In this lecture we will talk about capacity; we will talk about capacity of an operation and capacity of a process, which is composed of set of operations. Also, we will talk about flow time, cycle time and utilization and then we will expend on this concepts.

Let’s start with an example:

To produce each batch of muffin, you prepare the material, and then put the batch in the oven, there is only one oven which can bake on batch at a time. When the bake is done, your friend takes the batch out and does packaging and labeling.

So we do have 3 sequential activities: preparation, bake, package and label. Label them as Operation A (you), Operation B (oven) and Operation C (friend). Three resources: you, oven and your friend. Each activity takes some time. Estimating the time of each activity is in the framework of motion and time study when you observe an operation in several random occasions, measure the operation time, average them, and you assume the results as operation time. Alternatively, you may use the Little’s Law, because throughput times flow time is equal to your inventory.

In this situation we assume the flow time is already given for each operation. For operation A it’s 15 minutes, operation B is 20 minutes and operation C is 5 minutes.

Each day we work 4 hours, and as each hour has 60 minutes, 4hours \* 60 minutes =240, so there are 240 working minutes available per day.

In this example we saw **Capital Resources**, oven is a capital resource. Fixed assets such as land, buildings, facilities, machinery, and oven are capital resources.

We also saw **Human Resources**, you and your friend are human resources. People such as engineers, operators, assemblers, chefs, customer-service representatives are examples of human resources.

So we saw activities or operations and resources. Each activity may require one or more resources. Each resource may be allocated to one or more activities. The example we had, each resource was allocated to only one activity. And each activity needed only one resource. But in other situation it may require more resources. For example, a resource such as baker may be used by several activities such as mixing, kneading and forming dough. And an activity such as loading an oven may require multiple resources such as baker and an oven.

**Resource Unit** may be a single resource like you and your friend, or a baker, a chef, an oven or it may be a combination of several resources which perform like a unit. For example, all the people and equipment in operation room all together work as a resource. So the resource unit may be a single resource like a baker or a combination of resources performing as a unit such as operation room.

Let’s get back to our example;

We have the three operations A, B and C and their flow time of each operation 15 minutes, 20 minutes and 5 minutes. The operation A takes 15 minutes, one hour has 60 minutes, 60 divided by 15 equals 4, therefore the first operation’s capacity is 4 per hour. The capacity of the operation B is 3 (60 divided by 20 minutes). And the capacity of operation C is 12 (60 divided by 5).

Capacity per hour:

Capacity of the entire process is the smallest component of the capacities. In here, the oven can produce only 3 units at the time, therefore the entire process can produce only 3 units per hour.

**Process Capacity = Minimum of 4, 3, 12** is equal to **Capacity of the bottleneck equal to 3**

In our example we have several consecutive sequential operations. So the capacity of the process equals to the minimum of the capacities of the operations. Here I have three operations, the first one can produce 4, the second one 3 and the third one 12 per hour, the minimum of this is 3, therefore the capacity of the process is 3 units per hour. Every 60 minutes 3 units may enter, pass and leave the process. So, in every 20 minute one unit is completed, 60 minutes divided by 3 units.

So during 60 minutes 3 units pass the process every 20 minutes, we call it **interarrival time** and **interdeparture time** or **cycle time** of the process. The process we consider has capacity of 3, so every 20 minutes one unit of product is completed.

It doesn’t matter if we compute the capacity in hour or minutes. If we use minutes, in operation A every 15 minute we produce one unit, therefore the capacity of the operation A per minute is one fifteenth of a unit (1/15). In operation B every 20 minute we produce one unit, therefore the capacity of the operation B per minute is one twentieth of a unit (1/20). Similarly, in operation C every 5 minute we produce one unit, therefore the capacity of the operation C per minute is one fifth of a unit (1/5).

Capacity per hour:

Therefore,

**Process Capacity = Min of 1/15, 1/20, 1/5** = **Capacity of the bottleneck = 1/20**

Every 20 minute we can send out or take in one product or unit. So, the **interarrival time** (same as interdeparture time or the cycle time) is 20 minutes.

