4-7 in which standard size (BOM), flexibility range and lead-time is shown below:

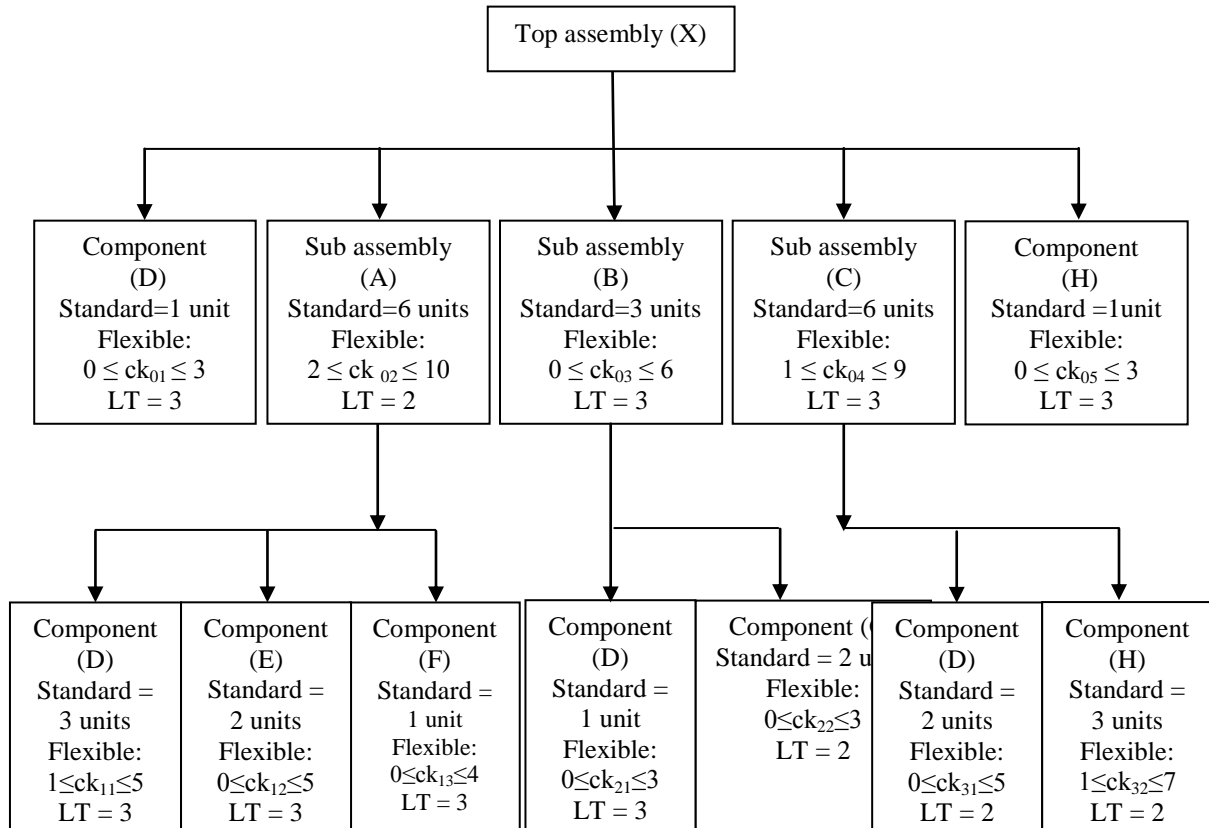


Figure 4-7 A flexible BOM for top assembly

This example is provided to show how the approach introduced in Figure 4-6. In this example, the end item is top assembly (X), sub-assemblies and components in second level and only components commonly used in each subassembly in third level. The BOM is given in Figure 4-8. The combination of sub-assemblies to make one unit of top assembly is 6 units of sub assembly (A), 3 units of sub assembly (B), 5 units of sub assembly (C), 1 unit of sub assembly (D) and 1 unit of sub assembly (H). There is the possibility of a shortage of one or more units in lower level sub-assemblies due to unforeseen failures in the production process. Figure 4-7 introduces the BOM that allows some flexibility in the proportions of the combination. This flexibility allows the sub-assemblies to compensate for one another in the case of a shortage.

