Chapter 2

Capacity Planning

The First Encounter with the Bottleneck

The Achilles' Heel in the Business Processes

Everything comes to us that belongs to us if we create the capacity to receive it.
Rabindranath Tagore, 1862-1941.

The key problems of this chapter can be accessed at

http://www.csun.edu/~aa2035/CourseBase/Capacity/CapacityKeyProblems.pptx

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In this chapter, we will discuss both the capacity of operation and the capacity of a process. We also define terms such as Bottleneck, Utilization, and Throughput.

Problem 1. A process is composed of two sequential activities A and B.

→ [Activity-A] → [Activity-B] →

Activity-A: Activity Time 5 min

Activity-B: Activity Time 10 min

a) Compute the Theoretical Flow Time.

The **theoretical flow time** of this process is = 5+10= 15. Theoretically, it takes a flow unit (a patient, a product, etc.) 15 minutes to flow from input form into output form.

b) How do we compute the Flow Time of the process?

We do not know the **Flow Time** of this process. The flow time is the **activity** times plus the buffer times which is represented as **Rectangle** (representing value-added activities) times and **triangle** times (representing non-value-added buffers or waiting lines).**Buffer or Waiting** times are usually 10, 20, and 100 times of the activity times. We will discuss flow time in future chapters.

Activity Time (or **Work Content**) of Activity-A = 5 min. We also refer to it as **T_p of Activity-A.**

Activity Time (or **Work Content**) of Activity-B = 10 min. We also refer to it as **Tp of Activity-B.**

If each activity is completed using a single resource, for example, if Resource-1 is assigned to Activity-1, and Resource-2 is assigned to Activity-2, then the **Unit Load of Resource-1 is 5 minutes,** and the Unit Load of Resource-2 is 10 minutes. We also refer to 5 minutes as **Tp or Unit Load of Resource-1**and 10 minutes as **Tp or Unit Load of Resource-2.**

Tp: When applied to activity, is called Work Content, Activity Time, or Activity Load.

Tp: When applied to a resource, is called Unit Load or Resource Load.

c) Compute Effective Capacity of each resource.

The Effective Capacity (or simply Capacity) of a Single Resource-Unit is equal to 1 divided by its unit load, or 1/Tp. The Unit Load of Resource-1 is 5 minutes. If Resource-1 can complete 1 Activity-A in 5 minutes, how many units it can complete in 1 minute?

Unit	Time
1	5
X	1

$X = (1 \times 1)/5 = 1/5$

In 1 minute, it can complete 1/5 Activity-A. That is 1/Tp.

The capacity of the single resource-unit of **Resource-1 = 1/Tp =1/5 per minute or 60(1/5) = 12 per hour.** Capacity of the single resource-unit of Resource-2 = 1/Tp =1/10 per minute or 60(1/10) = 6 per hour. If we had two units of Resource-1, we would have referred to them as the **Resource-Pool** of Resource-1.

d) What is the Capacity of the process?

The Capacity of the process = Rp= min {1/5, 1/10} = 1/10 per minute or Rp= min {12, 6} = 6 per hour.

A chain is as strong as its weakest link. The bottleneck is the resource-unit (resource-pool) with the minimum effective capacity.

The capacity of a process is equal to the capacity of its bottleneck.

Capacity is the maximum stable flow rate. During periods of heavy congestion, throughput reaches the capacity, but in most of the time Throughput < Capacity.

e) What is the Cycle time of this process?

Cycle time (CT) is the duration of time that the process needs between completing two consecutive flow units. It is not the flow time. It depends on the number of sequential operations and, indeed, on the capacity of the process (bottleneck). The higher the capacity, the shorter the cycle time. If the capacity is 6 per hour, then the process has the capability to send a product out (or complete a service) every 60/6 = 10 minutes; cycle time is 10 minutes.

We can achieve the same outcome using 10-minute cycles by using Cycle time = 1/Capacity. Capacity was 6 per hour or 1/10 per minute. CT (Cycle time is then equal to 1/6 hour or 1/(1/10) = 10 minutes.

In a synchronized operation we will have Throughput = Demand. The Demand (that our process gets), which is equal to our Throughput, is always less than Capacity.

Suppose that the throughput in our problem is R = 5 per hour (or 1/12 per minute).

f) Compute Capacity Utilization.

Capacity Utilization (or simply Utilization) of a Resource-Pool = Throughput/Capacity of a resource-pool ➔U = R/Rp

Process Utilization (or simply Utilization) of the process

U= Throughput/Capacity of the bottleneck resource-pool➔ U = 5/6

g) Compute Takt Time.

Cycle time is the amount of time that the process **needs** between completing two consecutive flow units. It depends on capacity; CT = 1/Rp.

Takt time (TT) is the amount of time that the process **has** between completing two consecutive flow units. Takt Time is related to Throughput (Demand). If the throughput is 5 per hour, then the process has a 60/5 = 12 minutes. Takt time is 12 minutes; this means the system has 12 minutes to send the next flow unit out. In general, Takt time = 1/Throughput. Throughput is 5 per hour or 1/12 per minute.

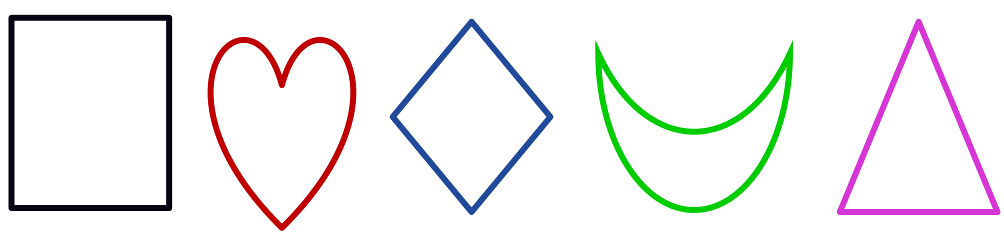
TT = 1/(Throughput) = 1/5 hour or 60(1/5) = 12 minutes, or 1/(1/12) = 12 minutes.

Demand = Throughput ≤ Capacity

Takt Time ≥ Cycle Time

R ≤ Rp, where TT ≥ CT

Cross-Training (Pooling). If we cross-train Resource-1 and Resource-2 so that each resource can perform both Activities A and B, then things may change. Usually, if we assign only one task or a limited number of tasks to a resource, the resource becomes specialized and efficient. But if several tasks are assigned to a resource, efficiency goes down. To illustrate this reality, consider drawing 20 of each of the following shapes. First,try drawing 20 of the first shape under each other (in the same color), then 20 of the second shape in the next column adjacent to your already drawn shapes, and then continue for the third, fourth, and fifth shapes. Now you have 20 rows and 5 columns of drawings of 5 shapes each in its assigned color. Now let's prepare the same thing differently.



