Capacity and resource planning and scheduling in manufacturing processes

Best Practice Guide

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Contents

1. Introduction

This document focuses on three areas – process optimization by theory of constraints, operations planning and scheduling, and a detailed view on resource planning. It is a compilation work based on Operations Management: processes and supply chains[1].

2. Theory of constraints

Constrains are any factors that limit the performance and restrict outputs of the system. The theory of constraints is a systematic management approach that focuses on active management of constraints. Those would otherwise impede the company's progress towards its goals. The theory of constraints focuses on making materials flow rapidly and efficiently through the system.

The key principles of the theory of constraints are the following:

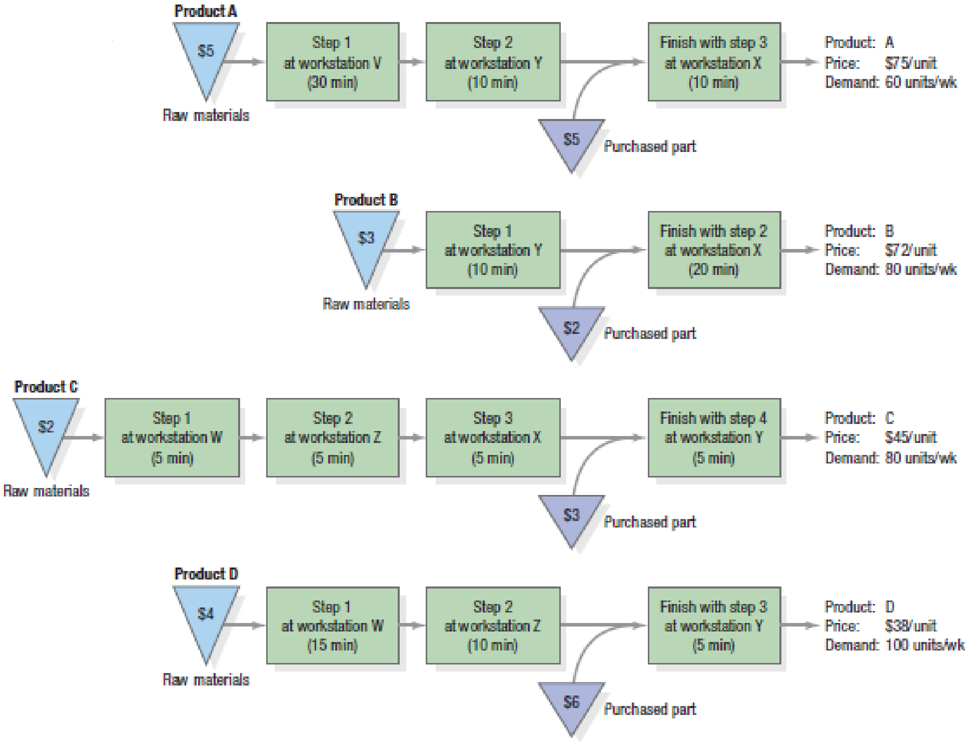
1. Identifying the system's bottlenecks
2. Exploit bottlenecks (create schedules to maximize throughput of the bottleneck)
3. Subordinate all decisions to exploit the bottlenecks (non-bottleneck resources should be scheduled to support the schedule of the bottleneck and not produce more than the bottleneck can handle)
4. Elevate the bottlenecks (increase capacity of the bottleneck)
5. Check repeatedly for new sets of constraints after altering the system

The bottleneck operation can be identified by its utilization. If multiple products are invovled, extra setup time is usually needed at a workstation, to change over from one product to the next. This can increase the overload at the workstation. The setup times represent unproductive time for workers and machines, thus the goal is to minimize them.
When setup times are large, the highest total time per unit processes would typically bet he bottleneck. Variability in workloads will can also create floating bottlenecks. In practice, we can identify the bottleneck by pinpointing material piled – up in front of workstations, waiting to be processed.

Bottlenecks can be relieved by:

- keeping bottleneck resources as busy as is practical
- minimizing idle time at the bottlenecks caused by delays elsewhere in the system and making sure that the bottleneck has all the resources it needs to stay busy
- when a changeover or setup is made at a bottleneck, the number of units processed before the next changeover should be large compared to the number processed at less critical operations

[1] Krajewski, L., Malhotra, M., & Ritzman, L. (2021). *Operations management: Processes and supply chains, global edition* (13th ed.). Pearson Education.



- maximizing the number of units processed per setup means fewer setups per year and, thus, less total time lost to setups

Example: Identifying the bottleneck in a batch process

The manufacturer produces 4 products (A, B, C and D), that are fabricated and assembled in 5 different workstations (V, W, X, Y and Z) in small batches. Each workstation is operated by one worker for a single shift per day. Setup times are reduced and considered negligible. The following chart depicts the path of each product through the manufacturing process.

The goal is to identify the workstation with the highest utilization, thus being the bottleneck of the system.
Solution:
In one week, the workstations are operational for 2400 minutes. We compute the aggregate workloads at each workstation.
The workload of one workstation represented by one product is given as its processing time in the workstation multiplied by its number of units demanded per week.