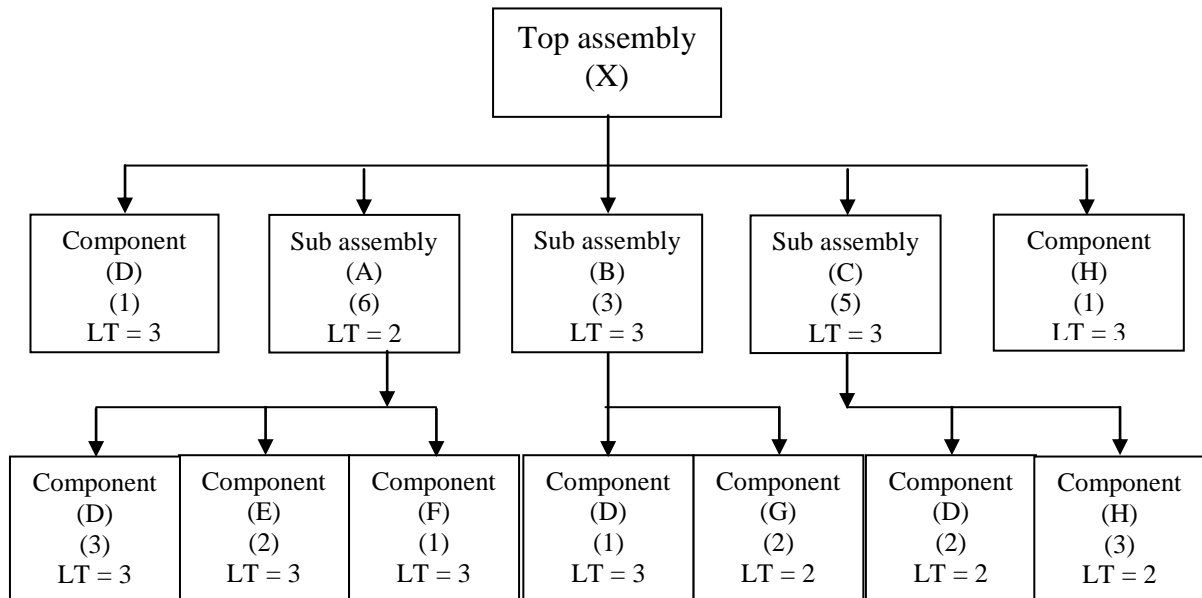


Figure 4-8 An example of top assembly BOM

The MPS for top assembly is shown in Table 4-11. Period 4 is when failure occurs, which requires flexible BOM for completion. The MPS for the eight-period planning horizon is shown in periods 1 and 4.

Table 4-11 Master production schedule for periods 1-11

		(a) Master production schedule for periods 1- 8							
		Independent demand							
		1	2	3	4	5	6	7	8
Planning horizon: Seven periods	Top Assembly	7	8	1	4	6	3	5	2
		(b) Master production schedule for periods 4-11							
		Independent demand							
		4	5	6	7	8	9	10	11
Name: Top Assembly	Top Assembly	4	6	3	5	2	7	8	1
Planning horizon: Seven periods									

Planned Order Release (PORL) tables for periods 1 through 8 (Table 4-12) using the standard sizes (BOM-Figure 4-8) are generating. In this example, the scheduled orders come in period 4. In Figure 4-9 the net requirement for subassembly (A) in period 4 is 20 units. In order to meet this requirement, an order of 20 units for sub assembly (A) has to be placed in period 2, since the lead-time for sub assembly (A) is two periods, this order is shown in period 2 of Table 4-12 as a PORL for sub assembly (A). When period 4 reaches, due to some problem, the actual order received for sub assembly is 12 units instead of 20 units. This is shown in Table 4-13 as a schedule receipt for the sub assembly (A) in period 4 (which is the current period in Figure 4-10). So finally, there is a NR of 8 units for the sub assembly (A) in period 4 and shortage occurs in period 4. However, the flexibility of the BOM for top assembly (X) compensates the shortage in period 4 using a

different proportion of sub assemblies. The LP problem (BOMLP) can be formulated for this situation and is shown in Figure 4-9.

Table 4-12 Planned order release table for periods 1-8

Top Assembly (X)										Sub Assembly (A)									
Period		1	2	3	4	5	6	7	8	Period		1	2	3	4	5	6	7	8
GR		7	8	1	4	6	3	5	2	GR		42	48	6	24	36	18	30	12
SR		0	0	0	0	0	0	0	0	SR		0	0	0	0	0	0	0	0
POH		0	0	0	0	0	0	0	0	POH	90	48	0	0	0	0	0	0	0
NR		7	8	1	4	6	3	5	2	NR		0	0	6	20	36	14	24	6
POR		7	8	1	4	6	3	5	2	POR		0	0	10	20	40	20	30	10
PORL	0	7	8	1	4	6	3	5	2	PORL	0	10	20	40	20	30	10	0	0
Sub Assembly (B)										Sub Assembly (C)									
Period		1	2	3	4	5	6	7	8	Period		1	2	3	4	5	6	7	8
GR		21	24	3	12	18	9	15	6	GR		35	40	5	20	30	15	25	10
SR		0	0	0	0	0	0	0	0	SR		0	0	0	0	0	0	0	0
POH	48	27	3	0	0	0	0	0	0	POH	80	45	5	0	0	0	0	0	0
NR		0	0	0	12	16	4	12	4	NR		0	0	0	20	28	10	24	1
POR		0	0	0	14	21	7	14	7	POR		0	0	0	22	33	11	33	11
PORL	0	14	21	7	14	7	0	0	0	PORL	0	22	33	11	33	11	0	0	0
Component (D)										Component (H)									
Period		1	2	3	4	5	6	7	8	Period		1	2	3	4	5	6	7	8
GR		7	8	1	4	6	3	5	2	GR		7	8	1	4	6	3	5	2
SR		0	0	0	0	0	0	0	0	SR		0	0	0	0	0	0	0	0
POH	16	9	1	0	0	0	0	0	0	POH	16	9	1	0	0	0	0	0	0
NR		0	0	0	4	4	1	3	2	NR		0	0	0	4	4	1	3	2
POR		0	0	0	6	6	3	3	3	POR		0	0	0	6	6	3	3	3
PORL	0	6	6	3	3	3	0	0	0	PORL	0	6	6	3	3	3	0	0	0

GR (gross requirements) SR (scheduled receipts) POH (projected on-hand) NR (net requirements) POR (planned order receipts) PORL (planned order releases) lot method is fixed order quantity for Top assembly (X) =1, lot method is fixed order quantity for Sub assembly (A) =10, lot method is fixed order quantity for Sub assembly (B) =7, lot method is fixed order quantity for Sub assembly (C) =11, lot method is fixed order quantity for Component (D) =3, lot method is fixed order quantity for Component (H) =3.