This time, first draw the 5 shapes (each in its corresponding color), then go to the next row and repeat what you did in the first row, and then repeat for the next 18 rows.

Which procedure took more time? Drawing all 20 instances of each shape together or switching between the shapes? That is the difference between specialty and flexibility. Cross-training and pooling lead to flexibility. Flexibility means longer processing times (larger Tp). However, it does not necessarily mean lower capacity (smaller Rp).

Returning to our process with two activities, suppose that when both activities are assigned to both resources, the efficiency of both workers goes down. Perhaps that is due to setup for switching from one activity to the other. Suppose that when task 1 is assigned to each of the two resources, in the new situation, it takes 6 minutes instead of 5 minutes. Also, suppose that when task 2 is assigned to each of the two resources, it takes 12 minutes instead of 10 minutes.

h) Compute capacity under cross-training.

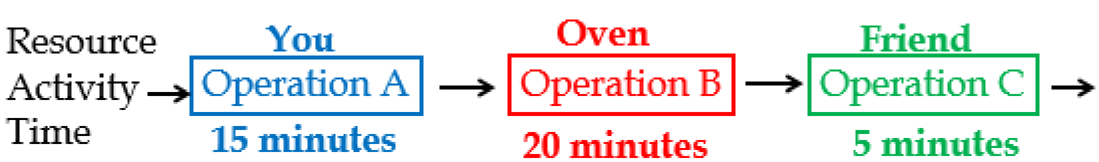
Now we have a Resource-Pool that contains two Resource-Units. The Unit Load of the Resource-Pool = 6+12 = 18 minutes. We also refer to it as **Tp of the Resource-Pool**. Again, note that there is a different naming for Tp. When Tp is referring to an activity, we call it the **activity time** (or work content). When Tp is referring to a resource, we call it the **Unit Load of the Resource** (or load of a flow unit on a resource).

Given the unit load of 18 minutes, the capacity of a single Resource-Unit = 1/18 flow units. But we also need a unit of time. Since Tp is 18 minutes, the capacity of a single resource-unit is 1/Tp =1/18 per minute.

The capacity of a single Resource-Unit = 60(1/18) = 3.333 flow units per hour.

However, there are **2** resource-units in the resource-pool. Therefore, the capacity of the resource-pool is 2(1/18) = 1/9 per minute, or 2(3.333) = 6.666 per hour. While the total unit load increased from 5+10 to 18, the capacity did not decrease, but instead, it increased by about 11%. That is the power of **cross-training, pooling, and centralization.**

Problem 2. We are making batches of muffins. There are three sequential activities: A (preparation), B (baking), and C (packaging and labeling). There are three resources: you and your friend (human resources), and the oven (capital resource).



To produce each batch of muffins, you prepare the material and put the batch in the oven (there is only a single oven, and it can just bake one batch at a time). Then your friend takes the batch out and completes packaging and labeling. The processing time for each operation is given above. Estimating the processing times is the subject of motion and time studies. This system works for 4 hours, that is, 4×60 = 240 minutes.

Compute the capacity of each resource, the capacity of the process, and the utilization of each resource if throughput is at 100% capacity of the process, the cycle time, and the takt time.

Capital Resources—Fixed Assets such as land, buildings, facilities, machinery, oven, etc.

Human Resources—People such as operators, assemblers, engineers, waiters, chefs, customer-service representatives, you, your friend, etc. Each activity may require one or more resources, and each resource may be allocated to one or more activities. A resource, a baker, may be used by several activities such as mixing, kneading and forming a dough. An activity like loading an oven may require multiple resources such as a baker and an oven.

Resource-Unit—An individual resource (chef, mixer, oven), or a combination of different individual resources, for example, an operating room.

Capacity (per hour): You: 60/15 = 4, Oven: 60/20 = 3, Friend: 60/5 = 12

Process Capacity = Min {4, 3, 12} = Capacity of the bottleneck = 3 per hour.

Each hour we produce 3 units. Starting from the second unit, every 60 minutes, 3 units may enter, pass, and leave the process. We refer to this 60/3 = 20 as the average inter-arrival time, average inter-departure time, or cycle time.

We computed the capacity/hour. We could also have computed the capacity per minute:

Capacity/minute: You: 1/15 per minute, Oven: 1/20 per minute, Friend: 1/5 per minute.

Process Capacity = Min {1/15, 1/20, 1/5} = 1/20.

The capacity of the bottleneck = 1/20 per minute. Each minute we produce 1/20 units. In 20 minutes, we can send out, or take in, one product. Twenty minutes is the inter-arrival time, inter-departure time, and cycle time.

a) **How long does it take to produce a batch of muffins?**

In formal terms, the question is asking what the flow time in this process is. We cannot yet determine this because we also need the waiting times.

b) **How long does it *theoretically* take to produce a batch of muffins?**

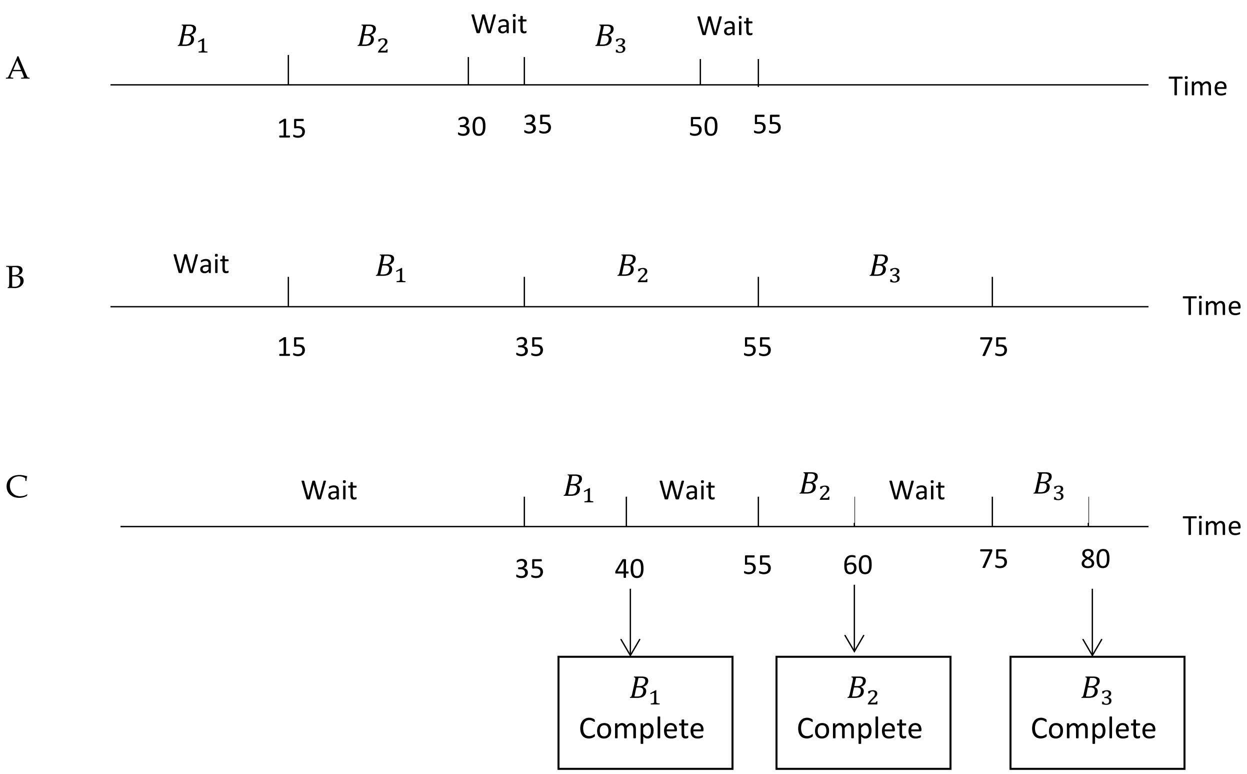
In formal terms, the question is asking what the theoretical flow time in this process is.

