Introduction to Reliability Engineering
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Lecture 36
Maintainability and Availability

Hello everyone. In previous lectures we discussed about reliability and data analysis. Today, we will start discussing about Maintainability and then subsequently we will also discuss about the Availability.

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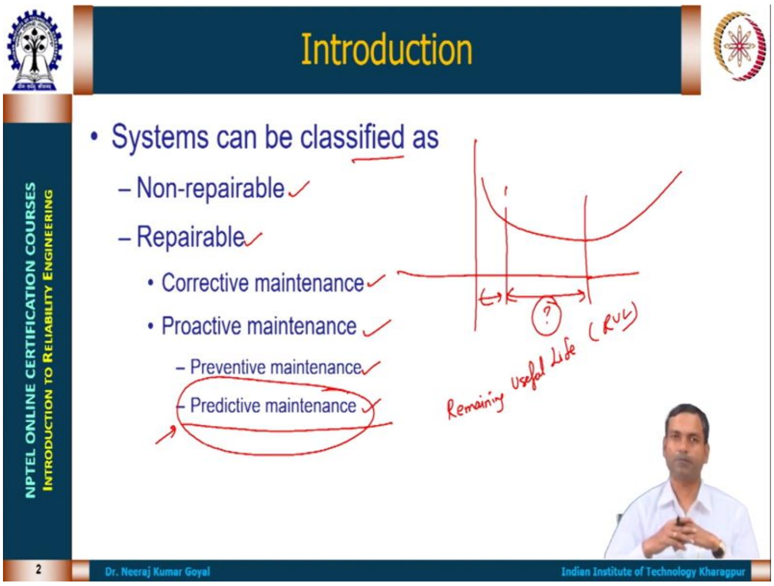

So, generally, as we see those systems, so, we can classify the systems as non-repairable or repairable. Non-repairable system means that system which is not considered for repair. So, when a system is not considered for repair, there can be various reasons for that. One reason can be that repair is costly or system inherently has characteristics which does not allow repair. Let us say if we talk about, let us say satellite.

So, satellite will be difficult to repair because whatever automatic features are there that is only possible but manual repair may not be feasible. Similarly, if we talk about missiles, etcetera, they will be just launched, if they fail you cannot repair them. But many times, so, there is a economic reason for that also, like if I am having a problem with my pen etcetera, most of the time I will be throwing it away because they are cheaper.

So, cheap things if they fail, generally, I will be throwing but if there is a bulky and big and costly equipment, I would like to get it repaired because repair will be cheaper. So, if repair is not cheaper then I would like to make it, consider the system as a non-repairable. So, sometimes cost also becomes a reason for a system to be repairable or non-repairable. So a system which is cheaper, nobody will be having the repair shops etcetera or you will be able to repair them but the systems which are costly.

If there is some fault you want to remove the faulty part, so that rest of the good part you are able to continue to use and by removing and replacing or repairing the faulty part, what happens, you are able to continue to use the system. Like when we have problem with our ACs, fridges, refrigerator, etcetera, then we would like to make them repair. We will not just throw them away because there is some fault or some failure happen.

In repairable systems there can be two types of maintenance one is the corrective maintenance. So, generally, our household items, etcetera, which are not very prone to span of when they fail, these are not going to cause any kind of bigger problems. Like a function will not be available but we can survive without that function. And losses from the because of the function loss, like if my AC is not working, so, I will be feeling discomfort, I will be trying to switch over to another place where I have the AC etcetera.

So, I will try to manage the situation. But that when AC is not working, it is not affecting my health or it is not affecting my because of that some bigger losses I may not be making. But in some cases we are ACs are installed in a location let us say if let us say you are doing some biomedical equipment is there which is need to be made sure that temperature is maintained, if their AC fails then it may happen that if AC is not corrected within the time then you may have the losses, bigger losses there.

So, in that case, so, the cases where losses are high or you have the safety problems, like if a some failure happens because of which safety will be affected, let us say, if we talk about, let us say cylinder leakage, etcetera, so, any system which has a safety consequence. If let us say my bike related problem is there, if I am going somewhere and my motorbike stops on the way, so, I will be stranded, I will have lot of problems.

So, for that kind of problems, I will not be depending on the corrective maintenance. Because I cannot say that that let it fail, then once it is failed then I will correct it. Because when failure happens, I will be in trouble. That trouble is because I am stranded, my work is stopped, wherever I was supposed to do, I will not be able to do. Alternate measures will be difficult to find. So, what will happen?