Table 4-13 Planned order release table for periods 4 -11

Top Assembly (X)										Sub Assembly (A)									
Period		4	5	6	7	8	9	10	11	Period		4	5	6	7	8	9	10	11
GR		4	6	3	5	2	7	8	1	GR		24	36	18	30	10	42	48	6
SR		0	0	0	0	0	0	0	0	SR		12	40	0	0	0	0	0	0
POH		0	0	0	0	0	0	0	0	POH	4	0	4	0	0	0	0	0	0
NR		4	6	3	5	2	7	8	1	NR		8	0	14	24	6	38	46	2
POR		4	6	3	5	2	7	8	1	POR		0	0	20	30	10	40	50	10
PORL	0	4	6	3	5	2	7	8	1	PORL	0	20	30	10	40	50	10	0	0
Sub Assembly (B)										Sub Assembly (C)									
Period		4	5	6	7	8	9	10	11	Period		4	5	6	7	8	9	10	11
GR		12	18	9	15	6	21	24	3	GR		20	30	15	25	10	35	40	5
SR		14	21	7	0	0	0	0	0	SR		22	33	11	0	0	0	0	0
POH	0	2	5	3	0	0	0	0	0	POH	0	2	5	1	0	0	0	0	0
NR		0	0	0	12	4	18	21	3	NR		0	0	0	24	1	25	32	4
POR		0	0	0	14	7	21	21	7	POR		0	0	0	33	11	33	33	11
PORL	0	14	7	21	21	7	0	0	0	PORL	0	33	11	33	33	11	0	0	0
Component (D)										Component (H)									
Period		4	5	6	7	8	9	10	11	Period		4	5	6	7	8	9	10	11
GR		4	6	3	5	2	7	8	1	GR		4	6	3	5	2	7	8	1
SR		6	6	3	0	0	0	0	0	SR		6	6	3	0	0	0	0	0
POH	0	2	2	2	0	0	0	0	0	POH	0	2	2	2	0	0	0	0	0
NR		0	0	0	3	2	6	8	0	NR		0	0	0	3	2	6	8	0
POR		0	0	0	3	3	6	9	0	POR		0	0	0	3	3	6	9	0
PORL	0	3	3	6	9	0	0	0	0	PORL	0	3	3	6	9	0	0	0	0

GR (gross requirements) SR (scheduled receipts) POH (projected on-hand) NR (net requirements) POR (planned order receipts) PORL (planned order releases) lot method is fixed order quantity for Top assembly (X) =1, lot method is fixed order quantity for Sub assembly (A) =10, lot method is fixed order quantity for Sub assembly (B) =7, lot method is fixed order quantity for Sub assembly (C) =11, lot method is fixed order quantity for Component (D) =3, lot method is fixed order quantity for Component (H) =3.

On solving the LP model, the ck_i values for period 4 are $ck_{01} =4$, $ck_{02} = 3.5$, $ck_{03} = 5.5$, $ck_{04} = 1.5$ and $ck_{05} = 1.5$. The ck_i values will change the gross requirements for the items due to the shortage of sub assembly (A). The gross requirement for the sub assembly (A) is reduced to 16 from 24, which can now be reached by 4 unit’s on-hand and 12 units of scheduled receipt. The gross requirements for the sub assembly (B), sub assembly (C), component (D) and component (H) are changed to compensate for the shortage of sub assembly (A) and they are increased to 14 from 12 for sub assembly (B), to 22 from 20 for sub assembly (C), to 6 from 4 for component (D) and to 6 from 4 for component (H). Compensation for this period was possible because positive inventory was carried on-

hand. Since period 4 is the current period, the PORL tables are extended to period 11. For periods 5 through 11, the standard quantities (BOM- b) of sub-assemblies and components are used because the goal is always to use the default BOM whenever possible. Note that, for periods 5 through 11 in Table 4-15 the gross requirement for sub assembly (A), sub assembly (B), sub assembly (C), component (D) and component (H) is obtained by multiplying the PORL in each period by 6, 3, 5, 1 and 1, respectively, the values 6, 3, 5, 1 and 1 are values of standard BOM (b) respectively.

BOMLP-OBJ: Minimize: $dp_{01} + dp_{02} + dp_{03} + dp_{04} + dp_{05}$	
Subject to:	
1.	BOMLP-C1: $ck_{01} + ck_{02} + ck_{03} + ck_{04} + ck_{05} = 16$
2.	C2: $ck_{01} - dp_{01} + dn_{01} = 6$
3.	$ck_{02} - dp_{02} + dn_{02} = 3$
4.	$ck_{03} - dp_{03} + dn_{03} = 5$
5.	$ck_{04} - dp_{04} + dn_{04} = 1$
6.	$ck_{05} - dp_{05} + dn_{05} = 1$
7.	C3: $-(ck_{01} * 4) + (4 + 12) \geq 0 \rightarrow ck_{01} \leq 4$
8.	$-(ck_{02} * 4) + (0 + 14) \geq 0 \rightarrow ck_{02} \leq 3.5$
9.	$-(ck_{03} * 4) + (0 + 22) \geq 0 \rightarrow ck_{03} \leq 5.5$
10.	$-(ck_{04} * 4) + (0 + 6) \geq 0 \rightarrow ck_{04} \leq 1.5$
11.	$-(ck_{05} * 4) + (0 + 6) \geq 0 \rightarrow ck_{05} \leq 1.5$
12.	C4: $2 \leq ck_{01} \leq 10$
13.	$0 \leq ck_{02} \leq 6$
14.	$1 \leq ck_{03} \leq 9$
15.	$0 \leq ck_{04} \leq 3$
16.	$0 \leq ck_{05} \leq 3$

Figure 4-9 Linear programming model for shortage shown in period 4 of Table 4-14
The shortage in period 4 for second level sub assemblies could be conducted with by adjusting the proportions in the BOM. After this compensation no shortages occur in periods 5 through 11.