Theoretical Flow Time = 15 + 20 + 5 = 40

c) How often does a batch of muffin could enter (exit) this process?

In formal terms, what is the **cycle time** of this system?

The following shows the timeline for each activity—A, B, and C—in a three-batch baking process, where B_1 is batch 1, B_2 is batch 2, and B_3 is batch 3.Please note that we do not allow inventory in the process, and therefore Activity A may need to wait for the availability of the oven (Activity B) before preparing for the next batch.



You prepare a batch and place it in the oven at minute 15. You then start the next batch and complete it at minute 30. The oven is still baking the first batch. It will be done at minute 15+20 = 35.

At minute 35, your friend can take the first batch out of the oven, and after 5 more minutes, at minute 40, he is done. The **first batch exits at minute 40.** The oven is the **bottleneck** since you and your friend need 15 and 5 minutes, respectively, but the Oven needs 20 minutes. At minute 35 you can put the second batch in the oven. Your friend takes it out of the oven at minute 35+20 = 55 and then sends it out of the process at minute 60. That is 60 − 40=20 minutes after the first batch. Similarly, the third batch exits at minute 80.

Therefore, the capability of the process regarding the time between exits of two consecutive batches, the cycle time, is?

Cycle time = Max {15, 20, 5} = 20. The oven is the bottleneck.

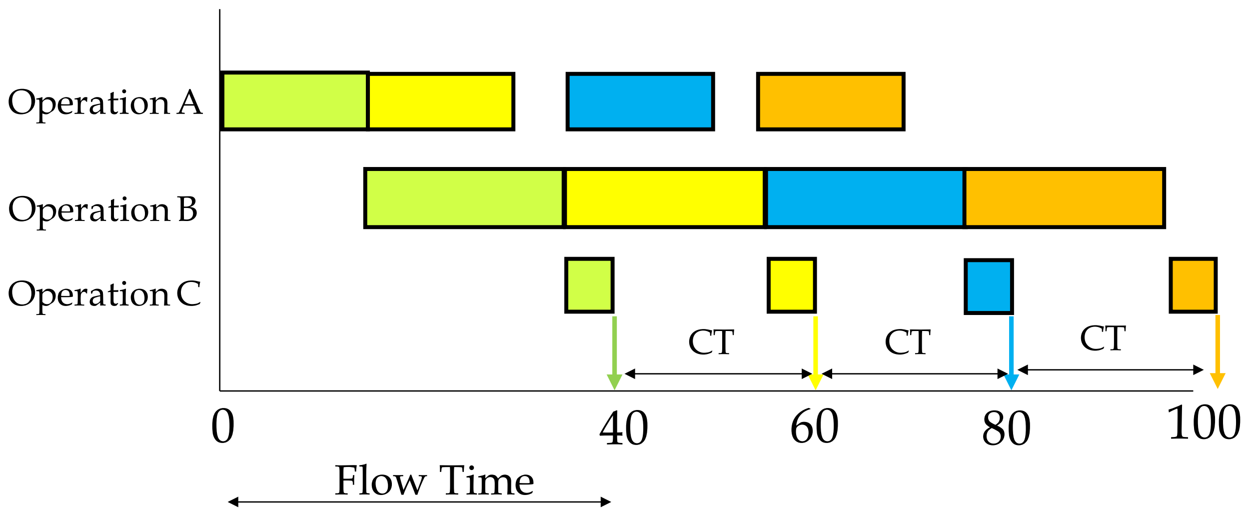
Or we can do it in a long way:

- Capacity = Min {1/15, 1/20, 1/5} = 1/20
- Cycle time = 1/Rp = 1/(1/20)=20 min.

Cycle Time: Starting from 0 vs. Continual

d) How many batches can you produce per day?

Case 1, Starting at 0. We have **4×60** minutes. It takes you **40** minutes to produce the first batch. In the remaining 240 − 40 = 200 minutes, given the cycle time is 20 minutes, we produce 1 batch per 20 minutes, and that gives us 10 batches in 200 minutes. We produce 1+10 = 11 per 4 hours. We could also have said that in the first 40 minutes, we produced 1 batch and in the next 200 minutes we produced 1/20 batch per min. That is 1+200(1/20) = 11 per 4 hours.



Case 2, Continual. Suppose we are not producing muffins, but something else, such that at the start of each day there is work-in-process (WIP) from the previous day in the system. For example, suppose it is a small portion of a painting and you can make that part ready today, and put it into the oven at the start of the next day. What is the capacity (or maximum Throughput)?

The flow time is 40 minutes. The cycle time is 20 minutes. Therefore, capacity is 1/20 per minute. In 4 hours, it is 240(1/20) = 12.

By now we should know the terms Flow Time, Cycle Time, and Capacity.

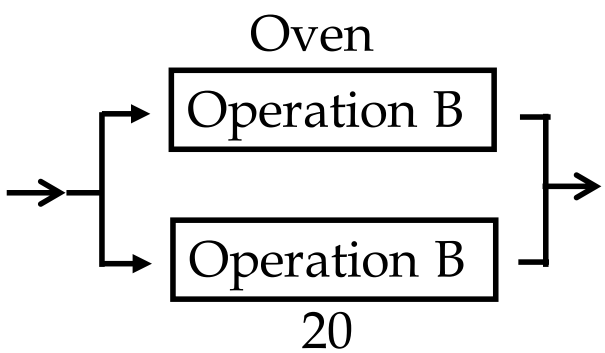
e) What is the Utilization of the oven if the process works at full capacity?

