Manufacturing Systems Management
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Lecture - 35
Scheduling in SM

In this lecture we study the Principles of Synchronous Manufacturing. We have introduced the principles in the previous lecture, there are 7 important principles and these principles are shown in the slide.

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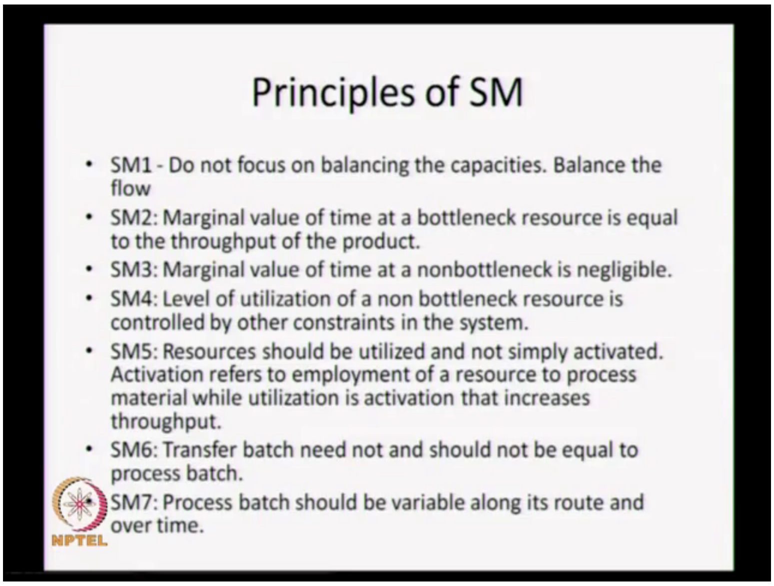

The first principle talks about balancing the flow and not balancing the capacity; which means that every machine will produce the same quantity which will be equal to that produced by a bottleneck machine. Second principle talks about the marginal value of time at a bottleneck is equal to the throughput it relates the bottleneck performance and the throughput and says that if we have to spend resources to increase the throughput then we should concentrate on the bottleneck resource and it also says that the value of an additional resource of the bottleneck is equal to the throughput.

The third principle talk about marginal value of time at a non bottleneck is negligible because non bottlenecks have additional capacity there is no need to spend extra money to increase their capacity because the existing capacity itself is not fully utilized. As mentioned in the previous lecture SM 2 and SM 3 essentially come from duality relationships in linear programming. The fourth principle talks about utilization fourth and fifth principles talk about utilization, the fourth principle says the level of utilization of a non bottleneck resource is controlled by other constraints in the system.

It is controlled by the bottleneck and depending on how much the bottleneck can produce, the non bottleneck produces the same quantity. And therefore, it is utilization will have to be less than 100 percent and is controlled by the production of the bottleneck resource. This immediately relates to the fifth principle which talks about activation resources should be utilized and not activated; the principle differentiates activation and utilization. Activation refers to the employment of a resource to process material while utilization is activation that increases the throughput. If the non bottleneck produces more than the requirement or more than that of the bottleneck the excess is treated as activation and not utilization.

The fifth principle relates to the 4 and says that if it produces in excess then that cannot be used, sixth and seventh principles talk about transfer batch and process batch, 6th principle essentially says that the transfer batch need not and should not be equal to the process batch. If the transfer batch is equal to the process batch then machines wait for longer period for material to arrive and non bottlenecks can become capacity constrained resources. The last principle or the seventh principle says that process batch should be variable along it is route and over time, here it talks about the process batch in the bottleneck machine and in the non bottleneck machine now bottleneck machine always has capacity less than the demand placed on it.

The amount of time spent on changeovers or setups on the bottleneck machine should be reduced in order to do that bottleneck machines should process in large process batches. Non bottleneck machines have excess time available and this excess time can be used for multiple setups resulting in smaller process batches for the non bottleneck machine.

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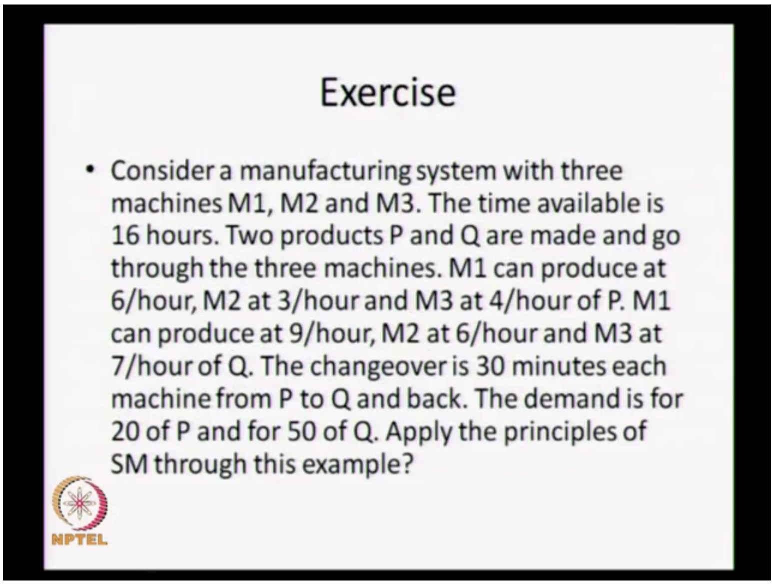

When having seen these principles we go through an example which will be like an exercise which helps us understand these principles through the example that is given.