Table 4-15 Fully adjusted planned order release table for periods 4 – 11

Top Assembly (X)										Sub Assembly (A)									
Period		4	5	6	7	8	9	10	11	Period		4	5	6	7	8	9	10	11
GR		4	6	3	5	2	7	8	1	GR		16	36	18	30	12	42	48	6
SR		0	0	0	0	0	0	0	0	SR		12	40	0	0	0	0	0	0
POH		0	0	0	0	0	0	0	0	POH	4	0	4	0	0	0	0	0	0
NR		4	6	3	5	2	7	8	1	NR		0	0	14	24	6	38	46	2
POR		4	6	3	5	2	7	8	1	POR		0	0	20	30	10	40	50	10
PORL	0	4	6	3	5	2	7	8	1	PORL	0	20	30	10	40	50	10	0	0
Sub Assembly (B)										Sub Assembly (C)									
Period		4	5	6	7	8	9	10	11	Period		4	5	6	7	8	9	10	11
GR		14	18	9	15	6	21	24	3	GR		22	30	15	25	10	35	40	5
SR		14	21	7	0	0	0	0	0	SR		22	33	11	0	0	0	0	0
POH	0	0	3	1	0	0	0	0	0	POH	0	0	3	0	0	0	0	0	0
NR		0	0	0	14	6	20	23	0	NR		0	0	1	25	2	26	33	5
POR		0	0	0	14	7	21	28	0	POR		0	0	0	33	11	33	33	11
PORL	0	14	7	21	28	0	0	0	0	PORL	0	33	11	33	33	11	0	0	0
Component (D)										Component (H)									
Period		4	5	6	7	8	9	10	11	Period		4	5	6	7	8	9	10	11
GR		6	6	3	5	2	7	8	1	GR		6	6	3	5	2	7	8	1
SR		6	6	3	0	0	0	0	0	SR		6	6	3	0	0	0	0	0
POH	0	0	0	0	0	0	0	0	0	POH	0	0	0	0	0	0	0	0	0
NR		0	0	0	5	1	5	7	0	NR		0	0	0	5	1	5	7	0
POR		0	0	0	6	3	6	9	0	POR		0	0	0	6	3	6	9	0
PORL	0	6	3	6	9	0	0	0	0	PORL	0	6	3	6	9	0	0	0	0

GR (gross requirements) SR (scheduled receipts) POH (projected on-hand) NR (net requirements) POR (planned order receipts) PORL (planned order releases) lot method is fixed order quantity for Top assembly (X) =1, lot method is fixed order quantity for Sub assembly (A) =10, lot method is fixed order quantity for Sub assembly (B) =7, lot method is fixed order quantity for Sub assembly (C) =11, lot method is fixed order quantity for Component (D) =3, lot method is fixed order quantity for Component (H) =3.

Now shortage occurs in any of the component of sub assembly (A) in third level. Here sub assembly (A) is assumed as the end item (or top assembly) having three components with partly divided BOM (c) is given in the Figure 4-8. The partly divided BOM (c) of components to make one unit of sub assembly (A) is three units of component (D), two units of component (E) and one unit of component (F). There is also the possibility of a

shortage of one or more component due to some failures in the production process. In Figure 4-7, the partly divided bill of material allowing some flexibility in the proportions of the combination. This flexibility gives the permission to components to compensate for one another in the case of a shortage. Period 4 is when unexpected problems or some failures occur, which requires completion using the flexible BOM approach. It is for the reason that the gross requirement “GR” for the eight-period planning horizon is shown in periods 1 and 4.

Table 4-16 Panned order release table for periods 1 – 8

Sub Assembly (A)										Component (D)									
Period		1	2	3	4	5	6	7	8	Period		1	2	3	4	5	6	7	8
GR		42	48	6	24	36	18	30	12	GR		126	144	18	72	108	54	90	36
SR		0	0	0	0	0	0	0	0	SR		0	0	0	0	0	0	0	0
POH		0	0	0	0	0	0	0	0	POH	288	162	18	0	0	0	0	0	0
NR		42	48	6	24	36	18	30	12	NR		0	0	0	72	108	54	72	36
POR		42	48	6	24	36	18	30	12	POR		0	0	0	72	108	72	72	36
PORL	0	42	48	6	24	36	18	30	12	PORL	0	72	108	72	72	36	0	0	0
Component (E)										Component (F)									
Period		1	2	3	4	5	6	7	8	Period		1	2	3	4	5	6	7	8
GR		84	96	12	48	72	36	60	24	GR		42	48	6	24	36	18	30	12
SR		0	0	0	0	0	0	0	0	SR		0	0	0	0	0	0	0	0
POH	192	108	12	0	0	0	0	0	0	POH	96	54	6	0	0	0	0	0	0
NR		0	0	0	48	66	21	54	24	NR		0	0	0	24	24	6	18	12
POR		0	0	0	54	81	27	54	27	POR		0	0	0	36	36	18	18	18
PORL	0	54	81	27	54	27	0	0	0	PORL	0	36	36	18	18	18	0	0	0

GR (gross requirements) SR (scheduled receipts) POH (projected on-hand) NR (net requirements) POR (planned order receipts) PORL (planned order releases) lot method is fixed order quantity for Sub assembly (A) =1, lot method is fixed order quantity for Component (D) =36, lot method is fixed order quantity for Component (E) =27, lot method is fixed order quantity for Component (F) =18.

Planned order release (PORL) tables for periods 1 through 8 (Table 4-16) using the partly divided BOM (Figure 4-8). In Table 4-16, the net requirement for component (D) in period 4 is 72 units. To meet this requirement, an order of 72 units for component (D) has to be placed in period 1, since the lead-time for component (D) is three period, this order is shown in period 1 of Table 4-16 as a PORL for component (D). When period 4 reaches due to some unwanted issues, the actual order received for component (D) is 54 units instead of 72 units. This is shown in Table 4-16 as a schedule receipt for the component

(D) in period 4 (which is current period in Table 4-17). So finally, there is a NR of 18 units for the component (D) in period 4.