The oven is always working. Every 20 minutes, 1 batch comes, and 1 batch leaves. Utilization of the oven is 1 or 100%.

In every 20 minutes, you only work 15 minutes. Your utilization is 15/20 = 0.75 or 75%. In every 20 minutes, your friend only works 5 minutes. Your friend's utilization is 5/20 = 0.25 or 25%.

Utilization: You: 3/4 = 0.75, Oven: 3/3= 1, Friend: 3/12 =0.25.

Increasing the capacity?Relaxing the bottleneck by increasing the level of resources. **Increasing the level of resources?** Adding a resource-unit to a resource-pool. Our oven resource-pool contains only one single resource-unit. By increasing its level, we mean adding a second oven.



Resource-Pool—A collection of **interchangeable** resource-units that can perform an identical set of activities. Processing time = Tp = 20 minutes.

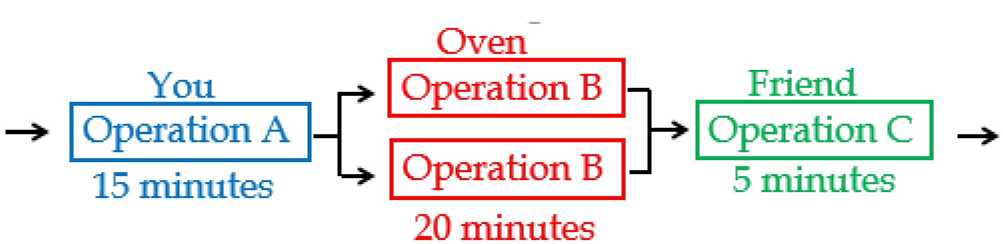
Resource-Pool contains 2 Resource-Units; c =2, and unit load is 20 mins, Tp=20 mins.

The capacity of a resource-unit = 1/20 per minute or 60(1/20) = 3 per hour.

Capacity of a resource-pool = 2(1/20) = 1/10 per minute, or 60(1/10) = 6 per hour.

f) What is the cycle time (after how many minutes a product can exit this system)?

If each minute produces 0.1 unit, then how many minutes are required to produce one unit? 1/0.1 = 10.Cycle time is 10 minutes.



g) Compute capacity of each of the three resource-pools.

Capacity of Resource-Unit (batch/min) Y: 1/15, O:1/20, F: 1/5

Capacity of Resource-Pool (batch/min) Y: 1/15, O:2/20, F: 1/5

Process Capacity = Capacity of the bottleneck = 1/15 per minute. Now, you are the bottleneck.

Each minute the system produces 1/15 units. In 15 minutes, we can send out or take in one product.

Inter-arrival time = inter-departure time = cycle time = 15 min.

h) Compute the utilizations, if the process can work at 100% capacity.

Utilizations are:

U-Y= (1/15)/(1/15) = 1,

U-O= (1/15)/(1/10) = 0.67,

U-F= (1/15)/(1/5) = 0.33.

Capacity of each resource-pool in one hour is **Y: 60(1/15) = 4, O: 60(2/20) =6, F: 60(1/5) = 12.**

Process Capacity = 4 per hour. Every hour the system produces 4 units. In 15 minutes, we can send out or take in one product. Interarrival time, inter-departure time, cycle time = 15 minute.

Utilizations are: U-Y= 4/4 = 1, U-O= 4/6 = 0.67, U-F= 4/12 = 0.33.

Two Ovens plus Cross-Functional Workers. Suppose you and your friend are flexible resources who can do both activities 1 and 3. Suppose the unit loads (Tp) remain the same.

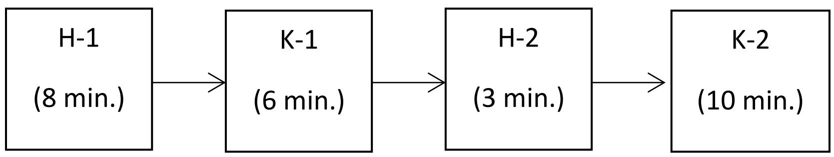
Resource	Human Resources	Capital Resources
Time	5+15	20
Capacity	60(2/20) = 6	60(2/20) =6

Cross-functional workers and resource-pooling are great operational strategies. However, in this specific example, we need to be careful. If the process works at 100% capacity, the utilization of all resources is 100%. This strategy is very risky as a small variation can reduce the capacity significantly. We will later show that no system can produce at 100% capacity and the more bottlenecks, the lower the actual throughput.

Resource Pooling—Combining separate resource-pools into a single more flexible pool that is able to perform several activities. To transform specialized resources into general-purpose resources, we can cross-train workers and use general-purpose machines.

Resource Pooling is a powerful operational tool that can significantly affect **not only capacity and throughput** but also **flow time**.

Problem 3. Four consecutive activities: Two human resources (H-1 and H-2) and two capital resources (K-1 and K-2). Flow units pass the four resources in the following sequence: H-1, K-1, H-2, and K-2. Unit loads Tp1=8, Tp2=3, Tp3=6, Tp4=10.



Compute the capacity of each resource per minute, the capacity of the process, and utilization at 100% capacity. Then increase the capacity by increasing the level of the bottleneck and by cross-training. In cross-training, assume that Tp remains the same for all resources.

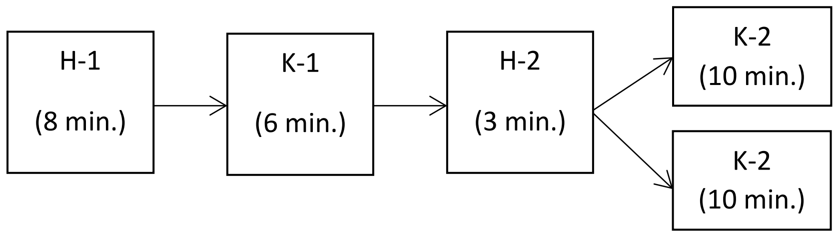
Specialization and one resource-unit at each activity:

	A	B	C	D	E	F	G
1	Cap. Per Minute						
2	Resource	H-1	K-1	K-2	H-2		
3	Tp	8	6	10	3		
4	Rp/min	0.125	0.16667	0.1	0.33333333	=1/B3	
5	Proc. Rp	0.1	0.1	0.1	0.1	=MIN($B4:$E4)	
6	U@100%Cap	0.8	0.6	1	0.3	=$B5/B4	

The same computations in a different way:

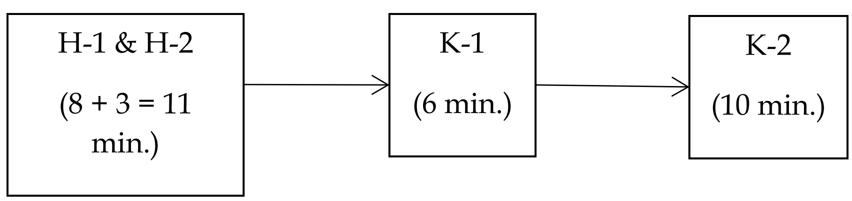
Cap. Per hour				
Resource	H-1	K-1	K-2	H-2
Tp	8	6	10	3
Rp/hr	7.5	10	6	20
Proc. Rp	6	6	6	6
U@100%Cap	0.8	0.6	1	0.3