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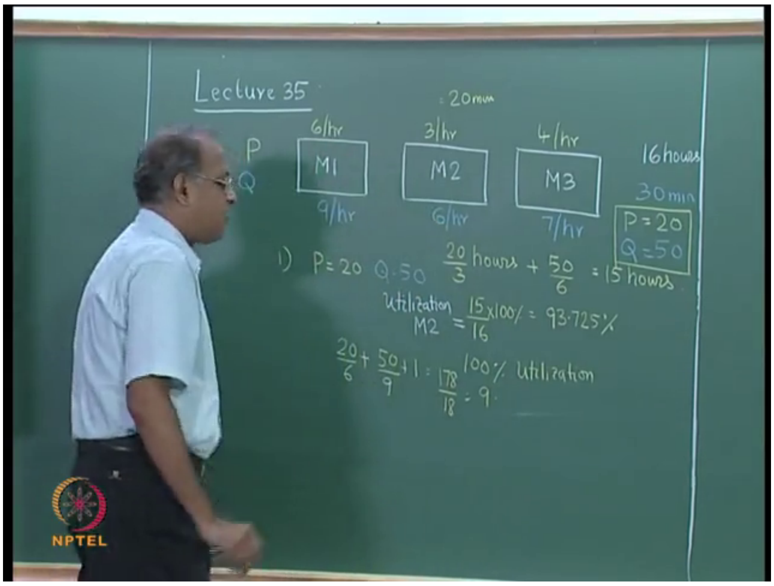

So, consider a manufacturing system with 3 machines which we call M1, M2 and M3 time available is 16 hours on each of them make 2 products P and Q are made through these machines.

Now, time required M1 can produce at 6 per hour, 3 per hour and 4 per hour of P, and 9 per hour, 6 per hour and 7 per hour of Q, changeover time is 30 minutes from P to Q and back changeover time is 30 minutes and demand for P for Q the demand is 50 and for P the demand is 20.

Let us try and study this system and try and understand the role of the principles.

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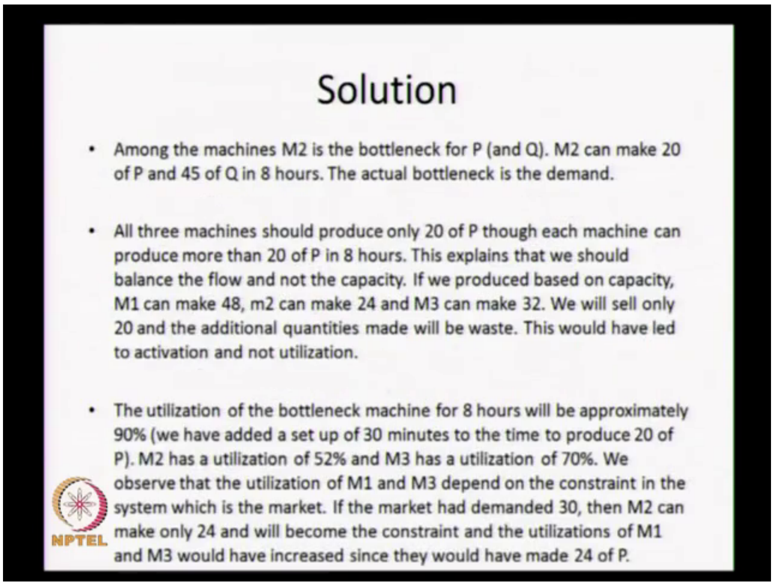

So, among the 3 machines this can produce at 3 per hour, this can produce 6 per hour for both P and Q, machine M2 is the bottleneck because the time it takes per piece is more 3 per hour and 6 per hour. We go back and check that if we produce P then we need how much time on M 2, M 2 can produce at 3 per hour, time to produce 20 pieces is 3 pieces per hour, 20 pieces is 20 by 3, time taken is 20 by 3 hours for P. So, per hour it produces 3, time is equal to 20 minutes, time taken to produce is 200 minutes, 200 minutes is 20 by 3 hours.

Now, time taken to produce Q on the bottleneck machine is 50 by 6, the sum of these 2 is 20 by 3 plus 50 by 6 is 90 by 6 which is 15 hours, in a way M 2 is not the bottleneck amongst the 3 machines M 2 is the bottleneck, but if we compare with the time requirement on M 2 which is 15 hours of M 2, but time available on M 2 is 16 hours, effectively the demand is the bottleneck.

So, we can actually produce more, effectively demand is the bottleneck, all applying the first principle all the 3 machines will produce P equal to 20 and Q equal to 50. The first principle talks about do not balance the capacity, but balance the flow, if we produce based on capacity then M 1 can make a lot more than what is required which we cannot sell which will be activation which will which takes us to principle number 5.

If we let M 1 produce as much as it can for example, this would take 20 by 3 hours, in 20 by 3 hours this will produce more than 6.6 hours this will produce nearly 40 items because time it takes to produce 20, this will produce 40 and extra 20 cannot be utilized and it is only activation.

Now, the utilization of this bottleneck machine is the time taken is 15 hours by 16 hours into 100 percent this is 9 are 144, 16 threes are 48, 120, 16 7 s are, about 93.725 percent is the utilization of M 2, which is M 2. We also have to take into account the changeover times between P and Q the changeover times between P and Q and if we assume that we are going to have one changeover from P to Q as well as another changeover from Q to P. Then this will be this is exactly the bottleneck because change over time is 30 minutes, if we have to change over to P and then change over to Q then this machine will be utilized for all 16 hours and will have 100 percent utilization when we add the changeover times the utilization will be 100 percent.

Now, what is the utilization of this, the utilization of this will be the time taken by this to produce this is utilization of the bottleneck. So, when we also consider the changeover time of 30 minutes per changeover and if we consider 2 changeovers one from P to Q and the other from Q to P. Then both this becomes a bottleneck this is also a bottleneck because in terms of time this requires 16 hours and exactly 16 hours are available. So, utilization for the bottleneck machine will be up will be 93.725 and if we add the changeover times it becomes 100 percent.

When we look at a non bottleneck, the time taken on the non bottleneck is 20 by 6 plus 50 by 9 plus 1 hour, this will be 60 by 18 plus 100 by 18, 100 and 60 by 18 plus 178 by 18, if we include the changeover time of 1 hour on this because to produce this can produce at 6 per hour. So, to produce 20 units this will require 20 by 6, 50 by 9 plus 1 hour on changeover, this would give us 60 by 18 plus 100 by 18 plus 178 by 18.

So, this would give us something like 9.0 roughly 10 hours we could say this is approximately 10 hours.