In such cases we will do the proactive maintenance. So, the cases where we have the large losses associated with the failure or another problem can be that there is a safety problem then we would be little bit scared of the failures or we are concerned about the failures. Since, we are concerned about the failures, we do not want failures to happen because there is a high risk associated with the failures. So, we want that our system should not fail, in that kind of scenario. So, what we will do?

We will try to proactively do the maintenance. That means we will do the maintenance before failure happens. So, we will maintain the system in a good health. Once we maintain the system in good health, we are ensuring that our chances of failures are bare minimum or our risk is also less. so that we are not able to have those kinds of problems. There are two kind of ways we can do that, preventive maintenance or predictive maintenance.

Preventive maintenance has been the first concept which has been used as a proactive maintenance. So, in preventive maintenance, as we know what happens that some, generally, if we consume consider the bathtub curve then initial this if we remove by the burning then here like when the degradation is start, what happens?

We know that fairly how long the time is there for which this kind of components or the parts of the system will work without any much chances of failure. But after certain period of the time these parts will tend to show the degradation. And because of the degradation the chances of failures will be high. Like we have the oil, machine oils, we have that is a filter, etcetera, we have the brakes.

So, what will happen that when we use them for sufficient kilometers or sufficient time, after that tire, etcetera, batteries, etcetera, they have a certain kind of life indicators that if I want to use battery, then, yes, I will not be able to use. So, what will happen that after battery works for three, four years. So, after every three and four year I have to replace them. So, that is the preventive maintenance.

Even if I do not see much problem with the battery, I will try to replace it, so that, that I have a fixed duration. I have this fixed duration and this duration if we will try to identify the manufacturer will suggest us that what is the time at which the scheduled maintenance has to be carried out.

So, preventive maintenance is also called the scheduled maintenance. So, like when we purchase new vehicle, we have that within a year I have to go. Even when I am using my car I have to every year, at least once, I have to go for the maintenance. That is a preventive maintenance. Because what happens, if I do not go for the maintenance then my car will develop the bigger problem, if I do not go for maintenance, do not change the oil, do not clean the filters, what will happen, my engine will be loaded and engine problems will start.

So, this is the preventive maintenance that to save the bigger failures, we are trying to do the maintenance. And by the preventive maintenance we are reducing the chances of failure. So, our risk of concerned failures has been reduced. But many times like what happens in preventive maintenance when we do, even if the part looks good, even if the system is functioning but still I have to do the replacement or I have to do the repair.

So, that sometimes is going against the principle of using this cost effectively or using it maximum So, many times if it is feasible, if we have the ways to identify that the current state of the system. So, in predictive maintenance, what we do, we try to assess that what is the current state of that part or that system. Like we will check, we will do the some sort of inspection.

So, we will do periodic inspection, we will try to find out that what is the health or what is the quality for this part. If the quality is good and if we see that for a certain period of the time the chances of failures are not there then we will say, okay, we will continue to use and we will check it again later on. And at that time, if we see that that the part is deteriorated then we will do the repair.

So, we nowadays lot of sensor technology is coming. So, sensor technology will try to sense the various parameters like temperature, vibration or acoustic signals and many other parameters like a oil content, etcetera. And based on that it will try to find out that whether the system health is good or not.

So, if system health is deteriorated then by using principles, we can try to assess that how much life is remaining. So, the concept of remaining useful life R U L comes into the picture. So, we try to assess that what is the estimated life in current condition is remaining. So, that means that is the time available for us to do the maintenance.

So, because time is available, we are not immediately forcing but we can plan that when to do the maintenance. So, we are trying to set some time at which we will go for the maintenance and do the repair. So, but here, the concern is to do the predictive maintenance, we should have a way.

We should have the way to identify the health condition and we should be having the reliable measures. Like whatever the way we are doing that, that should not be too much fluctuating. It should not happen that at one moment we are saying that it is good and next moment the signal comes it has become bad. If that happens then it is not of use So, when we are saying that our, so, whatever R U L we are estimating, that estimate has to be fairly good enough, fairly stable enough then only we are able to use these techniques.

So, this depends lot on technologies available. And this may not be possible for all types of failures but wherever it is possible we can do this so that we are ensuring high reliability and on the way we are making sure that we are not unnecessarily doing the maintenance which is there in case of preventive maintenance.