Specialization and two resource-units in K-2 single pool:



Cap. Per hour. Increase the level of the bottleneck. Two K-2.				
Resource	H-1	K-1	2(K-2)	H-2
Tp	8	6	10	3
Rp/hr.	7.5	10	12	20
Proc. Rp	7.5	7.5	7.5	7.5
U@100%Cap	1	0.75	0.625	0.375

Cross-Training at H (resources H1 and H2 are now in resource-pool H), and a single resource-unit at each K:



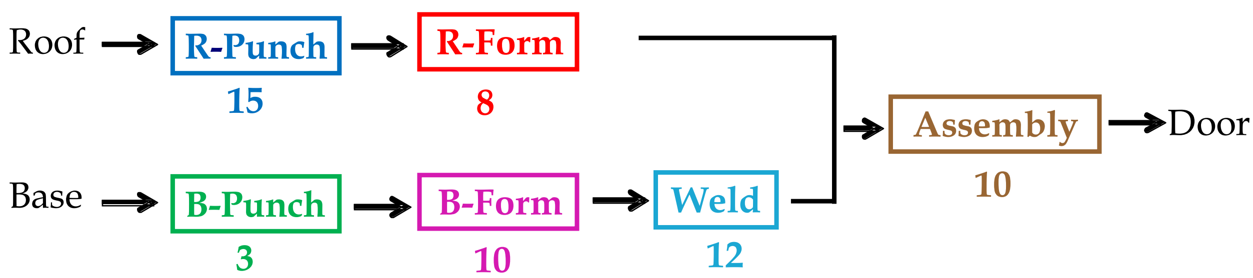
Cap. Per hour. One K-2, but Cross Functions H-1&H-2=> H				
Resource	H	K-1	(K-2)	
Tp	11	6	10	
Rp/hr	10.9091	10	6	
Proc. Rp	6	6	6	
U@100%Cap	0.55	0.6	1	

Do you know the general relationship between theoretical flow time and cycle time?

The number of sequential operations is ≥ (Flow Time)/(Cycle Time)

The minimal number of sequential operations is = (Flow Time)/(Cycle Time) rounded up.

Problem 4. This problem is based on the prototype example in our reference book MBPF. MamossaAssaf Inc. fabricates garage doors. Roofs are punched in a roof punching press (15 minutes per roof) and then formed in a roof forming press (8 minutes per roof). Bases are punched in a base punching press (3 minutes per base) and then formed in a base forming press (10 minutes per base), and the final base is welded in a base-welding machine (12 minutes per base). The base subassembly and the roof then go to the final assembly, where they are welded together (10 minutes per garage) on an assembly welding machine to complete the garage. Assume there is one operator at each station.



This problem is among our key problems. It can be accessed at http://www.csun.edu/~aa2035/CourseBase/Capacity/CapacityKeyProblems.pptx

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a) What is the Theoretical Flow Time? (The minimum time required to produce a garage from start to finish.)

Roof Path: 15+8 = 23

Base Path: 3+10+12 = 25

Max = 25 + 10 = 35

Critical Path = Max(33,35) = 35

Theoretical Flow Time = 35

b) What is the capacity of the system in terms of garages per hour?

R-Punch: 1/15 per minute or 4 per hour

R-Form: 1/8 per minute or 7.5 per hour

B-Punch: 1/3 per minute or 20 per hour

B-Form: 1/10 per minute or 6 per hour

Welding: 1/12 per minute or 5 per hour

Assembly: 1/10 per minute or 6 per hour

Therefore, R-Punch is the bottleneck, and the Process Capacity is 4 flow units per hour.

c) If you want to increase the process capacity, which is the resource-pool that you would put additional resource-units toward?

Obviously, the R-Punch is the best solution, because increasing capacity of any other resource is a mirage.

d) Compute utilization of all the resources at the full process capacity. Although in the real life, it is impossible for a process to perform at its 100% capacity, assume that the throughput is equal to the process capacity. Throughput = 4.Compute utilization of all resources.

R-Punch Utilization = 4/4 = 100%.

R-Form Utilization = 4/7.5 = 53.33%.

B-Punch Utilization = 4/20 = 20%.

B-Form Utilization = 4/ 6 = 66.67%.

Welding Utilization = 4/5 = 80%.

Assembly Utilization = 4/6 = 66.67%

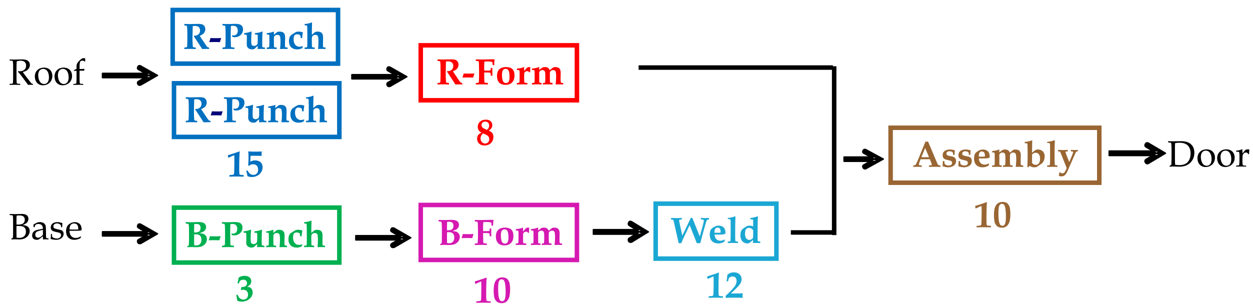
e) What is the utilization of the most utilized and least utilized resources?

The most utilized resource is obviously R-Punch. Its utilization is 100%.

However, utilization of the bottleneck in the real world is never 100% because no process can have a throughput equal to its capacity. In reality, utilization of all the resources will be less than what we have computed for this problem. **This process can never produce 4 flow units per hour continually.**

What is the utilization of the least utilized resource? Interestingly, our other Punch machine, B-Punch is the least utilized resource. U=20%.

f) Relaxing the bottleneck by lifting its level (i.e., adding a new R-Punch resource). Suppose we double the capacity of the bottleneck by adding the same capital and human resources. What is the new capacity of the system?



R-Punch: A single resource-unit, 1/15. Two resource-units, 1/15+1/15 = 2/15 per minute or 8 units per hour. In general, Rp=c/Tp.