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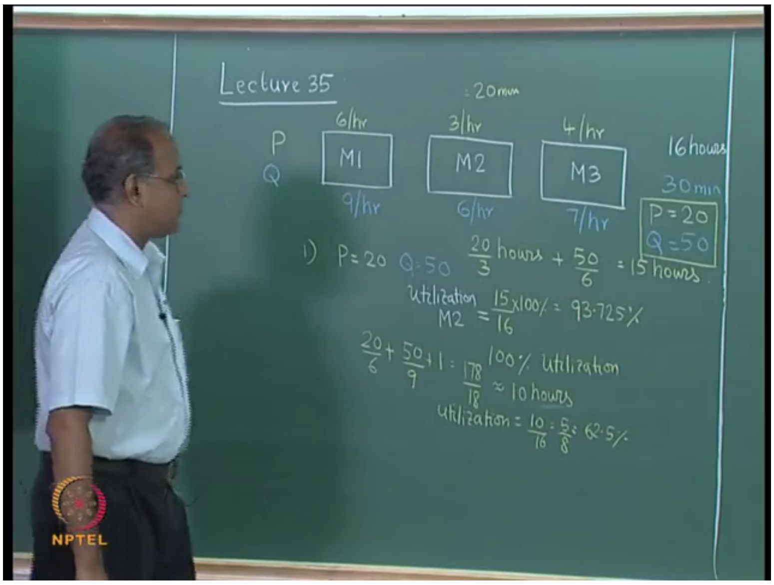

And utilization is approximately 10 by 16 which is 5 by 8 which is 62.5 percent, we see principles 2 and 3 which says that in this case the utilization of the bottleneck resources 100 percent. So, we can create additional capacity on this provided we can create additional demand here because this is a situation where both this is a bottleneck as well as this is a bottleneck if we fix the demand and say demand is 20 and 50 then the time required on the bottleneck including changeovers is exactly 16 hours.

In this situation if we increase this demand then this will automatically become the bottleneck if we increase this capacity this the bottleneck will shift, the moment we increase this capacity the excess capacity will be like a non bottleneck, we have to do both we have to see whether we can increase this demand. And depending on that the value of the one extra unit of capacity will be determined, at the moment both are bottlenecks, but depending on which one actually becomes the bottleneck the throughput will go up; For example, if this can increase then it is worth to increase this the utilization of a non bottleneck will depend on other constraints in the system that will depend on the utilization of the bottleneck and therefore, this becomes 62.5 percent.

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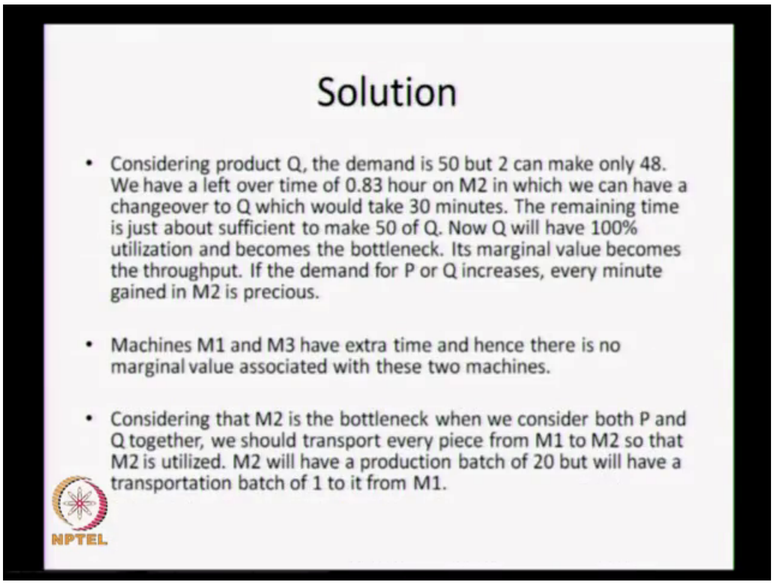

Which is what is shown in this bullet the demand is 50, but it can make only 48 we have a leftover time of 0.83 hour on M 2 which we can have a changeover which will take 30 minutes, Q will have 100 percent utilization and M 2 becomes the bottleneck. It is marginal value becomes the throughput and as demands increases every minute gained in M 2 is precious.

Machines M 1 and M 3 have extra time and there is no marginal value associated with them. The next thing is we have to talk principles 4 and 5, talk about 4 we have seen level of utilization of a non bottleneck resource is controlled by other constraints in the system which is what we have shown here this utilization is controlled by this. So, as far as principal 3 is concerned increasing time on this or this is does not add value cannot increase the throughput. And therefore, we do not do that. Principle number 5 has already been shown that if this produced to full capacity then the time this takes to produce 20 this would have take produced 40, the time this takes to produce 50 this would have produced 75 because it is 9 by 6 3 by 2 ratio, this would have produced 75. The extra 20 produced here and the extra 25 produced here is equivalent of activation and cannot be sold.

Now, we get into SM 6 which talks about transfer batch need not and should not be equal to the process batch, let us look at principle number 6 now let us assume that we are producing P first and then we are producing Q. If we include the changeover times that time on M 2 is exactly 16 hours because to produce at the rate of 3 per hour to produce 20 we need 20 by 3 hours at the rate of 6 per hour to produce 50 we need 50 by 6 hours. So, this will be exactly 15 hours and 30 minutes being the changeover if we assume 2 changeovers then it will be exactly 16 hours is required.

If we start at time equal to 0 now if we assume that the sequence is M 1 followed by M 2 followed by M 3, we have to make some simple assumptions 1 we will assume that All the 3 machines are set up at time equal to 0.