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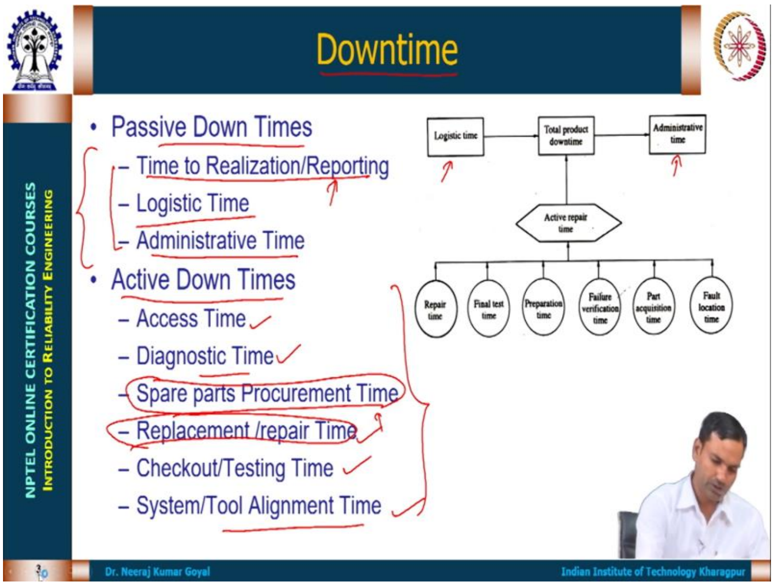

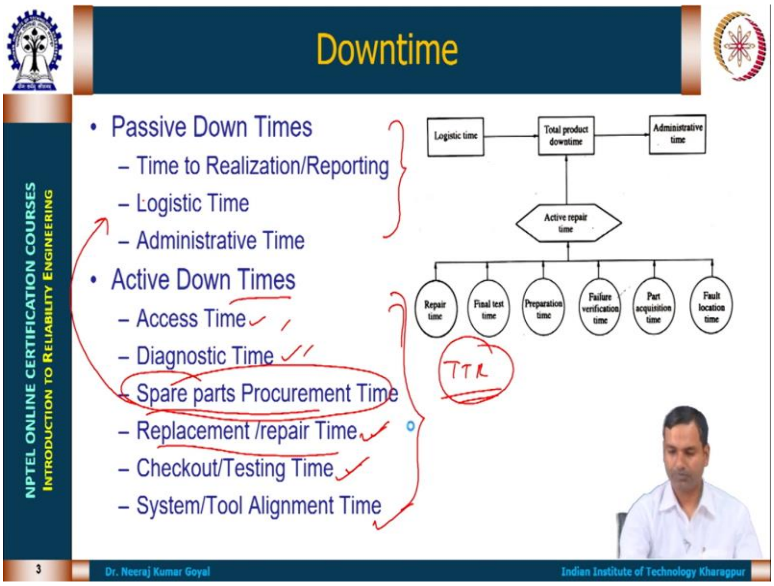

Why we do that maintenance concern is coming from the downtime. So, whatever time which we are spending after failure till it starts working again that is our downtime, for that time of the system for during that time the system is down, we are not able to use the system. So, downtime is the area of concern whenever we are studying the maintenance or maintainability.

This downtime can be passive downtime. Passive downtime is coming because of the delay in reporting or delaying realizing that failure has happened. So, many times the failure does not immediately reflect or it is not immediately observed by the people who are responsible for it or immediately report it to the concerned pupil who can do the maintenance. So, this takes some time.

So, there is a delay there. There is a logistic time delay. So, Logistics are also required. Administrative time is there, a lot of decisions need to be taken, a lot of the things need to be arranged then only repair happens. So, these delays happens whenever some failure happen. Logistics are related with the availability of the manpower, availability of the equipment, availability of the spare parts. If you do not have these, you will not be able to perform the repair.

So, you require sometimes and you have to ensure that these things are available. Once these things are available, these are mostly related with the administration and or the management. How well you manage that will decide that how well you are able to minimize these delays. But there are system related down times. So, like if these are the active down times. Active down times are related when you are actually doing a repair. So, what is affecting the repair.

So, repair time is affected by the access time. Access time is that you have an assembly. So, you have to access the part. Like a if you want to go to the motor problem in the pump then you have to first go to the motor, open it and go to the motor then only you can check it whether it is working or not working, what kind of problems are there.