So given this process

1. **How long does it take to produce one batch of muffin? In formal term, what is the flow time in this process?**

This process has 3 components, 15min, 20 min and 5 min, therefore

**Flow time** = 15 + 20 + 5 = **20 minutes**

It takes 40 minutes to produce one unit of product, but not every 40 min one product goes out of system, as we saw every 20 min one product is complete and goes out of the system. Therefore, the Flow time =40 min and Cycle time = 20 min

1. **How often a batch of muffin enter (exit) this process? In a formal term, what is the Cycle time of this system?**

You prepare a batch of muffin in 15 min and you’re ready to put it in the oven. When in 15th minute you put the batch into the oven, you start working on the next batch, that’s why in 30th minute the second batch is ready for operation B (oven), however the first batch in the oven is not done yet. Because you put the first batch into the oven in minute 15, and it takes 20 minutes for oven to bake the muffin, so oven will be done in minute 35. Until minute 35 you cannot put the second one into the oven. After the batch is out of oven your friend will package and label it in 5 minutes and it will be complete. So for the first batch the cycle time is the flow time 40 minute. At min 35 your friend can take the first batch out of the oven, and after 5 minutes at minute 40 he is done. **First batch is done at min 40.**

So, Oven is the **bottleneck**. Batches exit the oven every 20 minutes.

You also can put batches into the oven every 20 minutes.

At min 35 you put the second batch in the oven.

Your friend takes it out of oven at min 35 + 20 = 55 and send it out of the process at min 60.

That is 60-40=20 minutes after the first batch.

Therefore the time between the completions of two consecutive batches is, the **Cycle time** is 20 min. The oven is the bottleneck.

**Cycle time = Max {15, 20, 5} = 20**

**But Capacity = Min {4, 3, 12} = 3**

Now let’s answer to following questions:

1. How many batches can we produce per day?

**Case one starting from 0**, so when you start your process nothing is available there. It takes you 40 minutes to complete the first batch. So you do have 4x60=240 minutes available, but it takes 40 minutes to send the first batch out, therefore you have 240-40=200 minutes available for the following batches, and starting from 2 every 20 minute one batch will be out. 200minutes/20minutes=10 batches, so within the total available time (240minutes) we can produce 1+10=11 batches of muffin. 11 batches per day.