R-Form: 1/8 per minute or 7.5 per hour

B-Punch: 1/3 per minute or 20 per hour

B-Form: 1/10 per minute or 6 per hour

Welding: 1/12 per minute or 5 per hour

Assembly: 1/10 per minute or 6 per hour

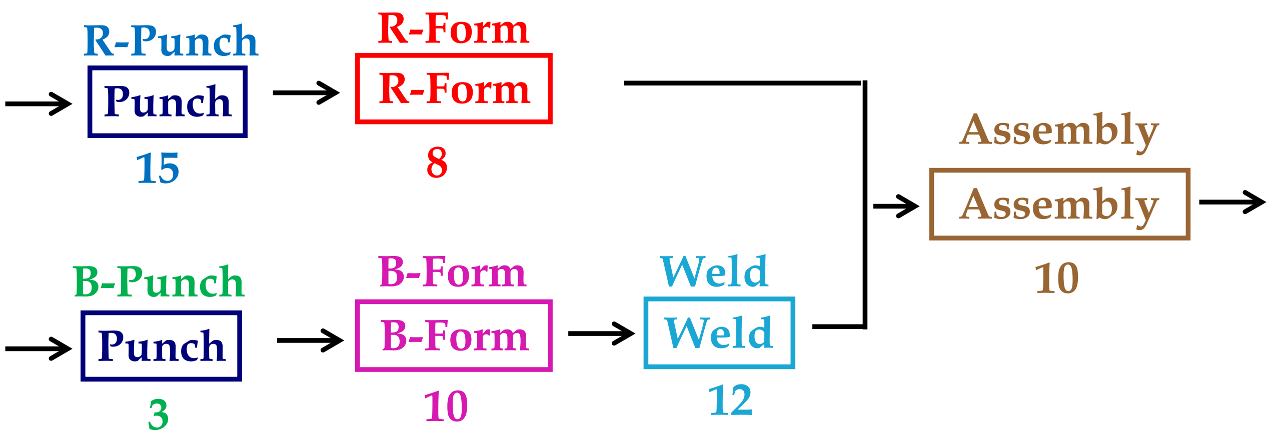
Process Capacity is 5 per hour.

g) We doubled the capacity of the bottleneck, but the capacity of the system increased by only 25%. This situation is an example of what managerial experiment?

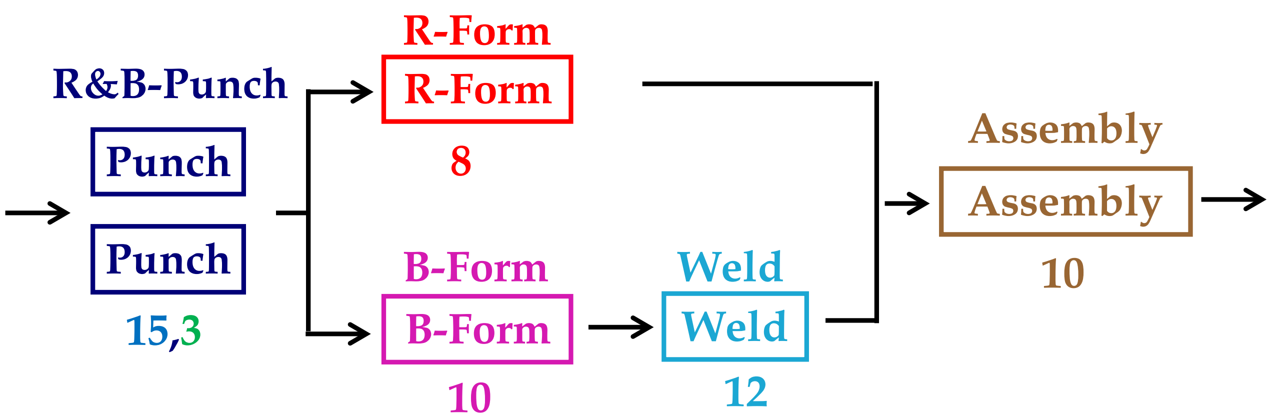
1) When we relax a bottleneck, the bottleneck shifts to another operation. The bottleneck shifts from R-Punch to Welding.
2) Diminishing Marginal Return. By increasing input, the output will not increase linearly.

h) Pooling and Cross-Training. Now, suppose we return to the original situation in which we have a single machine and a single operator at each operation. Suppose we pool R-Punch and B-Punch machines and we cross-train their operations. We form a new resource-pool named Punch in which both R-Punch and B-Punch operations are done in this resource-pool. What is the new capacity of the system?

In the new process, similar resources in the Punch resource-pool have been assigned to R-Punch and B-Punch activities. The process can be represented as follows:



We have pooled two special-purpose resources of R-Punch and B-Punch into a resource-pool of Punch, which can perform both R-Punch and B-Punch activities. In practice, when two special-purpose resources are pooled into a more general-purpose resource-pool, we observe an increase in the unit loads. However, for the purpose of simplicity, we assume that 15 minutes and 3 minutes remain the same and the total unit load of Punch resource-pool stays at 15 + 3 = 18. We also use the following representation.



The capacity of the process is computed as follows:

Punch: 2/18 per minute or 6.67 per hour

R-Form: 1/8 per minute or 7.5 per hour

B-Form: 1/10 per minute or 6 per hour

Welding: 1/12 per minute or 5 per hour

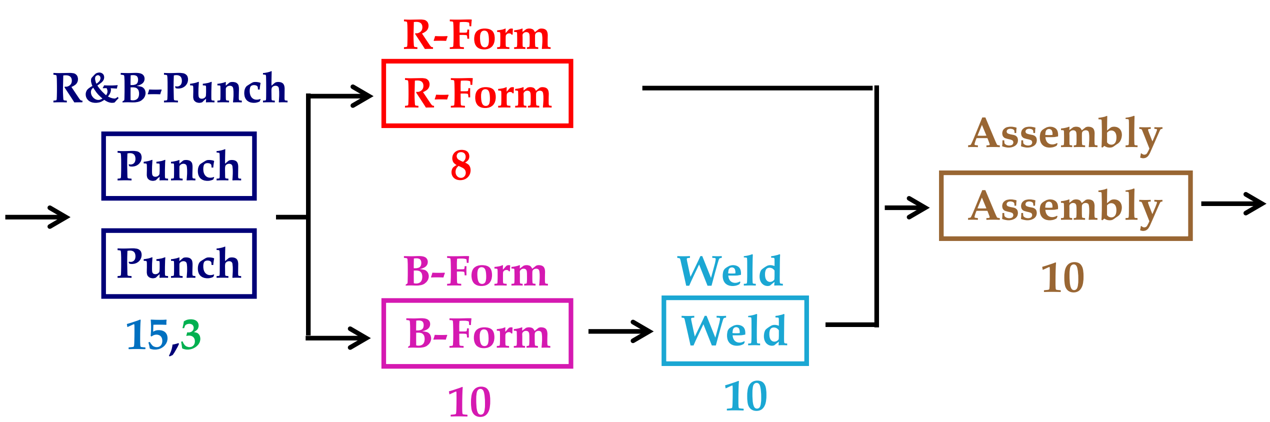
Assembly: 1/10 per minute or 6 per hour

Process Capacity is increased to 5 per hour, without adding any new resource.

i) This situation is an example of what managerial experiment?