So, access time is required to open it, open your system and you are able to reach to the problem areas. So, accessing the problem areas requires some sort of maintenance activity or repair activity. Then comes diagnostic time. So, you will be checking, once you have access that then you have to perform certain tests, then you have to use certain logics, you have to use your experience, knowledge and procedures.

Based on that you will be determining that what is the problem, which part is actually creating problem or which assembly is creating the problem. And once you find out that then you have to decide that what you will be doing about it. So, diagnostic will also take some time. Then comes up spare part procurement time.

Once you diagnose the problem, you will, you have to do the repair or replacement. So, for both the things you need certain parts, certain equipments then only you can do the repair or replacement. So, these parts should be available to you. So, how much time, this may take sometimes to be available to you.

So, once this spare time is available, if it is available, you can use them directly. Then comes the replacement or repair time. So, that is the actual time which if you have the spare part available to you or if you have the material which requires for repair is available to you, then you have to do the manual work or using the machines, and you will be doing the repair or replacement of that faulty part of the system.

Once you do that then you will be checking whether the system which of the changes which you make whether those changes have been effective or not, whether after the changes the problem is resolved or not, whether after these changes, all other things are not working as prior or as expected or not.

So, you will try to find out what kind of, you will try to assure that or ensure that after the changes which you have made, the normal working is not affected and the changes which you have made are also effective, the problem is resolved. Then comes the system or tool alignment time.

Many times for mechanical systems, you may have to align, make some certain alignments, make certain measurements, to make sure that a system is in perfect order or as good as as it was earlier. So, this time may also be required to, or you can also say that this is the installation time. Because once you have corrected the problem, you have to make the installation again and you have to again make sure that the device becomes the running condition again.

So, here generally, these times which we discussed earlier passive downtime, passive downtime is mostly coming from management side. How do you manage or how do you what kind of facilities you have created. Facilities will also impact the active down time. But active downtime is coming from the design perspective like access time. Access time is affected by the design.

So, in your design, if you keep frequently failing part as in deep inside in your design, what will happen? To get access to the problematic part, you have to disassemble all the parts which are working. In that case, what will happen? Every time you have to do more work time taken for repair will be high. So, this is in the designer hand, access time is in the designer hand.

So, he has to make sure that the parts which are failing faster, which are more prone to failure are more accessible so that repair can be done easily, while the part which generally do not fail or less probability of failure is there, they should be deep into the design, so that when they are accessing them, they do not need much many times to be accessed because they do not fail usually.

So, that way we have to design. So, this again is the concern for the designer, how much will be the access time. Diagnostic time is again dependent on the designer. So, if good diagnostic features has been built in the design, if good diagnostic process is or procedures has been provided by the designer, then the person will be able to diagnose it faster and correctly.

Spare part availability, etcetera, then it is partially affected by the designer, partially affected by the management. So, but like a spare part, here what type of spare part we are going to use? So, spare part procurement actually we can keep as the passive downtime. This is not active downtime.

But because this is the delay, procurement time is the delay. So, we can consider this as a passive downtime rather than the active downtime. But a spare part, whether appropriate spare part is there or not, that is the design feature. So, during the design if you have properly designed your spare part or if you have made sure that spare part is quickly replaceable or quickly they can be quickly diagnosed and quickly replaced, what will happen?

Your repair time will be smaller. Then comes replacement or actual repair time. That again depends on the how, what kind of material is there, what kind of design process is there. It will also depend on the maintenance facility. The maintenance facility, how the crew which is going to do that whether they are properly trained or not.

So, the crew training, crew experience will also come into the picture. But it will also depend on the design. By design, if repair is easy, you will be able to do it easy, replacement is easy, you will be able to do it easy. But for replacement, if you have to open 10 screws, 20 screws that also different size, different kind of things then you may have to take more time for replacement.

But if you make it simple, few screws only and those are also same type, same tool is required then it will be easier. Because if you have to use different kind of things, then you need require different tools. So, that will also take a lot of time. Then testing time again depends on the design.

So, designer will decide that how this checkout or testing, functional test will carry out at the end of the testing. So, if these are efficient good, it will take the less time. If they are not so efficient, the equipment is not so good, it may take more time. This will also in partially influenced by the design, but this can also be determined by how well this maintenance facility has been created.

If they have the tool and process, they will be able to do this in a faster way. If they have the good tools, good testing facilities, they will be able to do it in faster way. So, as we see that maintainability or active downtime or active repair time actually, it is a largely affected by the design, while other delays etcetera may be affected by the management.