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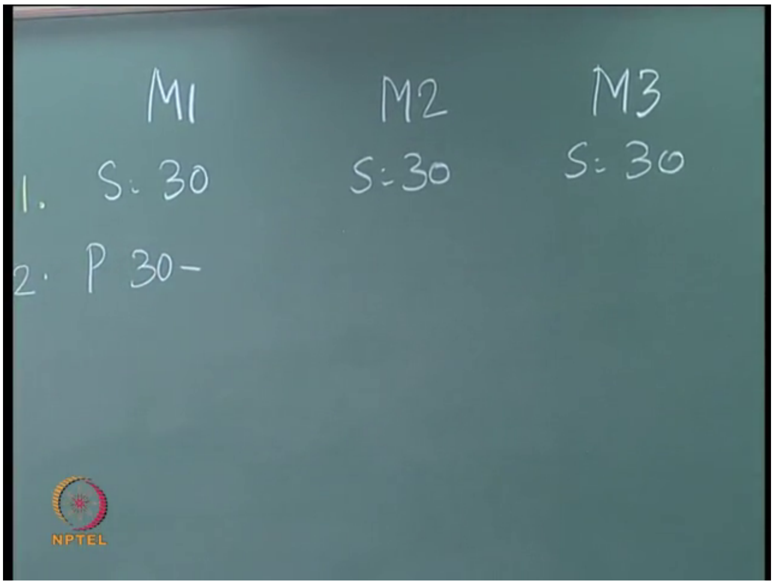

This will be M 1, this will be M 2, this will be M 3, first 30 minutes we will have set up equal to 30 minutes, set up equal to 30 minutes, set up equal to 30 minutes. Now, we will have a production batch, a production P will start from 30 to this is going to take 20 by 3 hours which is 6 hours and 40 minutes. So, 30 minutes then it will become 6 hours is we will keep it in hours rather than minutes to make it easier.

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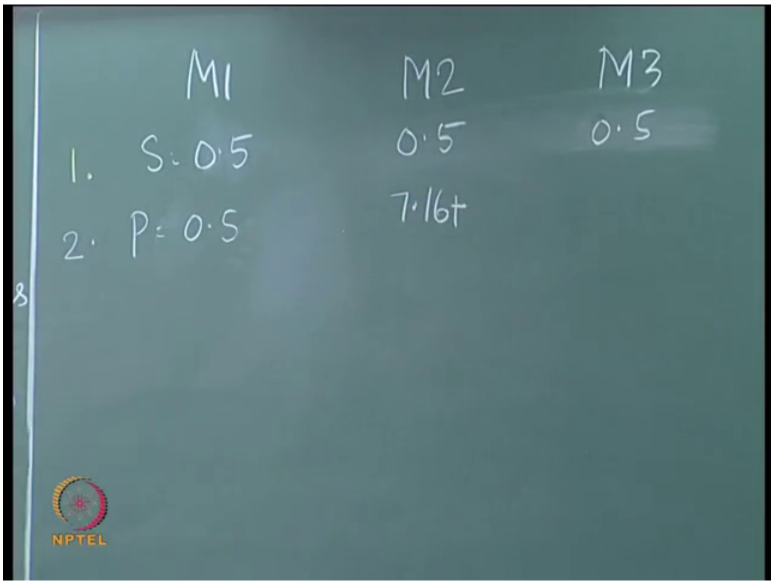

We will say S is equal to 0.5 hours, 0.5 hours, 0.5 hours, now this is going to take 6.66 hours, 6.66 hours plus 0.5 hours is 0.5 to 7.16 hours. If we have a full transfer batch after all this 20 is made if that goes here then the time will start at 7.16 hours plus to produce this will take 20 by 6 hours which is 3.33 hours, this is a non bottleneck, this will take 3.33 hours so 3.83 hours.

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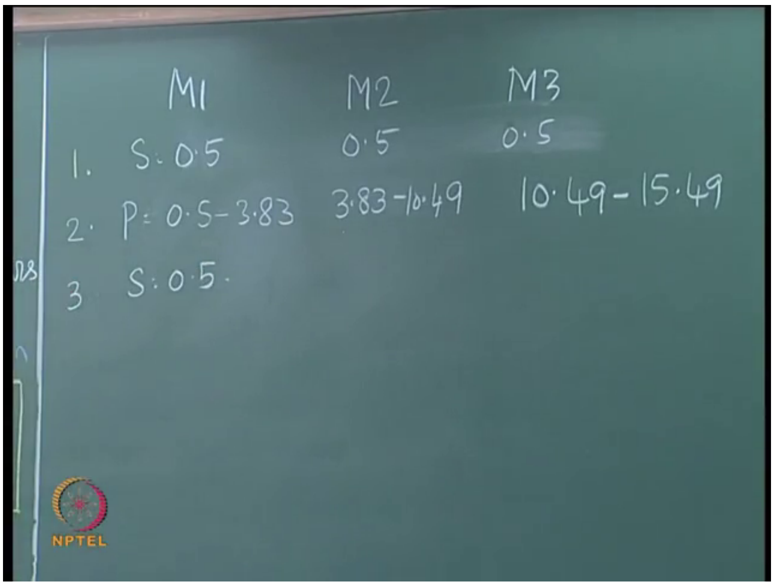

If the transfer batch is also 20 then this will start at 3.83 hours and this will require another 6.66 hours, this will become 10.49 hours. So, this will go at 10.49 hours to this is going to take another 5 hours 20 by 4 is 5, 15.49 hours now there will be another setup changeover from P to Q, this is 3.83 plus 0.5, 4.33.

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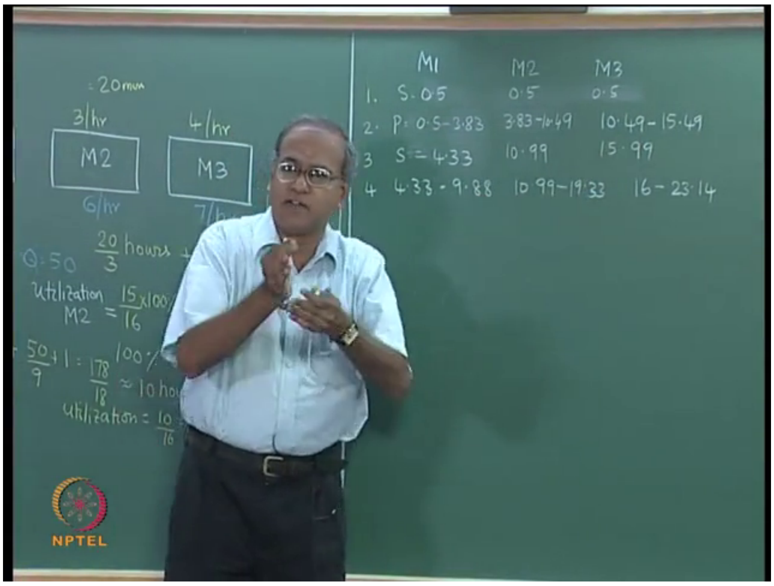

This will become 10.49 plus 0.5. 10.99 and this will become 15.49 to 15.99, actually this is 11 and this is 16 due to rounding off errors because 2 by 3 is taken as 0.66 and not 6 6 6 recurring.