Table 4-17 Planned order release table for periods 4 – 11

Sub Assembly (A)										Component (D)									
Period		4	5	6	7	8	9	10	11	Period		4	5	6	7	8	9	10	11
GR		24	36	18	30	12	42	48	6	GR		72	108	54	90	36	126	144	18
SR		0	0	0	0	0	0	0	0	SR		54	108	72	0	0	0	0	0
POH		0	0	0	0	0	0	0	0	POH	0	0	0	18	0	0	0	0	0
NR		24	36	18	30	12	42	48	6	NR		18	0	0	72	36	126	126	0
POR		24	36	18	30	12	42	48	6	POR		0	0	0	72	36	144	144	0
PORL	0	24	36	18	30	12	42	48	6	PORL	0	72	36	144	144	0	0	0	0
Component (E)										Component (F)									
Period		4	5	6	7	8	9	10	11	Period		4	5	6	7	8	9	10	11
GR		48	72	36	60	24	84	96	12	GR		24	36	18	30	12	42	48	6
SR		54	81	27	0	0	0	0	0	SR		36	36	18	0	0	0	0	0
POH	0	6	15	6	0	0	0	0	0	POH	0	12	12	12	0	0	0	0	0
NR		0	0	0	54	24	81	96	0	NR		0	0	0	18	12	36	48	0
POR		0	0	0	54	27	81	108	0	POR		0	0	0	18	18	36	54	0
PORL	0	54	27	81	108	0	0	0	0	PORL	0	18	18	36	54	0	0	0	0

GR (gross requirements) SR (scheduled receipts) POH (projected on-hand) NR (net requirements) POR (planned order receipts) PORL (planned order releases) lot method is fixed order quantity for Sub assembly (A) =1, lot method is fixed order quantity first Component (D) =36, lot method is fixed order quantity for Component (E) =27, lot method is fixed order quantity for third Component (F) =18.

As in third level flexible BOM of components do compensation for this shortage. The LP model (BOMLP) can be formulated for this situation and is shown in Figure 4-10.

On solving the LP model, the ck_i values for period 4 are $ck_{11} = 2.25$, $ck_{12} = 2.25$ and $ck_{13} = 1.5$. The ck_i values will change the gross requirements for the sub assemblies due to the shortage of component (D). The gross requirement for the component (D) is reduced to 54 from 72, which can now be reached by 0 unit's on-hand and 54 units of scheduled receipt. The gross requirements for the component (E) and component (F) are changed to compensate for the shortage of component (D) and they are increased to 54 from 48 for component (E), to 36 from 24 for component (F). Since period 4 is the current period, the PORL tables are extended to period 11. For periods 5 through 11, the partly divided BOM (c) of components is used because the goal is always to use the default BOM whenever

possible. It is noted that, for periods 5 through 11 in Table 4-19, the gross requirement for component (D), component (E) and component (F) is obtained by multiplying the PORL in each period by 3, 2, and 1 respectively, the values 3, 2 and 1 are values of partly divided bill of material (c).

BOMLP-OBJ: Minimize: $dp_{11} + dp_{12} + dp_{13}$		
Subject to:		
1.	BOMLP-C1: $ck_{11} + ck_{12} + ck_{13} = 6$	
2.	C2: $ck_{11} - dp_{11} + dn_{11} = 3$	
3.	$ck_{12} - dp_{12} + dn_{12} = 2$	
4.	$ck_{13} - dp_{13} + dn_{13} = 1$	
5.	C3: $-(ck_{11} * 24) + (0 + 54) \geq 0$	$\rightarrow ck_{11} \leq 2.25$
6.	$-(ck_{12} * 24) + (0 + 54) \geq 0$	$\rightarrow ck_{12} \leq 2.25$
7.	$-(ck_{13} * 24) + (0 + 36) \geq 0$	$\rightarrow ck_{13} \leq 1.5$
8.	C4: $1 \leq ck_{11} \leq 5$	
9.	$0 \leq ck_{12} \leq 5$	
10.	$0 \leq ck_{13} \leq 4$	

Figure 4-10 Linear programming model for shortage shown in period 4 of Table 4-18

Table 4-19 Fully adjusted planned order release table for periods 4 – 11

Sub Assembly (A)										Component (D)									
Period		4	5	6	7	8	9	10	11	Period		4	5	6	7	8	9	10	11
GR		24	36	18	30	12	42	48	6	GR		54	108	54	90	36	126	144	18
SR		0	0	0	0	0	0	0	0	SR		54	108	72	0	0	0	0	0
POH		0	0	0	0	0	0	0	0	POH	0	0	0	18	0	0	0	0	0
NR		24	36	18	30	12	42	48	6	NR		0	0	0	72	36	126	126	0
POR		24	36	18	30	12	42	48	6	POR		0	0	0	72	36	144	144	0
PORL	0	24	36	18	30	12	42	48	6	PORL	0	72	36	144	144	0	0	0	0
Component (E)										Component (F)									
Period		4	5	6	7	8	9	10	11	Period		4	5	6	7	8	9	10	11
GR		54	72	36	60	24	84	96	12	GR		36	36	18	30	12	42	48	6
SR		54	81	27	0	0	0	0	0	SR		36	36	18	0	0	0	0	0
POH	0	0	9	0	0	0	0	0	0	POH	0	0	0	0	0	0	0	0	0
NR		0	0	0	60	3	60	75	6	NR		0	0	0	30	6	30	42	0
POR		0	0	0	81	27	81	81	27	POR		0	0	0	36	18	36	54	0
PORL	0	81	27	81	81	27	0	0	0	PORL	0	36	18	36	54	0	0	0	0

GR (gross requirements) SR (scheduled receipts) POH (projected on-hand) NR (net requirements) POR (planned order receipts) PORL (planned order releases) lot method is fixed order quantity for Sub assembly (A) =1, lot method is fixed order quantity for Component (D) =36, lot method is fixed order quantity for Component (E) =27, lot method is fixed order quantity for Component (F) =18.