**Case 2, continual**. Now let’s talk about the second situation where at the end of the each working day we put one unit of work in process (WIP) in front of each operation. Suppose it’s not muffin to lose its quality if it is waiting there over the night suppose it oven for painting a part. So in this case if each operation has one unit of work in process in front of it at the beginning of the day it takes only five minutes to produce the first product. And then we have two hundred and 40 minutes minus 5 which is 235. And then every twenty minutes we produce a new product. Therefore, there will be 11.75 products per day. And one was here, therefore the total production is 12.75. I gave this second example just to see the difference between the situation where we have inventory in front of each operation at the beginning of the next period and the situation where we should start from scratch. Now we want to discuss the concept of utilization in a fully utilized process. In a fully utilized process, utilization of the process is 100%. But utilization of different operations may be less than 100% and I will explain it in a minute, capacity or maximum throughput, we talk about that in the example we saw that capacity, our maximum throughput of the system was 3 units per hour. Or 1/20 units per minute. The flow time was 40 minutes, which was summation of the flow time of the 3 operations. 15+20+5. Cycle time was 20 minutes which was the processing time of the bottleneck operation. So the capacity, because every 20 minutes we can produce one product, the capacity is 1/20 product per minute. 1/20 per minute. If I multiply this by 60, that would be per hour. 60 times 1/20 is 3 per hour. And because I work 4 hours a day, if I multiply 3 by 4 then I will get 12. Capacity of this process is 12 per day. By now we should have understood the following concepts: flow time, cycle time, capacity, and utilization. What is utilization for the oven? Oven is always working. Every 20 minutes, one batch of muffins comes out. Utilization of oven is 100% of 1. Because the oven can produce 3 units per hour, and we are producing 3 units per hour. So at full capacity, utilization of oven is 1 or 100%. In each 20 minutes, you only work 15 minutes for 5 minutes you wait for the oven. Therefore, your utilization is 15 divided by 20, which is .75 or 75%. In each 20 minutes, where the oven is working at full capacity and you are working at 75% capacity, your friend only works 5 minutes. Therefore, for your friend his utilization or her utilization is 5 divided by 20 which is 25% or .25. We computed utilization of each operation based flow time, operation time, activity time. However, usually utilization is computed based on capacity. But they both give the same results. We will see utilization of 3 operations when we compute it based on the capacities. Would be exactly the same as the numbers we got based on flow times, based on operation times. We already know that the capacity of the first operation is 4, capacity of the second is 3, and capacity of the third is 12. Therefore the process capacity is equal to the minimum of these three numbers, which is 3. Process capacity is 3. Now we can compute utilization of the first, second, and third operations. Process capacity is 3, capacity of the first operation is 4 therefore utilization is .75 or 75%. Capacity of the second operation is 3 and it produces 3 per hour. Therefore, utilization is 1 or 100%. Capacity of the third operation is 12, but it only produces 3 per hour. Therefore, utilization is equal to 3 divided by 12, which is .25 or 25%. So, utilization .75, 1, and .25, which is what we have already got. No operation can perform at 100% capacity. Let it alone that some people will say that we are performing at 120% of capacity. We will discuss it later. Suppose we have two ovens, in case when we had 1 oven, oven was the bottleneck. Our production is limited by the capacity of the oven. Let’s buy a second oven. Let’s increase the capacity of the bottleneck. Let’s elevate the capacity of the bottleneck by increasing the size of the bottleneck from one oven to two ovens. Still it takes 20 minutes for each flow unit to pass through this operation. We can say here that we have a resource pool of two ovens. Which handle operation B. Processing time is 20 minutes, but is no change in it. So capacity of each of these units is 1/20. Right? But we have 2 units of these resources (noted by c). C, the number of units is equal to 2. If capacity of one of them is 1/20 units per minute, capacity of two of them is 2 times 1/20 which is 1/10 per minute. That is the capacity of this operation. 1 over 10 units per minute, or if I multiply it by 60 that will be 6 units per hour. Now we want to compute the new capacities and new cycle time. Here in the second operation we know that because the capacity is .1 per minute, therefore each one minute .1 products leave the system and .1, if we had ten .1 together that will be 1. Therefore, every 10 minutes one product leaves oven operation. Cycle time for this operation is 10 minutes. Now we define a new concept. Resource pool is a collection of interchangeable resource units (first oven, second oven) that can perform exactly the same set of activities. They both are able to do operation B. So now we have a new process. 15 minutes in operation A, 20 minutes in operation B, 5 minutes in operation C, but we doubled capacity of operation B. Capacity of each resource unit is 1 over 15 per minute, 1 over 20 per minute, 1 over 5 per minute. But we have one resource unit in the first operation so it remains 1/15. But we have two resource units in the second operation so it is changed to 1 over 10, and in the third operation it remains 1 over 5. 1/15, 1/10, 1/5. The minimum number here is this one, 1/15 is smaller than 1/10 and 1/5. Process capacity is 1/15 per minute. Flow time is still 20 + 15 + 5, which is 40. There is no change in flow time. But capacity has changed. It is 1/15 per minute. In other words, every 15 minutes one flow unit leaves the system. In the previous situation, cycle time was 20 minutes; here it is 15 minutes. Process capacity is 1/15. Every minute, 1/15 units are produced, so in 15 minutes, one unit is produced. Or you may say capacity is 1/15 per minute, so it is 60 times 1/15 which is 4 per hour. 4 per hour. An hour is 60 minutes, divided by four (60/4 = 15). Every 15 minutes, one unit of product, by having two ovens. Flow time remains the same. Capacity, it doesn’t move from 3 to 6. It doesn’t increase from 3 to 6 because capacity of oven was 3. We doubled the oven, however the capacity of the process didn’t go from 3 to 6 because bottleneck shifted from oven to the first operation. Therefore, capacity, instead of going up to 6, it just went up to 4. From 3 to 4. And cycle time reduced from 20 minutes down to 15 minutes. These were the net impact of buying the second oven. And utilization of the three operations, the first operation utilization is equal to 1, the 2nd operation is 67% and the third operation is 33%. We can reach the same results by playing with the hourly capacity. First operation is 15 minutes. One hour is 60 minutes effective. 60 divided by 15 is 4. I do have one resource unit. Capacity at the first operation is 4 per hour. In the 2nd operation, 60 divided by 20 is 3. Capacity of each resource unit is 3. But I have two resource units in this resource pool, and the capacity is 6, 2 times 3. And in the third one, 60 minutes divided by 5 is 12. I have one resource unit, therefore the capacity of that resource unit, the capacity of that operation is 12 per hour. And therefore the capacity of the process is equal to minimum of these three numbers, which is 4. The first operation is the bottleneck. Each hour, the system can produce 4 units and one hour is 60 minutes, therefore 60 divided by 4 is 15. Every 15 minutes, we produce 1 unit which is the flow time at bottleneck resource, inter-arrival time, inter-departure time, or the cycle time is 15 minutes. Where the process works at 100% capacity. Utilization for the first operation is 1, for the 2nd is 67%, and for the 3rd one is 33%.