Now, 4 production will begin at 4.33 to 9 per hour, 50 by 9 5.55, 4.33 plus 5.55 is 9.88. So, here this will start at 10.99 to 50 by 6, 50 by 6 is 8.33. So, 10.99 we can keep it as 11, 19.33 and this is 16 to this will take 50 by 7 which is 7.14 so, 23.14. We also assume that by the time each one of these pieces comes out this machine is available otherwise it will get further delayed. If we do this if we allow the transfer batch is same as process batch we find that the bottleneck is going to take more than 16 hours.

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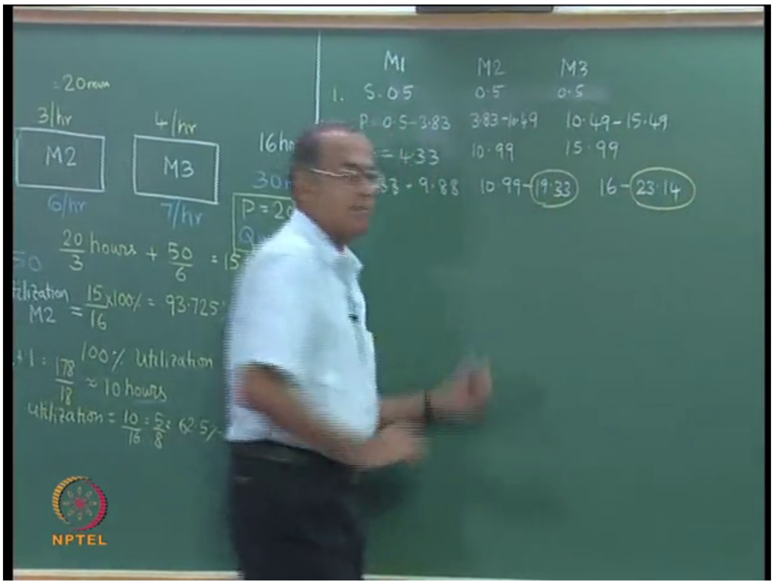

And most importantly a non bottleneck will also take more than 16 hours and will become a bottleneck.

This is a non bottleneck, but this has taken more than 16 hours and will become a bottleneck. And therefore, M 3 will become a C C R.

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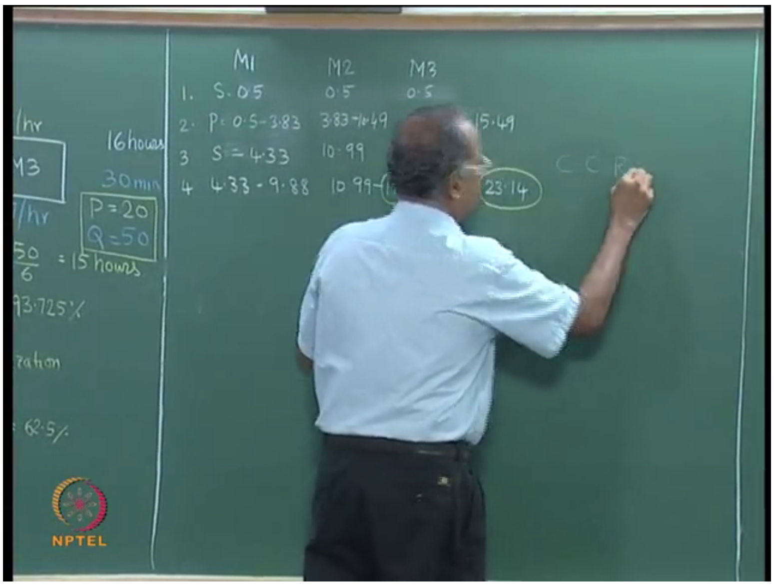

It will become a Capacity Constraint Resource, in order to prevent this from happening transfer batch should be smaller than the process batch and if for some reason these 3 are located very close to each other with time taken for transportation negligible then we will see that assuming that it is possible to have a single piece transportation.

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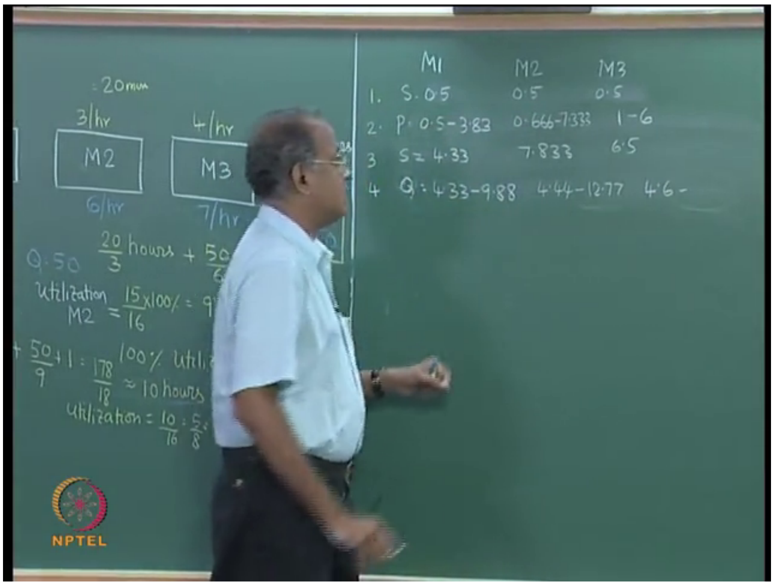

So, this will be from 0.5 to 3.83 now the first piece will take since it is doing 6 per hour, the first piece will take 10 minutes which is 0.1 hour 6 per hour 10 minutes 10 minutes is 0.166 hour.