For second sub assembly shortage occur in any of the component in third level. Here sub assembly (B) is assumed as the end item (or top assembly) having two components with partly divided BOM is given in the Figure 4-8. The partly divided BOM of components to make one unit of sub assembly (B) is one unit of component (D) and two units of component (G). There is also the possibility of a shortage of one or more component due to some failures in the production processes. Figure 4-7 the partly divided bill of material allowing some flexibility in the combination. Period 4 is when some unexpected problems occur, which requires completion using the flexible BOM approach. It is for the reason that the gross requirement “GR” for the eight-period planning horizon is shown in periods 1 and 4.

Table 4-20 Planned order release table for periods 1 – 8

Sub Assembly (B)										Component (D)									
Period		1	2	3	4	5	6	7	8	Period		1	2	3	4	5	6	7	8
GR		21	24	3	12	18	9	15	6	GR		21	24	3	12	18	9	15	6
SR		0	0	0	0	0	0	0	0	SR		0	0	0	0	0	0	0	0
POH		0	0	0	0	0	0	0	0	POH	48	27	3	0	0	0	0	0	0
NR		21	24	3	12	18	9	15	6	NR		0	0	0	12	12	3	9	6
POR		21	24	3	12	18	9	15	6	POR		0	0	0	18	18	9	9	9
PORL		21	24	3	12	18	9	15	6	PORL	0	18	18	9	9	9	0	0	0
Component (G)																			
Period		1	2	3	4	5	6	7	8										
GR		42	48	6	24	36	18	30	12										
SR		0	0	0	0	0	0	0	0										
POH	90	48	0	0	0	0	0	0	0										
NR		0	0	6	24	36	18	30	12										
POR		0	0	6	24	36	18	30	12										
PORL	0	6	24	36	18	30	12	0	0										

GR (gross requirements) SR (scheduled receipts) POH (projected on-hand) NR (net requirements) POR (planned order receipts) PORL (planned order releases) lot method is fixed order quantity for Sub assembly (B) =1, lot method is fixed order quantity for Component (D) =9, lot method is fixed order quantity for Component (G) =6.

Planned Order Release (PORL) tables for periods 1 through 8 (Table 4-20) using the standard size BOM (in Figure 4-8). In this example, the scheduled orders come in period 4. In Table 4-20, the net requirement for component (G) in period 4 is 24 units. To meet this requirement, an order of 24 units for component (G) has to be placed in period 2, since the lead-time for component (G) is two periods; this order is shown in period 2 of Table 4-20 as a PORL for component (G). When period 4 reaches due to some unwanted reasons, the actual order received for component (G) is 18 units instead of 24 units. This is shown in Table 4-21, as a schedule receipt for the component (G) in period 4 (which is the current period in Table 4-21). So finally, there is a NR of 6 units for the component (G) in period 4. As the flexibility of BOM in components compensate this shortage in third level. The LP problem can be formulated for this situation and is shown in Figure 4-11.

Table 4-21 Planned order release table for periods 4 – 11

Sub Assembly (B)										Component (D)									
Period		4	5	6	7	8	9	10	11	Period		4	5	6	7	8	9	10	11
GR		12	18	9	15	6	21	24	3	GR		12	18	9	15	6	21	24	3
SR		0	0	0	0	0	0	0	0	SR		18	18	9	0	0	0	0	0
POH		0	0	0	0	0	0	0	0	POH	0	6	6	6	0	0	0	0	0
NR		12	18	9	15	6	21	24	3	NR		0	0	0	9	6	18	24	0
POR		12	18	9	15	6	21	24	3	POR		0	0	0	9	9	18	27	0
PORL		12	18	9	15	6	21	24	3	PORL	0	9	9	18	27	0	0	0	0
Component (G)																			
Period		4	5	6	7	8	9	10	11										
GR		24	36	18	30	12	42	48	6										
SR		18	36	0	0	0	0	0	0										
POH	0	0	0	0	0	0	0	0	0										
NR		6	0	18	30	12	42	48	6										
POR		0	0	18	30	12	42	48	6										
PORL	0	18	30	12	42	48	6	0	0										

GR (gross requirements) SR (scheduled receipts) POH (projected on-hand) NR (net requirements) POR (planned order receipts) PORL (planned order releases) lot method is fixed order quantity for Sub assembly (B) =1, lot method is fixed order quantity for Component (D) =9, lot method is fixed order quantity for Component (G) =6.

On solving the LP model, the ck_i values for period 4 are $ck_{21} = 1.5$ and $ck_{22} = 1.5$. The ck_i values will change the gross requirements for the components due to the shortage of component (G). The gross requirement for the component (G) is reduced to 18 from 24, which can now be reached by 0 unit on-hand and 18 units of scheduled receipt. The gross requirement for the component (D) is changed to compensate for the shortage of component (G) and that is increased to 18 from 12 for component (D). Since period 4 is the current period, the PORL tables are extended to period 11. For periods 5 through 11, the partly divided BOM (c) of components is used because the target is always to use the default BOM whenever possible. Note that, for periods 5 through 11 in Table 4-23, the gross requirement for component (D) and component (G) is obtained by multiplying the PORL in each period by 1 and 2 respectively, the values 1 and 2 are values of (c).