Workstation	Load from Product A	Load from Product B	Load from Product C	Load from Product D	Total Load (min)
V	60 × 30 = 1800	0	0	0	1,800
W	0	0	80 × 5 = 400	100 × 15 = 1,500	1,900
X	60 × 10 = 600	80 × 20 = 1,600	80 × 5 = 400	0	**2,600**
Y	60 × 10 = 600	80 × 10 = 800	80 × 5 = 400	100 × 5 = 500	2,300
Z	0	0	80 × 5 = 400	100 × 10 = 1,000	1,400

Figure 2: Computation of aggregate workloads. From Krajewski, L., Malhotra, M., & Ritzman, L. (2021). Operations management: Processes and supply chains, global edition (13th ed.). Pearson Education, p. 247.

Ritzman, L. (2021). Operations management: Processes and supply chains, global edition (13th ed.). Pearson Education, p. 246.

Workstation X is the bottleneck, because the aggregate workload is larger than that of other workstations. Moreover, it exceeds the maximum available capacity of 2400 minutes per week.

To identify bottlenecks in the given system, we need to know:

- available production time
- processing time of each product
- production plan (number of units demanded per time interval)

Drum-buffer-rope

Drum-buffer-rope (DBR) is a planning and control system based on the theory of constraints that is often used in manufacturing companies to plan and schedule production. It works by regulating the flow of work-in-process materials at the bottleneck or the capacity constrained resource.

The drum is the bottleneck schedule, which sets production rate for the entire plant and is linked to the market demand.

The buffer is time buffer that plans early flows to the bottleneck, protecting it from disruption and ensuring that it always have work. It can be also placed before the shipping point to protect customer shipping schedules.

The rope is the tying of material release to the drumbeat (the rate at which the bottleneck controls the throughput of the entire system). It is thus a communication device to ensure that raw material is not introduced into the system at a rate faster than what the bottleneck can handle.

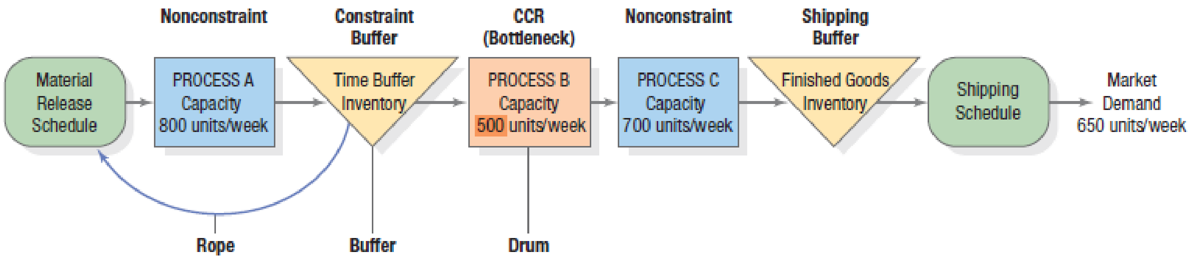


Figure 3: Drum-Buffer-Rope system. From Krajewski, L., Malhotra, M., & Ritzman, L. (2021). Operations management: Processes and supply chains, global edition (13th ed.). Pearson Education, p. 248.

On the figure above, the process B is identified as the bottleneck. The capacity of process B is only 500 units, even though the demand is 650 units per week. The goal is to satisfy the marked demand. A constraint time buffer, which can be in the form of materials arriving earlier than needed, is placed right in front of the bottleneck (Process B). A shipping buffer, in the form of finished goods inventory, can also be placed prior to the shipping schedule to protect customer orders. A rope ties the material release schedule to match the schedule at the bottleneck.

Line balancing

Line balancing is a process of assigning work to stations in a line process, with the goal of achieving the desired output rate with the smallest number of workstations. It brings a new approach to bottlenecks – creating workstations with workloads as evenly balanced as possible, i.e. the capacity utilization for the bottleneck is not much higher than for the other workstations in the line. Line balancing can only be applied to processes that do assembly work, or to work that can be bundled in many ways to create the jobs for each workstation in the line.

The procedure for line balancing consist of the following steps:

1. Separate the work into work elements, which are the smallest units of work that can be perform independently
2. Take the time standard for each element
3. Identify the work elements, called immediate predecessors, which must be done before the next element can begin

To vizualize the relationships of immediate predecessors, the precedence diagram can be constructed (see figure below). The nodes represent work elements and the arrows the precedence relationships between them. The time required to perform the work can be shown below each circle.

Work Element	Description	Time (sec)	Immediate Predecessor(s)
A	Bolt leg frame to hopper	40	None
B	Insert impeller shaft	30	A
C	Attach axle	50	A
D	Attach agitator	40	B
E	Attach drive wheel	6	B
F	Attach free wheel	25	C
G	Mount lower post	15	C
H	Attach controls	20	D, E
I	Mount nameplate	18	F, G
		Total 244	

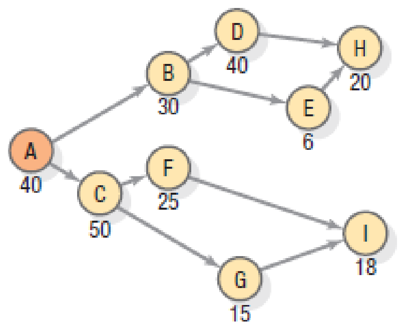


Figure 4: Construction of a precedence diagram. From Krajewski, L., Malhotra, M., & Ritzman, L. (2021). Operations management: Processes and supply chains, global edition (13th ed.). Pearson Education, p. 252-253.