The first piece will come out at 0.5 plus 0.166 which is 0.666, 6 per hour is 10 minutes, 10 minutes is 10 by 60, 1 by 6 hour, 1 by 6 hour is not is 0.166 1 by 6 is 0.166. So, 0.666, it starts at 0.166 and this is going to take another 6.66 hours, this will become 7.33 hours. Now the first piece would have taken 3 per hour, 3 per hour is 1 by 3 hour per piece 0.33 per piece, 0.66 plus 0.33 is one this will take another 5 hours from here, so 1 to 6.

We do a setup, 3.83 plus 0.5 is 4.33 this is 7.833 and this is over at 6.5. So, no production of this production of Q or let us say Q equal to, over Q it takes 50 by 9 hours, 50 by 9 is 5.55, 4.33 to 9.88. Now the first piece since it is making 9 per hour, plus 1 by 9, 1 by 9 is 0.111, the first piece will come out at 4.33 plus 0.111 which is 4.44 hours. The bottleneck will take another 8.33 hours, 4.44 plus 8.33 is 12.77 the first piece will take 0.166, this will become 4.44 plus 0.166 is for 4.6 roughly, but this is available only at 6.5.

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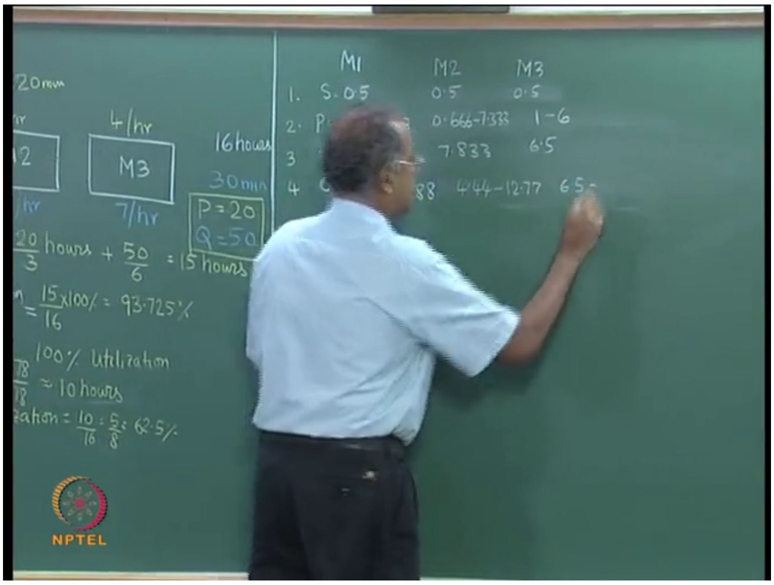

So, here the setup is over only at 7.833.

This machine can start producing only at 7.833.

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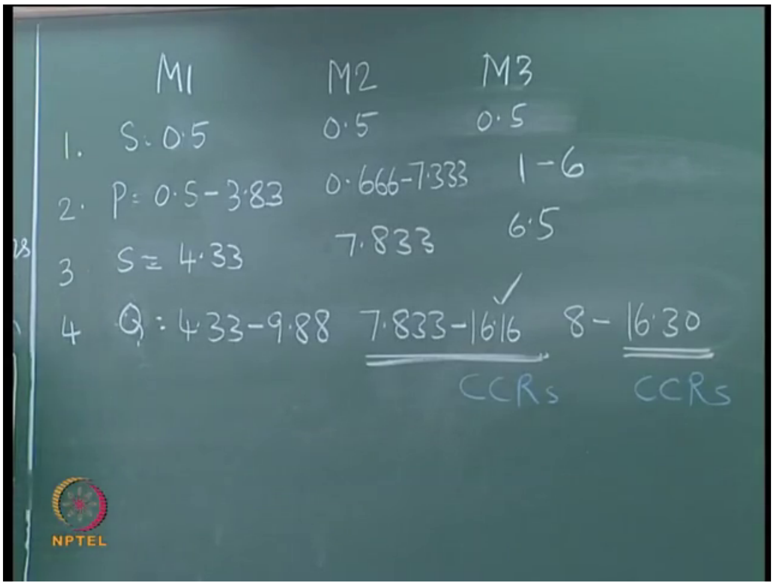

This will be 7.833 to the bottleneck will take 50 by 6, 50 by 6 is 8.33, this will give me 7.8 plus 8.33 is 16.16 here the first piece will come out at plus 0.166, this will become 8 to this is actually a bottleneck. The last piece will come out at 16.16, this will take another 1 by 7, 1 by 7 is 0.14, 16.3 hours. So, even if we allow a single piece transfer which normally does not happen in the context of synchronous manufacturing. The bottleneck machine will require 16.166 the 16 comes from this time required which is 15 time for 2 changeovers which is 1 hour so, 16.

The time it takes for the very first piece of P to come from this machine to this machine, that is 16.166 and because the bottleneck is here the last piece will come out of M 2 only at 16.166 and then it has to process in the last machine M 3 which would take another one by 7 hours. The output is 16.3 which is a little more than the 16 available, in some sense both of these become C C Rs, but the amount of extra time required is very very small.

We will have to understand this aspect and understand the role of the transportation batch, transportation batch should not be equal to the process batch. This is the best case scenario if these 3 machines are not located very close to each other they are located at some distance then we can do this calculation for a transport batch of 10 for this and maybe 25 for this assuming the transportation batches are done in 2 batches and in such a case this would also increase proportionate. The best scenario is when we can transport 1 piece and that gives us 16.3, in this situation, any case both will become C C R this is a bottleneck this will become C C R, but as the transport batch size increases this time will also keep increasing.

If we apply the 7 th principle process batch should be variable along it is route and over time, now here this is definitely a bottleneck here if we allow for example, even if we decide to produce instead of 20 P and 50 Q, if we decide to produce 10 P, 25 Q again 10 P and again 25 Q we will require one more hour of setup on this now we do not have that much time. So, here we should produce only 20 P and 50 Q because I am producing at 20 P and 50 Q my 20 P is going to come out my 50 Q is going to come out and because the bottleneck is here and this is the subsequent process even though at an aggregate level I have extra time on this machine because the actual time required on this machine is 20 by 4 which is 5 hours.