But many of the things are in the designer's hand. So, this active repair time is a design feature. So, that is why we say that we have to design for maintainability. So, this time to repair which we are saying, time to repair is consisting of this access time, diagnose time, then after the diagnosis actual replacement or repair, then testing and then checkout. Checkout, testing and then if alignment is required then the alignment.

So, this TTR is consisting of all this except this repair part procurement time. That is the logistic time. So, this TTR is governed by the designer. If you design well then this TTR can be smaller, if you design poorly, then this TTR can be higher. So, repair time can be controlled by the design. So, that is why when we are saying design for reliability, we also say design for maintainability. Smaller TTR means higher maintainability, as we discussed earlier.

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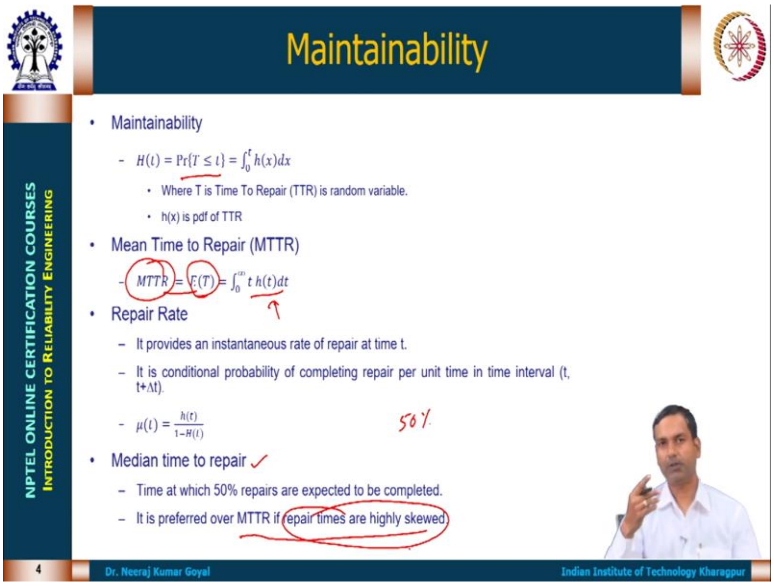

$$H(t) = \Pr\{T \le t\} = \int_0^t h(x)dx$$

$$MTTR = E(T) = \int_0^\infty t h(t)dt$$

$$\mu(t) = \frac{h(t)}{1 - H(t)}$$

This slide we have already discussed, I am reproducing or reshowing here just for the refreshing because this we discussed in the or during the first week of the lectures. What is the maintainability? Maintainability that our time to repair is below certain time. That means within time T, my repair completes. What is M T T R? M T T R is the expected value of time to repair.

So, which can I can use this formula. Small h t is the PDF of repair time. What is repair rate? Repair rate is similar to failure rate, it is the conditional probability of completing the repair per unit time. Then we have the median time to repair. So, like M T T R, M T T R is the mean value. What is median value?

Median value for any random variable is the fifty percent value. That means we expect that there is a fifty-fifty percent chance. That means this is the time at which we expect 50 chance is there that repair will complete or fifty percent chance is there that repair will not complete.

Or we can say that 50 percent of the time the repairs will be completed and fifty percent of the time repair will not be completed. So, it is a 50 50 value. So, if we say that way, it is the most dilemma value that because this is the value at which either it may be repaired or it may not be repaired and both are having equal chance, both are fifty percent.

Many times, so, we may use this value rather than MTTR, especially, when repair times are highly skewed. because for a skewed distribution, the MTTR may have a different understanding. So, that understanding development may be difficult.