**Resource Pooling**

Now let’s discuss a very important concept of resource pooling. In the first setting when we had one oven, you were idle 5 minutes per 20 minutes. In one hour you were idle 15 minutes. Your friend in one hour was idle 45 minutes because every 20 minutes, one batch of muffin goes to him and he works or she works on it for 5 minutes. In 1 hour, 3 batches goes out and he works only 15 minutes out of 60 minutes. In the second situation capacity was increased to 4 by doubling capacity of oven, the bottleneck shifted to you, you were busy 100% of the time but your friend was busy only 33% of the time. Now we want to train, cross train you and your fiend so that both of you can do both operation A and operation B. Now I have two human resources and on each flow unit they are busy 15 + 5 = 20 minutes. So I have 2 human resources and I have 2 capital resources. Human resource is busy 20 minutes on each flow unit, capital resource is also busy 20 minutes on each flow units. Capacity of one human resource is 60 divided by 20 which is 3 but I have two human resources, capacity 6, capacity of the capital resource which is oven is 6, capacity of both of them are equal. They both are bottleneck. Resource pooling is very good, but when it reach to having several resources working at 100% capacity that is not good. It is risky. Because when U is 100%, systems can easily end up with a lot of raw materials or a lot of people waiting in the line. We will discuss this concept later but as I mention before no system can work for a long time at 100% capacity, and if there are several resource pools in as system which they all work at 100% capacity, then the system is not in a very safe mode. Each of these links may break. But the concept of cross training, the concept of mixing different resources into each other, train them to be able to do several types of activities is one of the most important concepts in operations management. It can increase throughput and it can reduce flow time. The main idea is here: if we have two resources and they are working on different tasks, and they cannot combine the tasks, one resource cannot do the job of the other resource. In that case, sometimes this resource is busy and several people or several units of product are waiting for it and the other one is idle and nothing is there. So if these two resources are not pooled together, the blue resource cannot take this product or this customer and handle it while this resource has waiting line and this one is idle. This resource cannot help this one. It is a powerful operational concept which significantly, not only affect flow rate, but also flow time. Now let’s go through this practice. We want to know cycle time and we want to know capacity. Here, we have 4 resources: Christine, her roommate, Mixer, Oven. And these are 4 sequence ??? operations. Capacity per hour is 60 divided by 8. 60/3, 60/6, and 60/10. Out of theses 4 numbers this one is the smallest. Therefore, capacity of the process is 6 per hour. It means cycle time is equal to 60/6 which is 10 minutes. What is flow time? Flow time is 8 + 3 + 6 +10 which is 27. Flow time. So each flow unit needs 27 minutes work but every q10 minutes we can send out one flow unit. Utilization, this one capacity 7.5. This one capacity is 20. This one capacity is 10. This one capacity is 6. And process capacity is 6, so these are Utilization of these operations. This is 1, this is .6, this is .3, and this one is 80%. .8. Now suppose because the bottleneck is oven, we have 2 ovens. Again, these are times at each operation. 7.5 remains the same. 20 remains the same. 10 remains the same but here we have two ovens. Therefore, capacity is 2 times 6 which is 12. 