BOMLP-OBJ: Minimize: $dp_{21} + dp_{22}$	
Subject to:	
1.	BOMLP-C1: $ck_{21} + ck_{22} = 3$
2.	C2: $ck_{21} - dp_{21} + dn_{21} = 1$
3.	Ck₂₂ - dp₂₂ + dn₂₂ = 2
4.	C3: $-(ck_{21} * 12) + (0 + 18) \geq 0 \rightarrow ck_{21} \leq 1.5$
5.	$-(ck_{22} * 12) + (0 + 18) \geq 0 \rightarrow ck_{22} \leq 1.5$
6.	C4: $0 \leq ck_{21} \leq 3$
7.	$0 \leq ck_{22} \leq 3$

Figure 4-11 Linear programming model for shortage shown in period 4 of Table 4-22

Table 4-23 Fully adjusted planned order release table for period 4 – 11

Sub Assembly (B)										Component (D)									
Period		4	5	6	7	8	9	10	11	Period		4	5	6	7	8	9	10	11
GR		12	18	9	15	6	21	24	3	GR		18	18	9	15	6	21	24	3
SR		0	0	0	0	0	0	0	0	SR		18	18	9	0	0	0	0	0
POH		0	0	0	0	0	0	0	0	POH	0	0	0	0	0	0	0	0	0
NR		12	18	9	15	6	21	24	3	NR		0	0	0	15	3	15	21	0
POR		12	18	9	15	6	21	24	3	POR		0	0	0	18	9	18	27	0
PORL		12	18	9	15	6	21	24	3	PORL	0	18	9	18	27	0	0	0	0
Component (G)																			
Period		4	5	6	7	8	9	10	11										
GR		18	36	18	30	12	42	48	6										
SR		18	36	0	0	0	0	0	0										
POH	0	0	0	0	0	0	0	0	0										
NR		0	0	18	30	12	42	48	6										
POR		0	0	18	30	12	42	48	6										
PORL	0	18	30	12	42	48	6	0	0										

GR (gross requirements) SR (scheduled receipts) POH (projected on-hand) NR (net requirements) POR (planned order receipts) PORL (planned order releases) lot method is fixed order quantity for Sub assembly (B) =1, lot method is fixed order quantity for Component (D) =9, lot method is fixed order quantity for Component (G) =6.

For third sub assembly shortage occur in any of the component in third level. Here sub assembly (C) is assumed as the end item (or top assembly) having two components with partly divided BOM (c) is given in the Figure 4-8. The partly divided BOM of components to make one unit of sub assembly (C) is two units of component (D) and three units of component (G). There is also the possibility of a shortage of one or more component due to some failures in the production processes. Figure 4-7 the partly divided bill of material allowing some flexibility in the combination. Period 3 is when some problems occur, which requires completion using the flexible BOM approach. The gross requirement “GR” for the eight-period planning horizon is shown in the periods 1 and 3.

Table 4-24 Planned order release table for period 1 – 8

Sub Assembly (C)									Component (D)										
Period		1	2	3	4	5	6	7	8	Period		1	2	3	4	5	6	7	8
GR		35	40	5	20	30	15	25	10	GR		70	80	10	40	60	30	50	20
SR		0	0	0	0	0	0	0	0	SR		0	0	0	0	0	0	0	0
POH		0	0	0	0	0	0	0	0	POH	150	80	0	0	0	0	0	0	0
NR		35	40	5	20	30	15	25	10	NR		0	0	10	40	60	30	50	20
POR		35	40	5	20	30	15	25	10	POR		0	0	10	40	60	30	50	20
PORL		35	40	5	20	30	15	25	10	PORL	0	10	40	60	30	50	20	0	0
Component (H)																			
Period		1	2	3	4	5	6	7	8										
GR		105	120	15	60	90	45	75	30										
SR		0	0	0	0	0	0	0	0										
POH	225	120	0	0	0	0	0	0	0										
NR		0	0	15	55	85	40	75	25										
POR		0	0	20	60	90	40	80	30										
PORL	0	20	60	90	40	80	30	0	0										

GR (gross requirements) SR (scheduled receipts) POH (projected on-hand) NR (net requirements) POR (planned order receipts) PORL (planned order releases) lot method is fixed order quantity for Sub assembly (C) =1, lot method is fixed order quantity for Component (D) =5, lot method is fixed order quantity for Component (H) =10.

Planned Order Release (PORL) tables for periods 1 through 8 (Table 4-24) using the partly divided bill of material BOM in Figure 4-8 is generated by C program. In this example, the scheduled orders come in normally until period 4. In Table 4-24, the net requirement for component (G) in period 4 is 24 units. In order to meet this requirement, an order of 24 units for component (G) has to be placed in period 2, since the lead-time for component (G) is two periods; this order is shown in period 2 of Table 4-24, as a

PORL for component (G). When period 4 reaches due to some unwanted reasons, the actual order received for component (G) is 18 units instead of 24 units. This is shown in Table 4-25, as a schedule receipt for the component (G) in period 4 (which is the current period in Table 4-25). So finally, there is a NR of 6 units for the component (G) in period 4. The LP problem (BOMLP) can be formulated for this situation and is shown in Figure 4-12.