For line balancing, let us introduce the following metrics.

The desired output rate is the number of unit produced per a time interval. It matches the output rate to the staffing and production plan. E.g. if the plan calls for 4800 units per week and the line operates 80 hours per week, the desired output rate is ideály 60 units per hour.

Cycle time is the maximum time allowed for work on a unit at each station. We computed the cycle time as:

$$c = \frac{1}{r}$$

where c is the cycle time in hours per unit and r the desired output rate. E.g. if the line's desired output is 60 units per hour, the cycle time is $c = \frac{1}{60}$ hours per unit, that is 1 minute.

Theoretical minimum is a benchmark or goal for the smallest number of stations possible. We compute it as:

$$TM = \frac{\sum t}{c}$$

where $\sum t$ is the sum of all work element standard times and c is the cycle time. E.g. if the sum of the work-element times is 15 minutes and cycle time is 1 minute, $TM = \frac{15}{1}$, thus 15 stations.

Idle time is the total unproductive time for all stations in the assembly of each unit. We compute it as:

$$DN = nc - \sum t$$

where n is the number of stations.

Efficiency is the ratio of productive time to total time expressed as a percentage.

$$E = \frac{\sum t}{nc} . 100$$

With fixed cycle time c, by minimazing the number of stations n we optimize the idle time and efficiency.

Example: Line balancing

The plant operates 40 hours per week. The desired output rate is 2400 units per week. The total required time to assemble 1 unit is 244 seconds.
We compute the cycle time, theoretical minimum and efficiency.

Solution:
Output rate is = 2400/40 = 60 units per hour.
Cycle time is c = 1/60 hours per unit, therefore 60 seconds per unit.

The theoretical minimum is TM = 244/60 ≈ 4.067, meaning 5 stations.

Efficiency is $E = \frac{244}{5 . 60} . 100$ *= 81,3%*

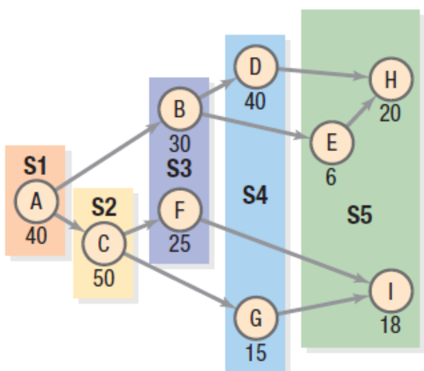


Figure 5: Precedence diagram solution. From Krajewski, L., Malhotra, M., & Ritzman, L. (2021). Operations management: Processes and supply chains, global edition (13th ed.). Pearson Education, p. 246.

The thoretical minimum is 5 workstations. All the precedence and cycle time requirements are satisfied. Each worker at each station must perform the work elements in the proper sequence. The solution with 5 stations is the optimal solution, however the efficiency will be only 81.3 %. Operating the line for less than 40 hours per week (adjusting the cycle time) should be reconsidered.

The next goal is to divide work elements among the stations in the line process. Some heuristic rules can be followed in assigning the next work element to a workstation being created.
We create one station at a time. For the station now being created, we the work elements not yet assigned, that qualify for assignment. They are good candidates if:

1. All of their predecessors have been assigned to this station or stations already created.
2. Adding them to the workstation being created will not create a workload that exceeds the cycle time.

Decisions rules:

- Longest work element – we pick the candidate with the longest time to complete in order to fit in the most difficult elements first
- Shortest work element – we prefere the assignment of the quicker work elements
- Most followers – we choose the element that has the most followers first to maintain flexibility for creating the last stations at the end of the line
- Fewest followers – we pick the candidate with the fewest followers in the precedence diagram

For line balancing, we need to know the following:

- Work elements
- Standard processing time for each work element
- Order of work elements (identifying predecessors)
- Desired output rate per week
- Available production time per week

3. Operations planning and scheduling

Operations planning and scheduling is the process of making sure that demand and supply plans are in balance. It is taking place on different levels, from the aggregate level down to the short-term scheduling level. We distinguish the following types of plans:

A sales and operations plan (S&OP) is a plan of aggregate resources, that ensures that the supply and demand are in balance. It guides the production rate of the whole company and the individual departments, workforce levels, and inventory holdings, that are consistent with the forecasted demands and capacity constraints. S&OP is projected for several time periods into the future. There are two types of S&OP:

- Production plan – S&OP for a manufacturing company that centers on production rates and inventory
- Staffing plan – S&OP for a service provider that focuses on staffing and other human resources

A resource plan is a step between S&OP and scheduling. It determines the requirements for materiál and other resources on a more detailed level.

A schedules is a detailed short - term plan that allocates resources to accomplish specific tasks.