7.5, 20, 10, 12. By doubling the capacity of oven, capacity of the process doesn’t go to 12 because bottleneck shifts from the last operation to the first position which is Christine. Process capacity now is 7.5, flow time still is equal to 8 + 3 +6 + 10. Each hour, your produce 7.5 units. Therefore, 60 minutes divided by 7.5 is equal to ...every 8 minutes one unit of product goes out. The first one is 7.5, second one 20, third one 10, fourth one 12. Capacity of process 7.5, 7.5, 7.5, and 7.5. These are Utilization of different operations. Now let’s look at a third scenario. We have one mixer, two ovens, and we have cross trained our human resources. We have cross trained Christine and Roommate. They have become interchangeable resource units. We have done resource pooling. Two human resources, we have cross trained them now. They both can do both activities. First activity or second activity. The time of the first activity was 8, the time of the second activity was 3. Our human resource has a unit load of 8 + 3 minutes and in one hour, we have 60 minutes and the load is 11 minutes and we do have 2 resource units in our resource pool. Here we have 60 divided by 6 and we have 1 resource unit here. It is 60 divided by 10, and we have two ovens. Two resource units. The first resource pool, which is human resource pool can product 10.9 flow units per hour. Mixer can produce 10 units per hour, and oven can produce 12 units per hour. Out of these 3, mixer is the bottleneck. Flow time is still 8 + 3 + 6 + 10, which is 27 minutes cycle time, each 60 minutes we can produce 10 units so cycle time is 6 minutes. Here because I have only one resource unit, I could see 6 here. This 6 is the same as that 6. Utilization of the 3 resources, the capacity of this one is 10.9, capacity of this one is 10, and capacity of this one is 12. But we can maximally produce 10 units and as we will discuss it later no resource can perform at 100% capacity, therefore the best can do is produce 10 units per hour. 10 units per hour, 10 units per hour, and 10 units per hour. This is utilization of human resources, this is utilization of the mixer, and this is utilization of the oven. We can repeat the same computations per minute. Over there we did it per hour. We can do it per minute. I have shown in several occasions that doing per minute, per hour, per day reach the same results. What I will like is to do my computation based on the time unit given to me. Here, time unit given to me is minute. This is 8 minute; this is 3 minutes 6 minutes, and 10 minutes. So when I talk about capacity, I simply divide 1 by each of these. 1 over 8, 1 over 3, 1 over 6, and 1 over 10. This is the capacity of each of these resources per minute. Out of these 4 numbers, the smallest is 1 over 10. Therefore, oven is the bottleneck. My capacity is 1 over 10 per minute in one hour it is 1/10 times 60 which is 6 per hour. But if I just divide 1 by those 8 minutes, 3 minutes, 6 minutes, and 10 minutes I will get capacity. If this numbers were hours; 8 hours, 3 hours, 6 hours, and 10 hours then one divided by each of them will give me capacity per hour. 1 divided by Tp is capacity per the same time unit that Tp is stated. Flow time is still 8 + 3 + 6 + 10. Cycle time, because here is the bottleneck and because the bottleneck is a single resource unit therefore cycle time is 10. I don’t need to do any computation, if you want a computation because capacity is 1 over 10. Each minute you produce 1 over 10 therefore after 10 minutes you produce one and therefore cycle time is 10 minutes. Utilization is 1 over 8 capacity of the first one, 1/3 capacity of the second one, 1/6 capacity of the third one, and 1/10 capacity of the bottleneck. Production is equal to, maximum production is equal to capacity of the bottleneck which is 1/10, 1/10 1/10, 1/10. These are utilizations. And here are the computations. Capacity. Now suppose I have two ovens. Again capacity here is 1/8 per minute, 1/3 per minute, 1/6 per minute, 1/10 per minute for 1 resource unit but because this resource pool contains two resource units, therefore capacity of oven is 2 times 1/10, which is equal to 2/10. Out of these 4 numbers, 1/8 is the smallest. Therefore, capacity of the process is 1/8 per minute. And if I multiplied by 60 I will get 7.5 per hour. Flow time is a still 8 + 3 + 6 + 10. Cycle time 1 minute we produce 1/8, therefore after 8 minutes we produce 1 and this 8 can be ??? from there through. As long as only one resource unit exists in a resource pool then cycle time is equal to Tp. Tp for Christine is 8. Cycle time is equal to Tp of the bottleneck if I do have only 1 resource unit in the resource pool of my bottleneck. But if you don’t want to care whether you have one resource you need or 10 resource you need you just have the capacity of bottleneck, which is 1 over 8, in one minute you can produce 1 over 8 product, therefore