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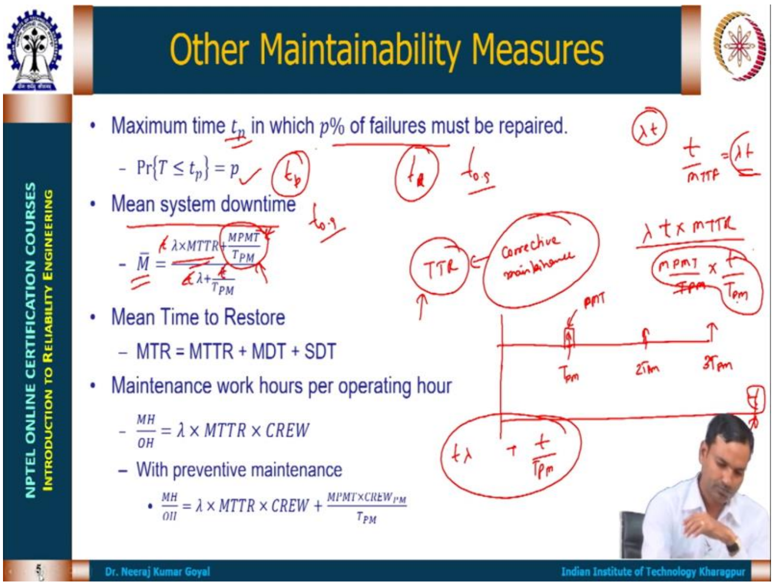

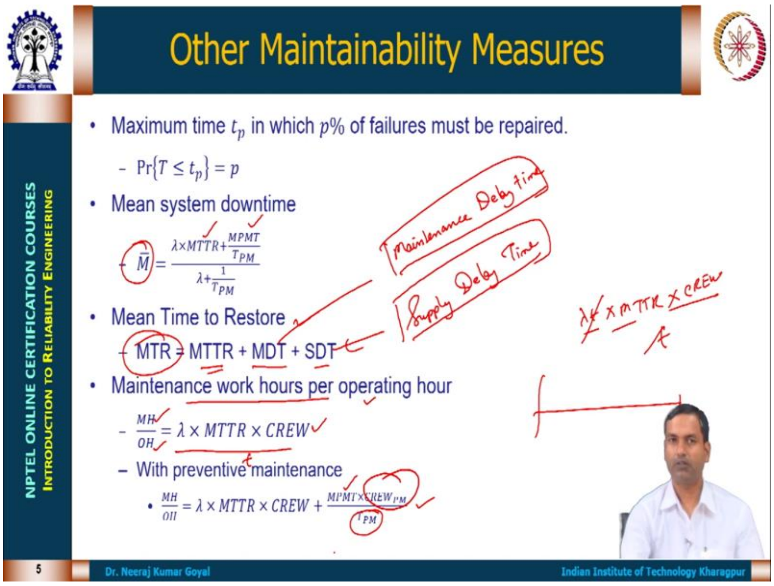

$$\bar{M} = \frac{\lambda \times MTTR + \frac{MPMT}{T_{PM}}}{\lambda + \frac{1}{T_{PM}}}$$

$$\frac{MH}{OH} = \lambda \times MTTR \times CREW + \frac{MPMT \times CREW_{PM}}{T_{PM}}$$

There are some other maintainability measures which are used, one is like tp. tp is the time at which we are expecting p percent of failures and that will be repaired. So, that is more like the design time, td, we used to have td in the reliability. What does td means? That means or we can say that tr, design life. That means for to, what is the time at which we will have the reliability equal to r.

So, when we were saying t 0.9, we were saying it is the value at which my reliability is 90 percent. Similarly here, what is the tp? t p is the time at which I will be having the maintainability equal to p. That means if I am saying t 0.9 that means this is the time in which I am 90 percent chance is there that my repair will be completed. Similarly, I have the mean system downtime.

So, mean system downtime like MTTR we considered. But MTTR is only considering the time to failure. So, most of the time this TTR is considered as the corrective maintenance time. Because this is the time of concern from the reliability point of view. Because from reliability point of view or availability point of view, corrective maintenance is the time which we are losing from the directly from the operation.

So, many times there is understanding that when we are doing preventive maintenance, then preventive maintenance we can do it in slack hours, that means we can do in the time where we do not need the system or when where we can within the schedule, we are making sure that the system may not be required so highly.

So, here, the time loss due to the corrective maintenance is generally the major concern. So, generally, MTTR whenever we are saying then we are saying that, that is a time which we are losing in maintenance or losing in repair, only the repair part, due to the corrective maintenance.

But actually we are losing the time not only due to the corrective maintenance, but we are also losing the time between the preventive maintenance. So, if we include the preventive maintenance time in our assessment that is in the downtime, then we are calling that as the mean system downtime.

So, mean system downtime is lambda into MTTR and M P M T divided by T P M. TPM is the preventive maintenance interval. So, that means, what is TPM? TPM is the time at which I will do the preventive maintenance. Again 2 TPM. So, here this is these are the places where I will do the preventive maintenance. 3 TPM. And how much is the what is MPMT?