The levels in operations planning and scheduling are:

1. *Sales and operations planning*
   Aggregation happen in 3 dimensions – services of product families, workforce, and time. The information inputs should come from all the departments (operations, distribution and marketing, accounting and finance, human resources, engineering, materials). Related plans are brought together, such as a business plan or annual/financial plan

2. *Resource planning*
   Resource planning provides due dates for the supply of materials, components, products, and other resources such as labor, space, vehicles, etc.

3. *Scheduling*
   The schedules translate the resource plan into detailed specific operational tasks. Workforce schedule is made.

The figure below illustrates the sales and operations plan for a specific make-to-stock product family. History from January till March shows how the actual sales matche the forecasts and the actual production matches the plan. This plan is projected for 18 months. The first 6 months are shown on a month-by-month basis, each in a separate column. The next 6 months are shown on a quarterly basis, with 3 months merged into one column. Finally, the last 6 months occupy a single column.
This product family has a seasonal demand. The company uses anticipation inventory, which is

built up from January though April. Vacations are planned on the months with low demand, November and December. Overtime is used in the peak season, from June through August.

Artic Air Company—April Sales and Operations Plan

Family: Medium window units (make-to-stock) — *Unit of measure:* 100 units

	HISTORY									3rd	4th	Mos	Fiscal Year	Business
SALES	J	F	M	A*	M	J	J	A	S	3 Mos**	3 Mos	13–18	Projection ($000)	Plan ($000)
New forecast	45	55	60	70	85	95	130	110	70	150	176	275	$8,700	$8,560
Actual sales	52	40	63											
Diff for month	7	–15	3											
Cum		–8	–5											
OPERATIONS														
New Plan	75	75	75	75	75	85	85	85	75	177	225			
Actual	75	78	76											
Diff for month	0	3	1											
Cum		3	4											
INVENTORY														
Plan	85	105	120	125	115	105	60	35	40	198	321			
Actual	92	130	143											

DEMAND ISSUES AND ASSUMPTIONS

1. New product design to be launched in January of next year.

SUPPLY ISSUES

1. Vacations primarily in November and December.
2. Overtime in June–August.

Figure 6: Sales and operation plan for make-to-stock product family. From Krajewski, L., Malhotra, M., & Ritzman, L. (2021). Operations management: Processes and supply chains, global edition (13th ed.). Pearson Education, p. 424.

This sales and operations plan doesn't account for the supply options and their cost implication. Therefore, detailed spreadsheets can be used to do that. In the figure below, we can see a manufacturer's plan.

	1	2	3	4	5	6	Total
Inputs							
Forecasted demand	24	142	220	180	136	168	870
Workforce level	120	158	158	158	158	158	910
Undertime	6	0	0	0	0	0	6
Overtime	0	0	0	0	0	0	0
Vacation time	20	6	0	0	4	10	40
Subcontracting time	0	0	0	0	0	6	6
Backorders	0	0	0	4	0	0	4
Derived							
Utilized time	94	152	158	158	154	148	864
Inventory	70	80	18	0	14	0	182
Hires	0	38	0	0	0	0	38
Layoffs	0	0	0	0	0	0	0
Calculated							
Utilized time cost	$376,000	$608,000	$632,000	$632,000	$616,000	$592,000	$3,456,000
Undertime cost	$24,000	$0	$0	$0	$0	$0	$24,000
Overtime cost	$0	$0	$0	$0	$0	$0	$0
Vacation time cost	$80,000	$24,000	$0	$0	$16,000	$40,000	$160,000
Inventory cost	$2,800	$3,200	$720	$0	$560	$0	$7,280
Backorders cost	$0	$0	$0	$4,000	$0	$0	$4,000
Hiring cost	$0	$91,200	$0	$0	$0	$0	$91,200
Layoff cost	$0	$0	$0	$0	$0	$0	$0
Subcontracting cost	$0	$0	$0	$0	$0	$43,200	$43,200
Total cost	$482,800	726,400	632,720	636,000	632,560	675,200	$3,785,680

Figure 7: Manufacturer's plan using a spreadsheet. From Krajewski, L., Malhotra, M., & Ritzman, L. (2021). Operations management: Processes and supply chains, global edition (13th ed.). Pearson Education, p. 426.

Workforce and workstation scheduling

This part of operations planning and scheduling determines when employees work. The possible constraints arising may be resources, individual requirements, or legal and behavioral considerations. The schedule can be fixed or rotating.

Example: Developing a workforce schedule with employees having two consecutive days off

The procedure is the following:

1. *From the requirements schedule, we select two consecutive days which have the lowest total requirements. A tie can be broken according to the employee's preference, or arbitrarily.*
2. *We assign the employee the selected pair of days off. We substract the requirements satisfied by the employee from the net requirements for each day the employee is to work.*
3. *We repeat these steps until all the requirements have been satisfied or a certain number of employees have been scheduled.*

The first steps of the algorithm are in the table below:

SCHEDULING DAYS OFF

M	T	W	Th	F	S	Su	Employee	Comments
6	4	8	9	10	3	2	**1**	The S–Su pair has the lowest total requirements. Assign Employee **1** to a Monday through Friday schedule and update the requirements.
5	3	7	8	9	3	2	**2**	The S–Su pair has the lowest total requirements. Assign Employee **2** to a Monday through Friday schedule and update the requirements.
4	2	6	7	8	3	2	**3**	The S–Su pair has the lowest total requirements. Assign Employee **3** to a Monday through Friday schedule and update the requirements.
3	1	5	6	7	3	2	**4**	The M–T pair has the lowest total requirements. Assign Employee **4** to a Wednesday through Sunday schedule and update the requirements.