1) Cross-training and pooling can increase the capacity.
2) Usually, the cost of cross-training and pooling is lower than the cost of adding the second resource-unit.

j) Productivity Improvement—Method, Training, Technology, and Management. Now suppose by (i) investing in improved jigs and fixtures (technology), (ii) implementing a better method of doing the job, (iii) training our human resources, and (iv) better managing human, capital, and information resources, we can reduce the welding time from 12 minutes to 10 minutes. **What is the new capacity of the system?**

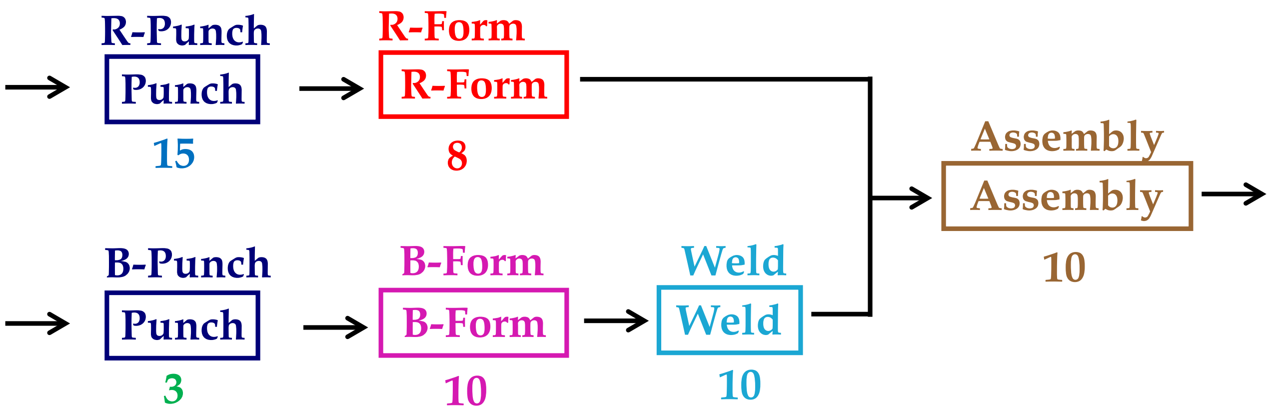


Process Capacity is now increased to 6 per hour.

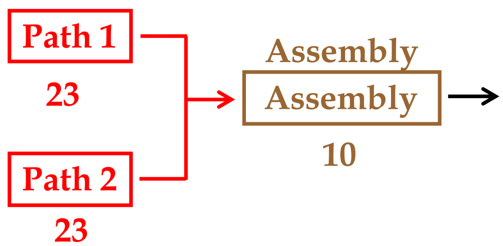
k) Why is it impossible to work at 100% of capacity?

There are 3 bottlenecks. This is a risky situation. Any of the bottlenecks could cause the throughput of the system to fall below 6 per hour. Suppose the input to a bottleneck resource is not ready and the resource stays idle waiting for input for 5 minutes. Assume the resource is a physician, and the patient has not shown up yet. Alternatively, suppose Punch fails to provide input to B-Form for 1 hour, or B-Form fails to feed Weld, or Weld fails to feed Assembly—that hour of capacity perishes. The more bottlenecks exist in the system, the higher the probability of not meeting the capacity. In addition, the system has three bottlenecks, but they are back-to-back, that is, one bottleneck feeds the next one.

l) Is flow time at risk?



Both paths to the last bottlenecks are critical. They can both increase the flow time.



Lessons learned throughout this problem:

1. When a bottleneck resource is relaxed, the bottleneck shifts to another resource.

2. By doubling the bottleneck resource, the capacity usually does not double. This could be interpreted as diminishing marginal return situation.

3. One other way to increase capacity is cross-training (for human resources) and pooling (for capital resources).

4. Usually, the cost of cross-training and pooling is lower than the cost of adding the second resource-unit.

5. One other way to increase capacity is to reduce the unit load. (i) Investing in improved jigs and fixtures (technology), (ii) implementing a better method of doing the job, (iii) training our human resources, and (iv) better managing human, capital, and information resources.

6. Processes cannot work at 100% capacity. Capacity is perishable—It is lost if the input is not ready. The more the bottleneck resources, the lower the utilization.

7. Convergence points are important in managing the flow time. The more convergence points, the higher the probability of the flow time exceeding the average flow time.

Problem 5. SAMOAK Industries. SAMOAK family has been in industrial developments for almost a century. They got the idea of smooth flow from Henry Ford and took it to a new dimension of time-based competition. The following data represents the inputs and outputs at one of their plants over a period of 6 weeks. Each column of the following tables represents 7 days of a week, a total of 42 days. Assume that the plant is working for 24 hours during 7 days a week. Each column of these matrices is corresponding to a week, where the first row is the first day of the week. Analyze these data and estimate the average inventory, average flow time, and capacity of this process.

Input					
2	0	2	3	1	5
2	3	1	3	2	2
1	4	6	3	2	0
0	0	1	3	7	5
2	1	2	5	0	5
1	3	1	4	3	0
0	3	2	2	1	6

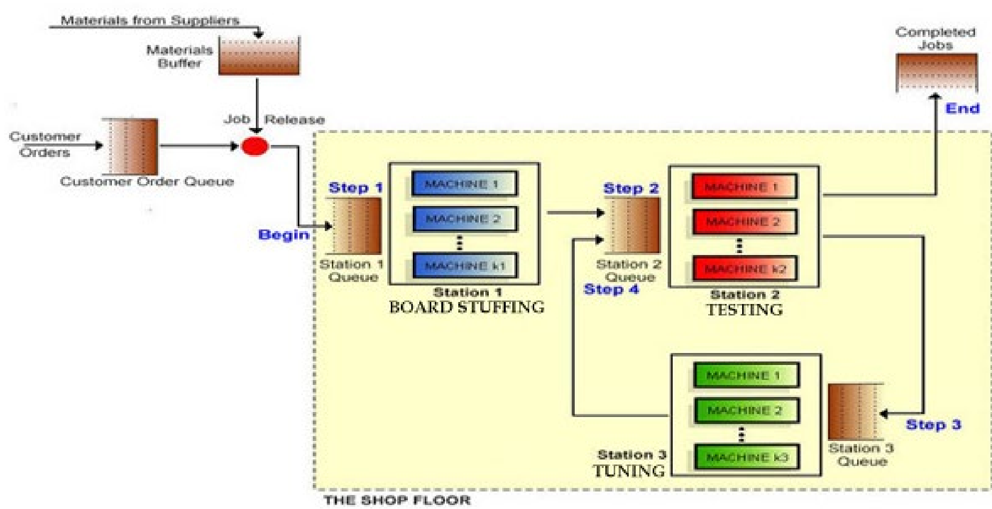
Output					
1	0	3	2	2	2
2	3	2	2	1	4
1	2	3	2	4	1
1	2	4	4	2	1
1	1	1	4	4	4
2	3	1	4	4	4
0	1	3	3	1	5

a) What is the capacity of this process?