This is the Mean Preventive Maintenance Time, that whenever I am doing repair how much time I will be spending in the repair that is the preventive maintenance time, PMT. And if you take my average of that that becomes the MPMT. So, on an average if I say that during the life, if I say my concern is time T, my system I am considering that it is working for time T.

So, for time T, how many fillers I am expecting? I am expecting let us say lambda T failure. What is the failure probability? That is lambda T. So, expected number of failures are generally given as T divided by MTTF or we can say this is equal to lambda T. So, lambda T is the failure, number of failures which are there. So, that means every time failure happens, we have to do the repair. That means time to repair. So, lambda T into MTTR. This is the time I am spending in corrective maintenance during time interval T.

And how much time I am spending in preventive maintenance? That is the, in each time T, in each cycle I am having the MPMT time which is spent out of TPM. So, out of T, how many maintenance sections I am going to take? So, I will say t upon TPM, that will give me the number of time I am doing the preventive maintenance. And each preventive maintenance is taking the MPMT time.

So, the time is spent in preventive maintenance is MPMT into t divided by TPM. So, this gives the like how many repair actions we have taken. So, this is the time which I am spending in repair in a when I am using the system for small t time. And how many repair actions I am doing, because mean downtime is down time in each repair action. This is the time.

So, this becomes If I multiply t here, If I multiply t here that becomes the top. But how many reperections I am taking? That that is number of failures and number of preventive actions. So, number of failures is t lambda or lambda t and number of repair actions is t of number of preventive maintenance expenses TPM but t divided by TPM. So, total time divided by total number of repair actions if you do, we will get the mean downtime.

And since t is common in all this t can be removed. Once we remove the t, we get this formula, that is that is lambda into MTTR, failure rate into MTTR plus MPMT into TPM. So, 1 upon TPM is kind of frequency of preventive maintenance divided by lambda plus 1 upon TPM.

So, effectively that gives me the how much is the mean system downtime. How much is the mean time to restore? So, there is in mean system downtime again we are considering only the active repair time. MTTR is also active repair time; mean preventive maintenance time is also active repair time.

The difference is MTTR is the time which you are spending corrective maintenance MPMT is the time which you are spending in the repairing the during the preventive maintenance. But there are delay times. MDT is called maintenance delay time. And SDT is called supply delay time. What are these?

So, not only taking mean time for actual repair, we are also taking the maintenance rate. What happens? If you go to any, let us say if you go to repair for your vehicle then you have to wait there because the person or the crew which is supposed to repair your equipment that crew is busy with certain another task.

So, availability of repair crew and the maintenance tools that is giving the maintenance delay time. When you do the repair and you have done the diagnosis, you require certain spare parts, certain materials, etcetera, if that material how much time that material. So, many times that material is available.

So, then supply delay time is zero. But many times that material or the spare may not be available, in that case, you have to order and get that spare. So, that is the supply delay time. So, supply delay time is due to the part requirement, maintenance delay time is due to the maintenance facility requirement.

If we combine all then we call it as the mean time to restore, which is the actual time which may be taking from failure to actually getting it up again. Then sometimes we try to find out that on an average how much maintenance work hour we are produced doing for every operating hour.

So, comparison of maintenance with the operating hour. So, that is maintenance hour divided by operating hour. So, maintenance our and operating hours if you do that that is given as, let us say if we have the t operating hour t time we are working in t time number of failures will be lambda t.

And every failure time taken will be MTTR. So, this is the time which you are spending in repair. But there may be more than one crew, if the crew facility is only one, then crew will become 1, but if more than one person is supposed to work, then number of men hours which are spending will be the crew size, if more people are supposed to be there.

So, this will become the men hour and out of t. So, t and t will get canceled and you will have lambda MTTR crew. If you also want to include time lost in preventive maintenance then same thing what we have done earlier. The crew, the preventive maintenance time will also add. That is mean time spent in preventive maintenance divided by TPM into the crew, same formula as we discussed earlier, same formula is coming here.