Figure 8: First steps of the algorithm for scheduling days off. From Krajewski, L., Malhotra, M., & Ritzman, L. (2021). Operations management: Processes and supply chains, global edition (13th ed.). Pearson Education, p. 431.

The final schedule could look like this:

FINAL SCHEDULE

Employee	M	T	W	Th	F	S	Su	Total
1	X	X	X	X	X	off	off	
2	X	X	X	X	X	off	off	
3	X	X	X	X	X	off	off	
4	off	off	X	X	X	X	X	
5	X	X	X	X	X	off	off	
6	off	off	X	X	X	X	X	
7	X	X	X	X	X	off	off	
8	X	X	X	X	X	off	off	
9	off	X	X	X	X	X	off	
10	X	X	X	X	X	off	off	
Capacity, C	7	8	10	10	10	3	2	50
Requirements, R	6	4	8	9	10	3	2	42
Slack, C – R	1	4	2	1	0	0	0	8

Figure 9: Final schedule. From Krajewski, L., Malhotra, M., & Ritzman, L. (2021). Operations management: Processes and supply chains, global edition (13th ed.). Pearson Education, p. 246.

This problem has multiple solutions. The goal is to minimize slack, that is the difference between the actual capacity and the requirements.

One of the possible visual outputs from the workforce scheduling is the *Gant progress chart*.

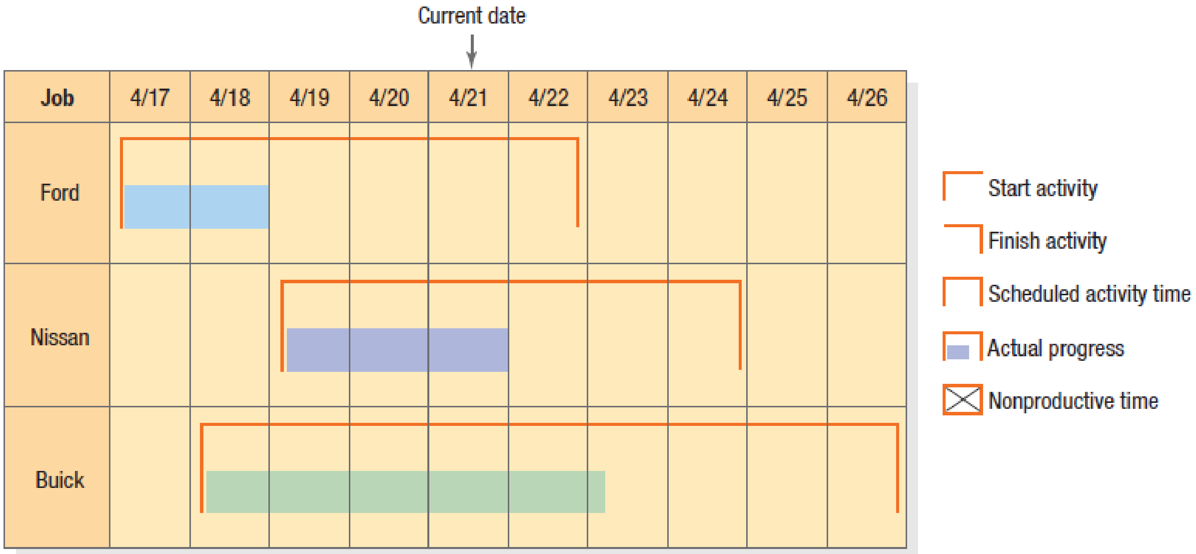


Figure 10: Gantt progress chart for and auto parts company. From Krajewski, L., Malhotra, M., & Ritzman, L. (2021). Operations management: Processes and supply chains, global edition (13th ed.). Pearson Education, p. 433.

Used in job and facility scheduling, it displays the current status of each job relative to its scheduler completion date. The horizontal axis is divided into time periods and it depicts the duration of the project and its current state. The vertical axis shows the projects. The *Gantt workstation chart* for scheduling, e.g. doctors assigned to operating rooms, is shown below.