Table 4-25 Planned order release table for period 3 – 10

Sub Assembly (C)										Component (D)									
Period		3	4	5	6	7	8	9	10	Period		3	4	5	6	7	8	9	10
GR		5	20	30	15	25	10	35	40	GR		10	40	60	30	50	20	70	80
SR		0	0	0	0	0	0	0	0	SR		5	40	0	0	0	0	0	0
POH		0	0	0	0	0	0	0	0	POH	0	0	0	0	0	0	0	0	0
NR		5	20	30	15	25	10	35	40	NR		5	0	60	30	50	20	70	80
POR		5	20	30	15	25	10	35	40	POR		0	0	60	30	50	20	70	80
PORL		5	20	30	15	25	10	35	40	PORL	0	60	30	50	20	70	80	0	0
Component (H)																			
Period		3	4	5	6	7	8	9	10										
GR		15	60	90	45	75	30	105	120										
SR		20	60	0	0	0	0	0	0										
POH	0	5	5	0	0	0	0	0	0										
NR		0	0	90	45	70	30	105	115										
POR		0	0	90	50	70	30	110	120										
PORL	0	90	50	70	30	110	120	0	0										

GR (gross requirements) SR (scheduled receipts) POH (projected on-hand) NR (net requirements) POR (planned order receipts) PORL (planned order releases) lot method is fixed order quantity for Sub assembly (C) =1, lot method is fixed order quantity for Component (D) =5, lot method is fixed order quantity for Component (H) =10.

On solving the LP model, the ck_i values for period 3 are $ck_{31} = 1$ and $ck_{32} = 4$. The ck_i values will change the gross requirements for the components due to the shortage of component (D). The gross requirement for the component (D) is reduced to 5 from 10, which can now be reached by 0 unit on-hand and 5 units of scheduled receipt. The gross requirement for the component (H) is changed to compensate for the shortage of component (D) and that is increased to 20 from 15 for component (H). Since period 3 is the current period, the PORL tables are extended to period 10. For periods 4 through 10, the partly divided BOM (c) of components is used because the target is always to use the

default BOM whenever possible. It is noted that, for periods 4 through 10 in Table 4-27, the gross requirement for component (D) and component (H) is obtained by multiplying the PORL in each period by 2 and 3 respectively, the values 2 and 3 are values of (c).

BOMLP-OBJ: Minimize: $dp_{31} + dp_{32}$	
Subject to:	
1.	BOMLP-C1: $ck_{31} + ck_{32} = 5$
2.	C2: $ck_{31} - dp_{31} + dn_{31} = 2$
3.	Ck₃₂ - dp₃₂ + dn₃₂ = 3
4.	C3: $-(ck_{31} * 5) + (0 + 5) \geq 0 \rightarrow ck_{31} \leq 1$
5.	$-(ck_{32} * 5) + (0 + 20) \geq 0 \rightarrow ck_{32} \leq 4$
6.	C4: $0 \leq ck_{31} \leq 5$
7.	$1 \leq ck_{32} \leq 7$

Figure 4-12 Linear programming model for shortage shown in period 3 of Table 4-26

Table 4-27 Fully adjusted planned order release table for period 3 – 10

Sub Assembly (C)										Component (D)									
Period		3	4	5	6	7	8	9	10	Period		3	4	5	6	7	8	9	10
GR		5	20	30	15	25	10	35	40	GR		5	40	60	30	50	20	70	80
SR		0	0	0	0	0	0	0	0	SR		5	40	0	0	0	0	0	0
POH		0	0	0	0	0	0	0	0	POH	0	0	0	0	0	0	0	0	0
NR		5	20	30	15	25	10	35	40	NR		5	0	60	30	50	20	70	80
POR		5	20	30	15	25	10	35	40	POR		0	0	60	30	50	20	70	80
PORL		5	20	30	15	25	10	35	40	PORL	0	60	30	50	20	70	80	0	0
Component (H)																			
Period		3	4	5	6	7	8	9	10										
GR		20	60	90	45	75	30	105	120										
SR		20	60	0	0	0	0	0	0										
POH	0	0	0	0	0	0	0	0	0										
NR		0	0	90	45	70	30	105	115										
POR		0	0	90	50	70	30	110	120										
PORL	0	90	50	70	30	110	120	0	0										

GR (gross requirements) SR (scheduled receipts) POH (projected on-hand) NR (net requirements) POR (planned order receipts) PORL (planned order releases) lot method is fixed order quantity for Sub assembly (C) =1, lot method is fixed order quantity for Component (D) =5, lot method is fixed order quantity for Component (H) =10.

Chapter 5 CONCLUSION

5.1 DISCUSSIONS AND CONCLUSION

This thesis considered a flexible bill of material to deal with possible shortages in lower level sub-assemblies in multi-level BOM with examples of second level and components in lower third level in material requirement planning. The sub-assemblies and the components in second and third level respectively are the dependent demands of top assembly. With the substitution of sub-assemblies and components, for one another in case of a shortages and try to meet the requirements stated in the master production schedule in given time interval. As the bill of material taken for required top assembly is variable, there is a possibility of compensation of its constituents with one another. Also, if there is a shortage in any specific period of sub assembly or component then, they will compensate with each other from in-hand inventory.

The results of the 3 level representative example show that the concept is possible to extend beyond two levels and a multilevel BOM can be considered as flexible as demonstrated for the three level examples. The application of flexible BOMs can be in metallurgical environments when there is a formation of an alloy with no. of metals and non-metals which are relevant with each other and can vary in different proportion. For example, beryllium copper alloys like Beryllium copper ingots and rods, Nickel Beryllium alloy, Aluminum Beryllium master alloy where substitute metals and non-metals may be available. Other applications of flexible BOMs can be in food industry, manufacturing where small components like screws are redundant and their number can be flexible.

5.2 SCOPE FOR FURTHER WORK

There are many issues that need to be addressed in the future. Other approaches need to be developed in which implementation of shortages is taking place by keeping flexible lead-time, variable lot size, variable lower and upper limits of adjusted (calculated) values etc. In short the developed methodology has addressed a general approach to a MRP considering a flexible BOM, but the various input and environment factors are considered as inflexible which may practically vary in many deterministic and random ways. There is

also the usage of common components with different BOM to make compensation with sub-assemblies, having the effect on their on-hand inventory.

Chapter 6 REFERENCES

6.1 LITERATURE REFERENCES

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