after 8 minutes you can produce 1 product. Utilization is 1 over 8, 1 over 3, 1/6, 2/10, and the process capacity is 1/8, 1/8, 1/8, and 1/8. The last scenario when we do have cross training. I create a new resource pool called human with two resource units. They are not Christine and Roommate anymore because they can do each other’s job so we refer to them as one type of resource unit. We do have two resource units of this type. Capacity of this one is 1/11, capacity of this one is 1/6, capacity of this one is 1/10. Out of these 3 numbers this one is the minimal so capacity of the process is 1/6. Cycle time 1/6 per minute, we need 6 minutes to produce 1 product so cycle time is equal to 6 minutes. And I could have ??? from here too. We are in page 19. You need to solve the previous 19 pages to be able to write the quiz. Now let’s look at this problem. We produce 2 product, product A and product BC. Product A needs to go through operation A. Product BC needs to go through operation B first and then operation C. Both product A and product BC. They need to go through operation D and operation E. Operation A can handle 60 product A per day. Operation B and C are only for product BC and their capacity are 80 and 45 as I have depicted here. And operation D and E are needed for both products, product A and product BC. Capacity of E is 90 and capacity of D is 100. Which operation is the bottleneck if the demand for product A is 50 units and demand for product BC is also 50 units per day. As long as product A is concerned, operation A is not bottleneck because the demand is 50 and this operation can handle 60 units per day. For product BC, operation B is not bottleneck because its capacity is 80 while the demand is only 50 for BC. But operation C has capacity of 45 while the demand for BC is 50. Therefore, operation C is bottleneck. We have 50 A and 50 BC, total of 100. D can handle 100 units of A and BC. It is not bottleneck. But E cannot handle 100 units of A and BC. It can handle only 90 units. Therefore, one bottleneck is here and the other bottleneck is there. Both stations C and E are bottleneck. This second part looks a little bit more difficult. Which one of the following is not correct? The utilization rate of station A is at least 75%. Look, we know that the maximum product of BC is 45. If this maximum reaches if we produce 45 units of BC. Here, we cannot produce more than 45 A because 45+45 is 90 and there is the capacity of this. However, we may produce 40 of BC. In that case, I can produce 50 of A. Therefore, production of A could be anything from 45 to 50. If demand is 50, we want to produce 50 units but if we produce 45 of BC we cannot produce 50 of A. we can produce only 45. So the minimum production of A is 45. Capacity of this operation A is 60. 45 divided by 60. This is the minimal utilization of station A. 45/60 is .75 or 75%. Therefore, this one is correct (A). Utilization of station B is at least 50%. For product BC, demand is 50. We cannot produce more than 45 as this constraint states as this bottleneck states. But if I want to produce 50 of A I will not be able to produce more than 40 of BC. Therefore production of BC is between 40 and 45. Station B’s capacity is 80 minimal production is 40, 40/80 is equal to .5. Therefore, the utilization rate of station B is at least 50%. Therefore, as we learned A could be between 45 and 50 and BC between 40 and 45. Now let’s go to the third question. The utilization of station B is at most 56.25. The maximum we can produce product BC is 45. Capacity of this station is 80. 45 + 11.25 = 56.25. So I did it manually you don’t need to be worry about how I computed this. It comes out to .0562 which is 56.25. that’s 56.25. utilization of station D is 90%. We produce 90 units of these two products because demand is 100 and department E allows us to produce 90 units. Therefore, 90/100 is equal to .9 or 90%. So the answer to this question is none of the above. All of these answers are correct. And here are repetition of what I just said. E we can produce at most 90 of AA and BC. Based on C we can produce at most 45 of BC. We may produce all combination of 50AA and 40BC to 45AA and 45BC. Station A at least 75%. Station D 90%. Station B 50% at least. Station B 56.25% at most and therefore all of the answers are correct.