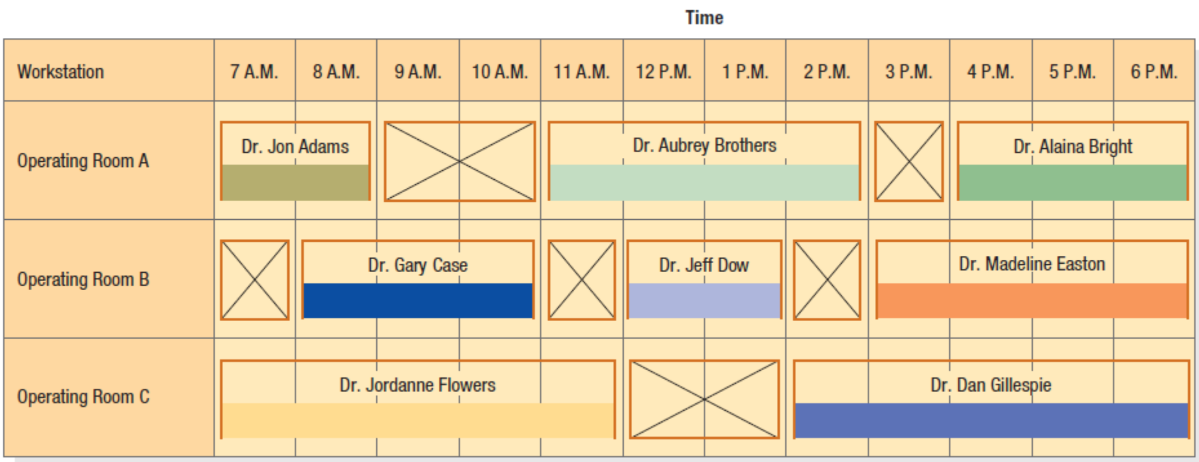


Figure 11: Gantt workstation chart for operating rooms at a hospital. From Krajewski, L., Malhotra, M., & Ritzman, L. (2021). Operations management: Processes and supply chains, global edition (13th ed.). Pearson Education, p. 434.

For developing a workforce schedule, we need to know:

- Employee requirements for each day
- List of employees

Sequencing jobs at a workstation

Another part of scheduling is to assign jobs to workstations. Job priority can be determined based on these priority rules

- FCFS (First – come, first-served) – the job arriving at the system first has the highest priority
- EDD (Erliest due date) – the job with the earliest due date has the highest priority
- SPT (Shortest processing time) – the job with the shortest processing time has the highest priority

Based on the chosen rule, these performance measures are changed:

- flow time – time a job spends in the manufacturing system
- past due – time by which a job missed its due date.

Example: Using priority rules to adjust flow time and past due

The table below describes the current orders in the sytem:

Customer	Time Since Order Arrived (days ago)	Processing Time (days)	Due Date (days from now)
A	15	25	29
B	12	16	27
C	5	14	68
D	10	10	48
E	0	12	80

Figure 12: Example of jobs in the system. From Krajewski, L., Malhotra, M., & Ritzman, L. (2021). Operations management: Processes and supply chains, global edition (13th ed.). Pearson Education, p. 435.

Using the FCFS rule, the priority of the jobs is A, B, D, C and E.
The average flow time is 60.2 days and the average past due is 3.4 days.

Using the SPT rule, the priority of the jobs is D, E, C, B and A.
The average flow time improves to 47.8 day, while the average past due becomes 14.6 days.

For effective sequencing jobs at a workstation, we need to know:

- time since order arrived
- processing time
- due date

For manufacturers, planning means keeping track of large amounts of materials, components, subassemblies, and equipment capacities, to ensure that the finished product is available in time.

Material requirements planning

The first concept that enables effective planning of resources is the *material requirements planning* (MRP). This information system was developer specifically to help manufacturers manage dependent demand and schedule replenishment orders. Its key inputs are:

- master production schedule
- bill of materials database
- inventory record database.

The MRP system identifies the actions that planners must take in order to stay on schedule, such are releasing new production orders, adjusting order quantities, expediting late orders, etc. The system translates the master production schedule and other sources of demand, such as independent demand for replacement parts and maintenance items, into the requirements for all subassemblies, components, and raw materials needed to produce the required parent items. This is called the *MRP explosion*.

Dependent demand is the demand for an item that occurs because the quantity required varies with the production plans for other items held in the firm's inventory. E.g. manufacturing of bicycles – demand for the final product, a bicycle, is *independent demand* because it is influenced only by market conditions. The demand for bike parts has a *dependent demand* because the quantity required varies with the production plans for other items held in the firm's inventory—finished bikes.
Dependent demand is characterized by erratic demand pattern for component. Those components are then manufactured or ordered occurs sporadically (usually where inventory falls to a certain amount) and in large quantities, as it is illustrated in the figure below.

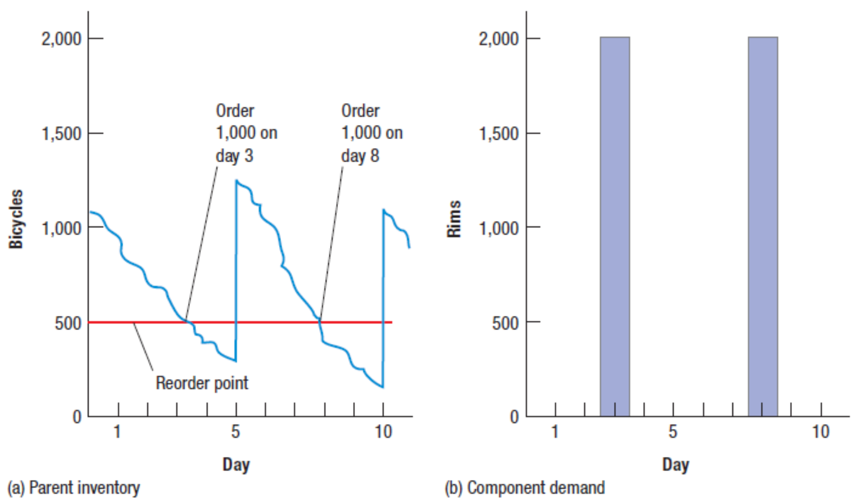


Figure 13: Lumpy dependent demand resulting from continuous independent demand. From Krajewski, L., Malhotra, M., & Ritzman, L. (2021). Operations management: Processes and supply chains, global edition (13th ed.). Pearson

Education, p. 482.