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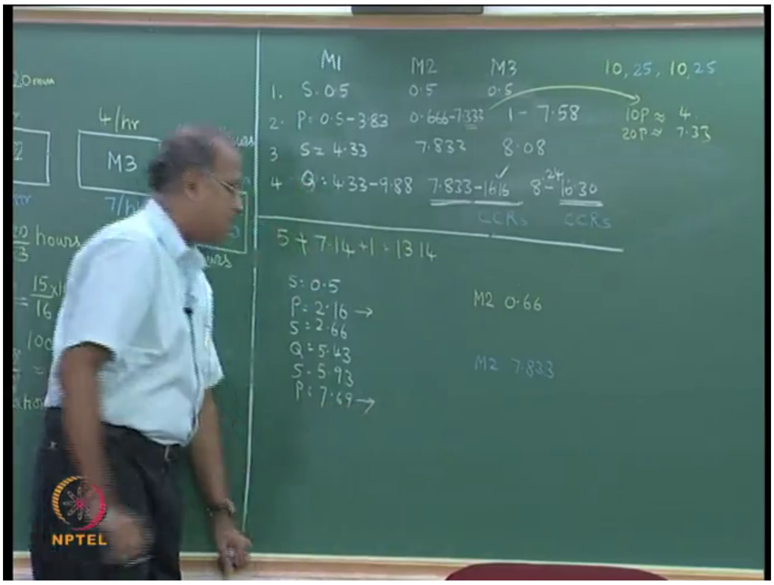

And 50 by 7 which is 7.14 hours, 12.14 hours plus 1 for changeover is 13.14 hours.

Now, one other thing I can do is to see that I have almost another 2.98 hours of extra time that I have, but then I do not have this 2.86 hours continuously. If you see carefully it is staggered because 0.5 is over, but 1 to 6 it is doing then 6.5 then you realize that the 2.0 something is hidden here it is idle somewhere in the middle and we do not have control over that after which it becomes a C C R. One other possibility that we can think of is this finishes P at 7.33, actually speaking some of these calculations also have to be done redone again because the first piece will come at 6 1 the last piece cannot be done at 6 the last piece can be done after this is done. So, this finishes at 7.33, on this it is plus 0.25, this will become 7.33 plus 0.25 which is 7.58 then the changeover happens 7.58 plus 0.5 is 8.08 this finishes.

This will be slightly more than that this is a 0.166, this will do from 8.08 plus 0.16, this will become 8.08 plus 0.16, 8.24 to 16.30. This time the idle time is actually hidden somewhere here it is actually hidden even here when we say that the last piece comes out and then the other one is done. It is not that this is fully utilized during this period it is utilized at some time and not utilized it is waiting for the pieces at some other time.

One other thing that is possible is while this is producing from 0. 666 to 7.33, now we can produce 10 pieces of this as it comes, but then if we are going to have multiple batches on this if we are on M 3 if we are looking at 10 25 10 and 25. Then I may have the extra time to create 3 more changeovers, but if I start doing those calculations I will realize that because it is coming after the bottleneck that time will only increase on M 3 if I try to do this. The reason being this will continuously produce 20 of P and it will be over at 7.33 now this will produce 10 of Q or 25 of Q this will produce 20 of P at 7.33. We can assume that roughly around 3.5 this would have produced 10 of P around half of this time because this is 0.66 around half of this time it would have produced 10 of P.

Let us just write that this will produce 10 of P at roughly about 4 and 20 of P roughly at 7.33 this will produce, now I can changeover and I can actually produce 10 of P here, but if I have to start another 25 of Q I have to wait till nearly about time equal to 12 for this to produce 25 of Q, to that extent I have to keep this idle and then I have to produce 25 of Q go back and produce 10 of P and again produce 25 of Q this will become far higher than 16.30. So, even though this is a non bottleneck and has extra time this non bottleneck does not allow us to produce in smaller batches because it is dependent on the bottleneck, but on the other hand we could possibly try on this and see whether it will affect or it will not affect.

In order to do this M 2 should start P by 0.66 or S by 0.66 that is when the first piece of P comes out of this, M 2 should start Q at 7.833. Now let us see what happens now if we decide to produce 10 of P 25 of Q and 10 of P and 25 of Q let us rework on this machine, first S equal to 0.5 then 10 of P is 1 by 6, or 10 by 6. So, 0.5 is 10 by 6 is 1 66. So, 0.5 plus 1.66 is 2.16.

Now, we look at another setup, 2.66 now 25 of Q, 25 of Q is going to take 25 by 9 2's are 18 70 2.77, 2.66 plus 2.77 is roughly 5.43 this is over. Now again a setup, 5.93 now again P, P will be 10 by 6 which is 1.66, 1.66 plus 5.93 is 9 6 7. So, the first 10 of P will come out at 2.16 the next 10 of P will come at 7.69, but this has to continuously be producing P between this time otherwise this will be starved this will be idle for want of material which we should not have. We should check whether we are able to finish all the P before 7.833, 7.69 the 28 piece of P will come out and then it takes another 0.166. So, 7.6 plus 0.16 exceeds this.

If we choose to do 10 of P 25 of Q followed by 10 of P followed by 25 of Q we will still keep this machine idle for some time which we should not do, but if on the other hand this is like 10 per hour this is like 12 per hour for example, clearly if this is double the speed of M 2 then we will be able to do 10 of P 25 of Q followed by another 10 of P followed by another 25 of Q on this. So, the learning is it depends on where the bottleneck machine is for all the machines that are after the bottleneck in the sequence then we have to do it very very carefully on multiple items because in any case the time will be more than that of the bottleneck, but the ones before the bottleneck the extra time can be used provided the bottleneck is not affected.

Now, in this particular example it became difficult because for both the products M 2 happen to be the bottleneck machine, if M 2 is bottleneck machine for P and let us say M 3 is the bottleneck machine for Q then the whole mechanics will change the computations will change and then we have to check very carefully, but wherever possible we should try and have process batch different from the transfer the process batch different on the bottleneck machine as well as on the non bottleneck machine.

So, that is the learning from this particular exercise.