The Excel file of this problem is at Prepare For The Game.

The input and output data are in columns A and B of the Excel file, respectively.

If we look at the daily output, we see 5 units of outputs on day 42. We may conclude that the capacity is at least 5. However, in several other days, such as days 25–27, although the beginning inventory is greater than 0 and the ending inventory is also greater than 0, we have not produced 5 units. Therefore, we can just conclude that the capacity of the process is about 5 units. The process blueprint is shown below. The incoming flow units go to the first station, next to the second, and last to the third. From the third station, they go back to the second station, and after processing in this station, they will leave the system in the form of output.



The utilization data for the three stations are shown in **Prepare for the Game**. You may prepare a descriptive statistic table similar to what we provided below.

Station 1		Station 2		Station 3		**Output**	
Mean	0.51269	Mean	0.18279	Mean	0.20619	Mean	2.31
Standard Error	0.0443	Standard Error	0.01592	Standard Error	0.02473	Min	0
Median	0.4525	Median	0.158	Median	0.152	Max	5
Standard Deviatio	0.28713	Standard Deviatio	0.10317	Standard Deviatio	0.16028	StdDev	1.32
Range	1	Range	0.385	Range	0.699	CV	0.57
Minimum	0	Minimum	0	Minimum	0	Count	42
Maximum	1	Maximum	0.385	Maximum	0.699	90%CM	0.14
Count	42	Count	42	Count	42		

Compute the capacity of each station.

U = R/Rp

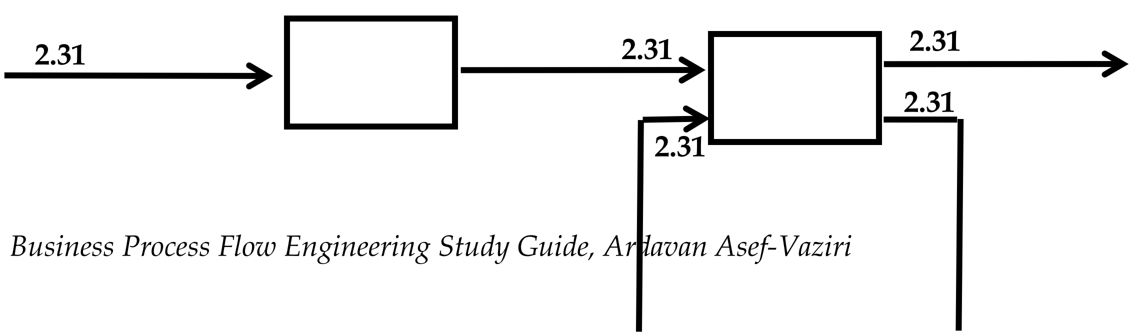
Average U values at the three stations are 0.513, 0.813, and 0.206. Average R is 2.31.

Capacity of station 1 is 0.513 = 2.31/Rp1 ➔ Rp1 ≈ 4.5.

Capacity of station 3 is 0.206 = 2.31/Rp2 ➔ Rp3 ≈ 11.2.

What about station 2?

Capacity of station 3 is NOT 0.183 = 2.31/Rp23 ➔ Rp3 ≠ 11.2. Why?



Capacity of station 3 is 0.183 = 2 × 2.31/Rp23 ➔ Rp3 ≠ 22.4.

Station 1 is the bottleneck. You may compute the Tp of each station by using Tp = 1/Rp. You need to be careful about two things.

1. If there is more than one machine in a station, say if there are c machines in a station, flow time is c/Rp.
2. The flow time is in days because Rp is per day. You need to either divide Rp by 24 or multiply Tp by 24.

Problem 6. The following graph shows a production process for two products: AA and BC. Station D and E are flexible and can handle either product. Regardless of the type of the product, Station D can finish 100 units per day. Station E can finish 90 units per day. Station A works only for Product A and has a capacity of 60 units per day. Station B and C are only for Product BC and have a capacity of 75 and 45 units per day, respectively. The demand for each product is 50 units per day.

a) Which stations are the bottlenecks?

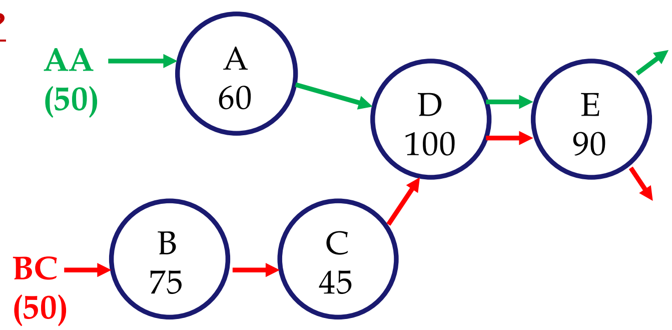
A) Stations A and C

B) Stations B and C

C) Stations C and D

D) Stations D and E

E) Stations C and E



b) If the system can work at the processing capacity, which of the following is NOT true?

A) The utilization of machine A is at least 75%

B) The utilization of machine B is at least about 53%

C) The utilization of machine B is at most 60%

D) The utilization of machine D is 90%

E) All of the above

E ➔ We can produce at most 90 AA and BC.

C ➔ We can produce at most 45 BC.

We may produce all combinations from 50AA and 40 BC to 45AA and 45 BC.

A) We produce at least 45 AA: 45/60 = 75%

B) We produce at least 40 BC: 40/75 = 53.33%

C) 45/75 = 60%

D) 90/100 = 90%

For more problems, the reader may look at

Assignment Capacity Problems

Assignment Capacity Problems—More

The reader is referred to the following link for better understanding of flow time in a nondeterministic world: https://www.youtube.com/watch?v=wqjGsLsadOo&t=870sIn this video, we will discuss the impact of interrelated activities, convergence points, and resource dependability on flow time. Flow time analysis also has extensive applications in project management. The reader is invited to watch the following video for better understanding of nondeterministic project scheduling: https://www.youtube.com/watch?v=7IEfN5OqtQ0&t=24s