Master production scheduling

The *master production schedule* (MPS) contains detail about how many end items will be produced within a specified time period. The production quantities must be allocated effectively over time. Capacity limitations and bottlenecks, such as machine or labor capacity, storage space, or working capital, may determine the timing and size of MPS quantities.

The figure below shows the master production schedule for a family of chairs:

	April				May			
	1	2	3	4	5	6	7	8
Dining-room chair	150					150		
Kitchen chair				120			120	
Desk chair		200	200		200			200
Sales and operations plan for chair family	670				670			

Figure 14: MPS for a family of chairs. From Krajewski, L., Malhotra, M., & Ritzman, L. (2021). Operations management: Processes and supply chains, global edition (13th ed.). Pearson Education, p. 484.

Developing a master production schedule consists of these steps:

1. Compute the projected on-hand inventories, i.e. an estimate of the amount of inventory available each week after demand has been satisfied
2. Determine the timing and size of MPS quantities. The first MPS quantity should be planned for the week when the projected on-hand inventory shows a shortage

In the table below, we can see an MPS for the dining-room chair for the next 8 weeks. The order policy requires production lot sizes of 150 units. We observe that a shortage of 13 chairs will occur in the second week unless the scheduler provides an MPS quantity for that time. The last row of the table indicates the periods in which production has to start so that the MPS quantities are available on time.

Item: Dining-room chair

Order Policy: 150 units
Lead Time: 1 week

Quantity on Hand: 55	April				May			
	1	2	3	4	5	6	7	8
Forecast	30	30	30	30	35	35	35	35
Customer orders (booked)	38	27	24	8				
Projected on-hand inventory	17	137	107	77	42	7	122	87
MPS quantity		150					150	
MPS start	150					150		

Explanation:
The time needed to assemble 150 chairs is 1 week. The assembly department must start assembling chairs in week 1 to have them ready by week 2.

Explanation:
On-hand inventory balance = 17 + 150 – 30 = 137. The MPS quantity is needed to avoid a shortage of 30 – 17 = 13 chairs in week 2.

Figure 15: Master production schedule for weeks 1-8. From Krajewski, L., Malhotra, M., & Ritzman, L. (2021). Operations management: Processes and supply chains, global edition (13th ed.). Pearson Education, p. 485.

A new row can be added to the table, which indicates the amount of end items that marketing can promise to deliver on specific dates. The *available-to-promise* (ATP) inventory is the difference between already booked orders and the quantity that is planned to be produced. In the example in the table below, it indicates to the sales department that it can promise as many as 17 units on week 1, 91 more units sometime in weeks 2 through 6, and 150 more units in week 7 or 8.

Item: Dining-room chair

Order Policy: 150 units
Lead Time: 1 week

Quantity on Hand: 55	April				May			
	1	2	3	4	5	6	7	8
Forecast	30	30	30	30	35	35	35	35
Customer orders (booked)	38	27	24	8				
Projected on-hand inventory	17	137	107	77	42	7	122	87
MPS quantity		150					150	
MPS start	150					150		
Available-to-promise (ATP) inventory	17	91					150	

Explanation:
The total of customer orders booked until the next MPS receipt is 38 units. The ATP = 55 (on-hand) + 0 (MPS quantity) – 38 = 17.

Explanation:
The total of customer orders booked until the next MPS receipt is 27 + 24 + 8 = 59 units. The ATP = 150 (MPS quantity) – 59 = 91 units.

Figure 16: MPS record with an ATP row. From Krajewski, L., Malhotra, M., & Ritzman, L. (2021). Operations management: Processes and supply chains, global edition (13th ed.). Pearson Education, p. 486.

The requirements to developing a master production plan are:

- Sales and operations plans (how many end items will be produced within specified time periods)
- Projected requirements
- Assembly times
- Production times

MRP explosion

The inputs to the MRP system include the bill of materials and inventory records. The MRP explosion results in reports that form the final materiál requirements plan.

The *bill of materials* is the record of all the components of an item, the parent-component relationships, and the usage quantities derived from engineering and process designs. We can see an example of a bill of materials in the figure below.