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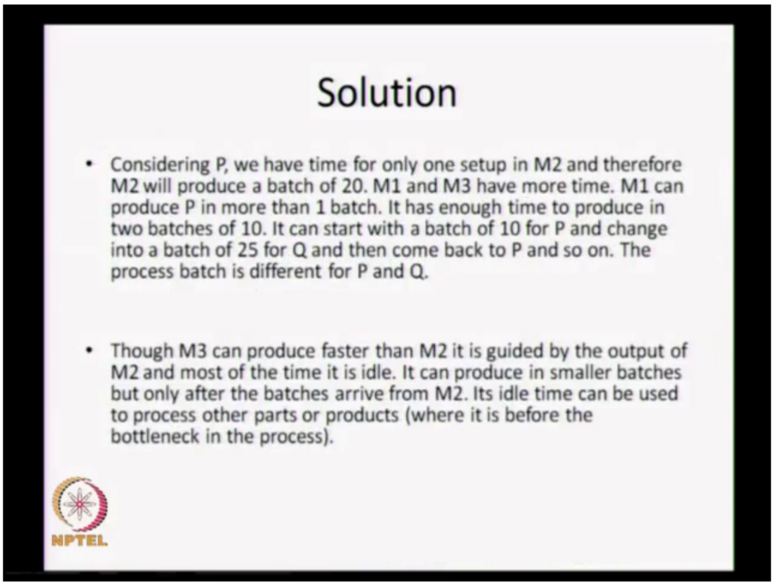

Where we have seen the principles of synchronous manufacturing explained through an example and we were able to see all the principles explained through this particular example. When having seen this much we actually then beyond the simple application of the principles the reason is we also took into account the direction of flow and the sequence of operations on the parts we assume that we will start with M 1 and then we will come to M 2 and then we will come to M 3 which is a correct assumption assuming that that is the sequence given at an aggregate level one may say in this case that here all the 16 hours are required here there is extra time there is extra more than 1 hour extra time here also there is more than 1 hour extra time.

So, at an aggregate level one would say that well I can have one more changeover of P and Q and therefore, we could think in terms of 10 P followed by 25 Q followed by 10 P followed by 25 at an aggregate level, but when we bring in the sequence of operations we observe that it is not economical to do it here as well as here, but here if in case these were faster then we could use that time to run multiple batches in one of the machines.

Now, we get into issues of actual control and how do we manage to do that through what is called the Drum buffer rope example.

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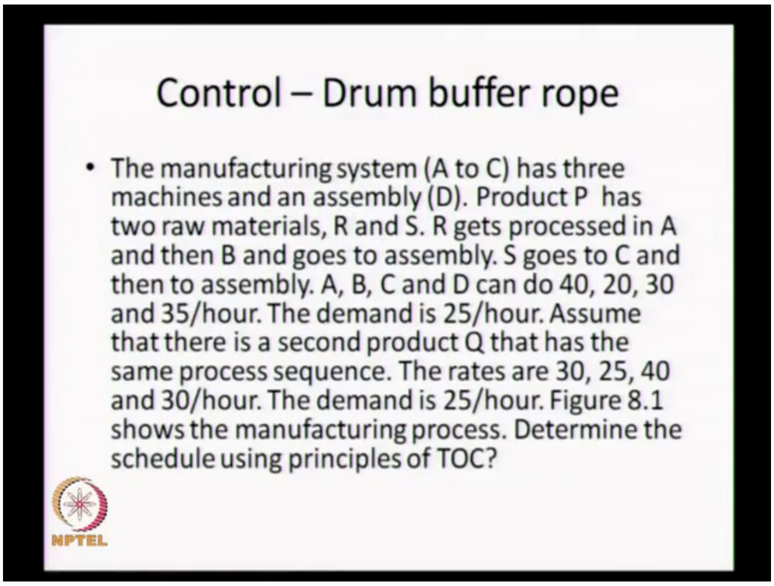

The drum buffer rope example is one that is given in the book called the goal and the concept is introduced in a very interesting manner. Now as part of the as one goes through the book at some point the plant manager who is the main character in the book takes his son for a trek along with some other children his son also goes for a trek and he leads the trek in the sense there are group of children who are undertaking the trek and he is controlling all of them, through the trek the process of production control is actually established.

Now, when you let us students or either we can think in terms of a trek or we can think in terms of a set of students running or walking, when you will let each one go at their speed they will not go together and the gaps will come, some of them will go faster some of them will go slower. In some sense the difference between a running race and this is the trek is over only when the last person reaches the destination, whereas in principle running race is over when the first person reaches the destination or first 3 people reach the destination. Now the distance covered is equivalent to throughput the gap is equal to the inventory that is built in the system because some of them have moved some of them have not, there is excess inventory and the energy spent is the operating expense.

So, that example comes through this trekking few other things come through this trekking which talks about different children are now moving at different speeds and we are not able to control. There is a slowest boy who also happens to be carrying a very heavy bag, to begin with he, the remain the plant manager will remove the bag from the slowest person to make him go faster now that is like controlling the bottleneck and keeping the bottleneck ready and available because the slowest moving student is going to be is equivalent of the bottleneck machine and the bottleneck machine should not be further constrained.

Now, then he tries a few other things he first keeps the slowest student first and then asks everybody to follow and then he realizes that the gap is widening and people are too close to each other and stepping on everybody shoes, now we tries to keep the slow person in the end and then he realizes that everybody is moving ahead and he is not able to have control.

So, at that point he tries to ask this question how do I get this control and then he compares it with a troop of marching soldiers and then he understands that the drumbeat essentially provides the control when a troop of soldiers are marching. So, that all of them are able to march in an extremely synchronous manner and it is called a drum buffer rope because the drum beat is the signal for everyone to produce at the same pace or to move at the same distance. The buffer is equivalent of the excess inventory that needs to be given. The rope is an imaginary rope which actually ties the bottleneck resource to the end. It is an imaginary rope where if we say that when 2 people are moving if there is an imaginary rope tying both of them the gap between them will be the same. This will not allow one person to move too fast or the other one to go too slow.

He combines these 3 ideas and comes up with what is called a Drum buffer rope scheduling system and this system has come to stay in the field of synchronous manufacturing and theory of constraints. So, more details about the drum buffer rope we will see in a next lecture.