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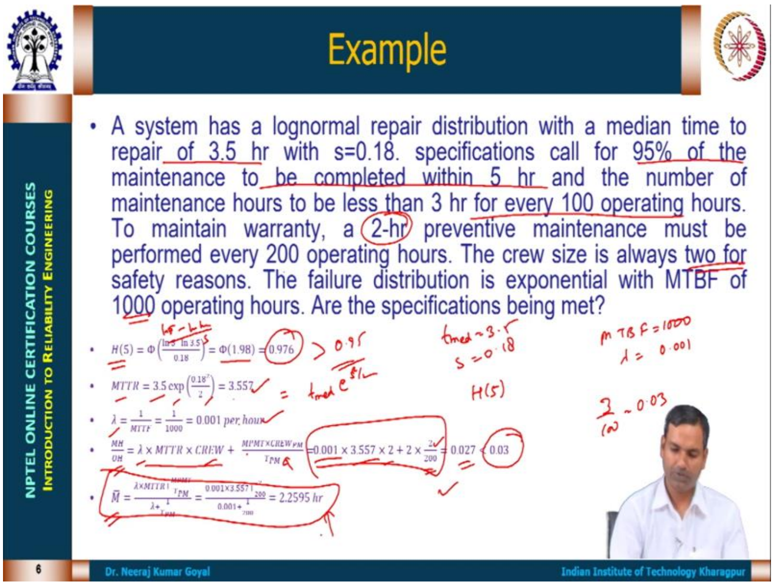

$$H(5) = \Phi\left(\frac{\ln 5 - \ln 3.5}{0.18}\right) = \Phi(1.98) = 0.976$$

$$MTTR = 3.5\exp\left(\frac{0.18^2}{2}\right) = 3.557$$

$$\lambda = \frac{1}{MTTF} = \frac{1}{1000} = 0.001 \text{ per hour}$$

$$\frac{MH}{OH} = \lambda \times MTTR \times CREW + \frac{MPMT \times CREW_{PM}}{T_{PM}} = 0.001 \times 3.557 \times 2 + 2 \times \frac{2}{200} = 0.027 < 0.03$$

$$\bar{M} = \frac{\lambda \times MTTR + \dfrac{MPMT}{T_{PM}}}{\lambda + \dfrac{1}{T_{PM}}} = \frac{0.001 \times 3.557 + \dfrac{2}{200}}{0.001 + \dfrac{1}{200}} = 2.2595\text{hr}$$

This we have tried to solve using this lognormal repair distribution. So, what is given to us? Median time 2 repair is given as 3.5 and S is given as 0.18. Now, we want to check whether my specifications are meeting or not. The specification is asking that 95 percent of the repair to be completed within 5 hour. So, that means H5, if I calculate here, I have calculated H5 is 5. Ln of 5 minus Ln of 3.5 divided by 18.

We know Ln of 5 minus Ln of T median divided by S. This comes out 5 of 1.98 which is 0.976. So, this is higher than 0.95. That means my criteria of 95 percent maintenance to complete in 5 hour is meeting. Number of maintenance hours to be less than 3 hours for every 100 operating hour.

So, that means we have to calculate MH upon OH. For calculating MH upon OH, we need the lambda and we need the MTTR, etcetera. So, what is MTTR, once we know this then MTTR is as we know for lognormal distribution MTTR is given as T median e to the power s square by 2. So, this is T medium this is exponential s square by 2. This becomes my MTTR.

And MTTF we have to get from here like a 95 percent to maintain warranty perform crew size. The failure distribution is exponential with MTBF of 1000 hour. So, MTBF is already given here that is 1000. So, if MTBF is 1000 then lambda will be 1 upon MTBF. So, lambda will be 0.001. So, lambda is 1 upon MTTF of that is this. Now I can calculate MH upon OH.

Lambda is here, MTTR is here, crew is already given that 2, 2 is required here for both, preventive maintenance as well as the corrective maintenance. So, we will calculate this here 0.001 3.557 into 2. And the due to preventive maintenance, the mean preventive maintenance time is 2 hour, 2 hour is taken in the maintenance. So, MPMT is 2. And how frequently that maintenance is carried out? Every 200 hours.

So, TPM is 200 and crew is 2. So, this if we calculate this turns out to be 0.027 which is less than 0.03. So, that means my requirement is met. Then we also can calculate the M bar here. So, that is what? Number of maintenance hours to be less than 3 hour for every, that is 3 divided by 100, that is 0.03. So, we have already verified that MH upon OH is less than 0.03. So, which is good.

And to maintain warranty 2-hour maintenance is this we have already seen. The crew size is 2 for failure distribution exponential. So, though it is not asking for M bar, we can calculate M bar here. That is mean a downtime. In the question is not given but we have calculated it here. So, it will stop here and we will continue our discussion about the topic in next class. Thank you.