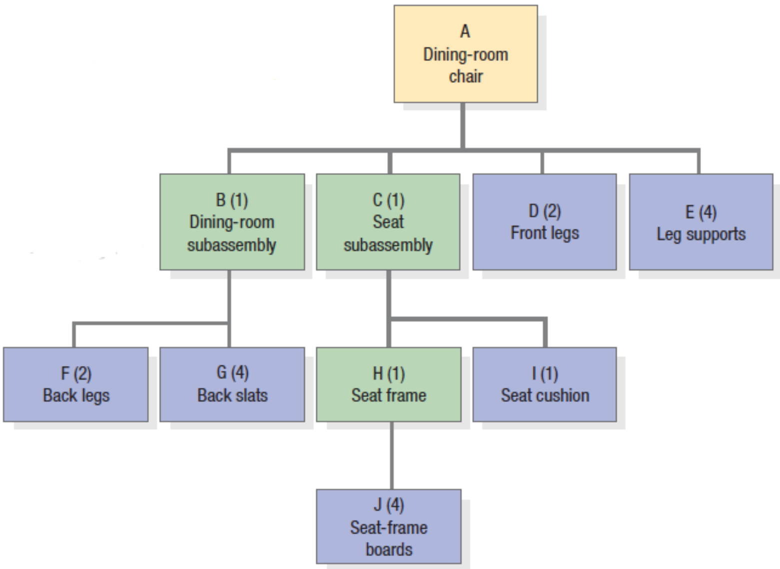


Figure 17: Bill of materials. From Krajewski, L., Malhotra, M., & Ritzman, L. (2021). Operations management: Processes and supply chains, global edition (13th ed.). Pearson Education, p. 488.

Inventory records show an item's lotsize policy, lead time, and various time-phased data. The following information can be found in the record:

- gross requirements – total demand derived from all parent production plans, also including demand not otherwise accounted for (e.g. replacement parts)
- scheduled receipts – open orders, orders that have been placed but not completed
- projected on-hand inventory – an estimate of the amount of inventory available each week after gross requirements have been satisfied
- planned receipts – orders that are not yet released to the shop or the supplier
- planned order releases – indication of when an order for a specified quantity of an item is to be issued

In the table below, an example of a completed inventory record for the seat subassembly is shown.

Item: C
Description: Seat subassembly

Lot Size: 230 units
Lead Time: 2 weeks

	Week							
	1	2	3	4	5	6	7	8
Gross requirements	150			120		150	120	
Scheduled receipts	230							
Projected on-hand inventory 37	117	117	117	227	227	77	187	187
Planned receipts				230			230	
Planned order releases		230			230			

Explanation:
Without a planned receipt in week 4, a shortage of 3 units will occur: 117 – 120 = –3 units. Adding the planned receipt brings the balance to 117 + 230 – 120 = 227 units. Offsetting for a 2-week lead time puts the corresponding planned order release back to week 2.

Explanation:
The first planned receipt lasts until week 7, when projected inventory would drop to 77 – 120 = –43 units. Adding the second planned receipt brings the balance to 77 + 230 – 120 = 187 units. The corresponding planned order release is for week 5 (or week 7 minus 2 weeks).

Figure 18: Completed inventory record for the seat subassembly. From Krajewski, L., Malhotra, M., & Ritzman, L. (2021). Operations management: Processes and supply chains, global edition (13th ed.). Pearson Education, p. 491.

The planning factors that affect the performance of the MRP system are planning lead time and lot-sizing rules.

Planning lead time is an estimate of the time between placing an order for an item and receiving the item in inventory. For purchased items, it is the time allowed for receiving a shipment from the supplier after the order has been sent, including the normal time to place the order. For items manufactured in-house, it can be an average of the actual lead times for recent orders, or computed from setup time, processing time, material handling between operations, and waiting time.

Lot-sizing rules determine the timing and size of order quantities. These rules are important because they affect setup, inventory and order costs. We distinguish these 3 rules:

- fixed order quantity (FOQ) – maintains the same order quantity each time an order is issued

- periodic order quantity (POQ) – allows a different order quantity for each order issued but issues the order for predetermined time intervals
- lot for lot (L4L) – special POQ rule, where the lot size ordered covers the gross requirements of a single week (P = 1) and the goal is to minimize inventory

When comparing all the three strategie, we observe that the FOQ rule generates a high level of average inventory because it creates inventory remnants. A remnant is inventory carried into a week. Remnants occur because the FOQ does not match requirements exactly. The POQ rule reduces the amount of average on-hand inventory because it does a better job of matching order quantity to requirements. It adjusts lot sizes as requirements increase or decrease. The L4L rule minimizes inventory investment, but it also maximizes the number of orders placed. This rule is most applicable to expensive items or items with small ordering or setup costs. It is the only rule that can be used for a low-volume item made to order. It can also approximate the small-lot inventory levels of a lean system. By avoiding remnants, both the POQ and the L4L rule may introduce instability by tying the lot-sizing decision so closely to requirements. If any requirement changes, so must the lot size, which can disrupt component schedules. Last-minute increases in parent orders may be hindered by missing components.

The outputs from a MRP system are mainly *material requirements*. MRP translates the MPS and other sources of demand into the requirements needed for all of the subassemblies, components, and raw materials the firm needs to produce parent items – this process generates the material requirements plan for each component item. Next, the system may generate automatic *action notices* – memos alerting planners about releasing new orders and adjusting the due dates of scheduled receipts. Another output may be *resource requirement reports.* Capacity requirements planning (CRP) reports project time-phased capacity requirements for workstations. Their purpose is to match the materials requirements plan with the capacity of key processes. Finally, performance reports, other outputs such as priority reports can supply information in an MRP system to other functional areas.

For materiál requirement plnanning, we need to know:

- Gross requirements
- Scheduled and planned receipts
- Projected on-hand inventory
- Planning lead time

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