Carbon Accounting and Sustainable Designs in Product Lifecycle Management

Prof. Deepu Philip
Department of Management Sciences

Dr. Amandeep Singh Oberoi
Imagineering Laboratory

Dr. Prabal Pratap Singh
Department of Management Sciences

Indian Institute of Technology, Kanpur

Week 08

Lecture 37

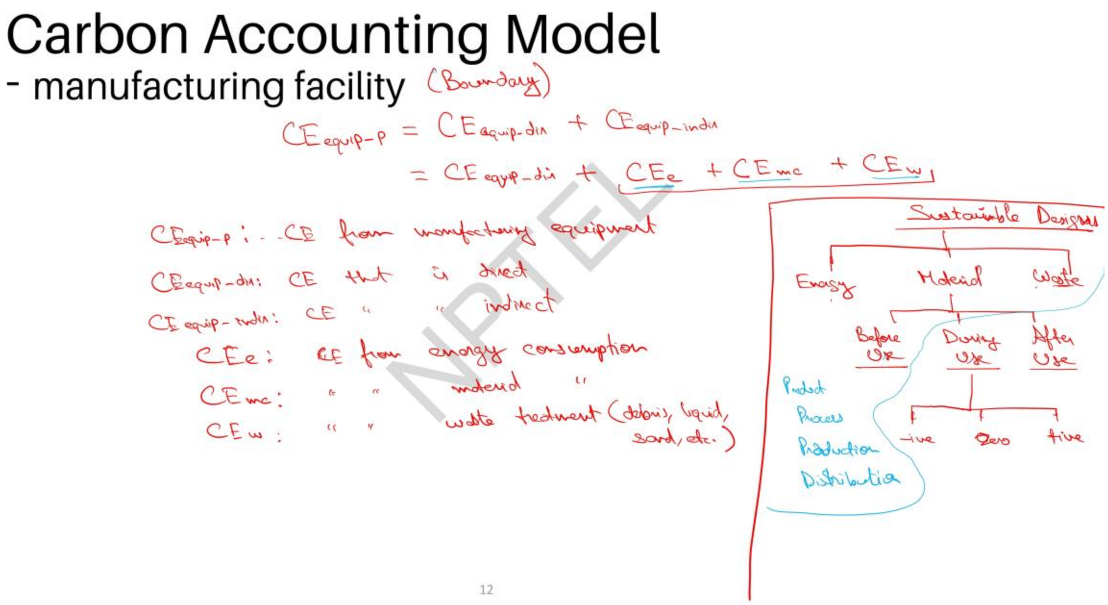
Carbon Accounting Model (Part-4)

Hello friends, we are in the course Carbon Accounting and Sustainable Designs in Product Life Second Management. And in this week, I am discussing about carbon accounting model that is quantitative model. I gave you introduction to the carbon accounting model and I talked about different layers of a workshop facility. And we talked about the facility umbrella, the product layer and part layer now we are talking about. In the last lecture, I talked about the part layer and now I will talk further about the part layer and the equipment carbon emissions direct and indirect in this lecture.

In the quantitative model, we started from here that is total carbon emissions in a workshop is some of the carbon emissions from the product and other miscellaneous emissions. It is not miscellaneous, those are also the important part of the production system that is distribution, inventory, auxiliary and medium of working. That is it could be compressed here, it could be nitrogen, it could be water operated any way other than electricity which are those, those were covered here. And then we talked about the carbon emission due to product that was in the product layer. Carbon emissions from the product I.

It consisted of part and the assembly, we explained it here itself. Then we talked about the part, carbon emissions from the part. Those are here, that is part from 1 to P. P is the number of processing steps, that is process 1, process 2, up to P number of processes. So, what is the carbon emission due to equipment?

When the equipment is working, that is in production, that is equipment underscore P. Plus equipment when it is waiting and equipment when it is transferring from one process to other. This we had a discussion in the last week. Now, in this lecture, I will talk in detail about this part that is carbon emission for the ith process execution that is when it is actual working.



So, to put that in a quantitative form, this carbon emission from equipment when it is being executed.

$$CE_{equip\_p} = CE_{equip\_dir} + CE_{equip\_indir} = CE_{equip\_dir} + CE_e + CE_{mc} + CE_w \quad (1)$$

Or other one is the carbon emission from the equipment that is indirect in which the three components are carbon emission E, carbon emission MC. That is material consumption and carbon emission W that is waste treatment. So, these all are carbon emission from energy, that is energy consumption or by power consumption in the production process. So, this is during the production process when the power consumption is there. This is carbon emission because of that.

And for the material consumption also, the carbon consumption is there. I will put it as carbon emission from the material consumption. This W is carbon emission from the waste treatment. This waste treatment could be debris or waste liquid or waste sand etc. From the material, if I talk about material could be carbon-based synthesis generated during the preparation of the process of the raw materials.

Or auxiliary materials that could be primary or secondary energy anything because we are not talking about the indirect energy. We will consider it secondary energy as well. One thing I will also like to put here that whenever we are talking about the sustainable designs. And because now I am talking about the indirect as three of its components that is energy, material and waste. So, sustainable designs majorly work in these three directions that is from energy viewpoint, from material viewpoint and from quality waste treatment or pollution mitigation, whatever steps we take.

So, present product whatever status it is, if we are trying to reduce the energy consumption that we say is a sustainable design than the previous one. Or if you are trying to use the energy or take the energy from the renewable sources or some part of the energy is taken from the renewable sources, so that is also a sustainable design. On the other hand, the material that is being used here in the development of the product or a part of a product. That if is a biodegradable material or if it is a material that is recycled material, that also is a step forward to the sustainable design. And third part is waste here.

That is when we are trying to reduce the waste, reduce the waste or we are trying to completely take off the waste. For example, in additive manufacturing, there is no waste of material. In forging, material scrap is not there. In casting, yes, some scrap is there. But in machining, conventional machining or in the CNC machining, which is cutting processes, lot of scrap is there.

I will show you a video in the end of this lecture. We will observe the scrap coming out of the material when we try to machine it. So, in all these three directions, whatever we try to take as a focus of our study, so we can move towards a sustainable design. So, in these as well, we try to then focus upon whether we are trying to use the material or focus our area. As I talked about this in one of the previous lectures, that is, are we talking about before use, during use or after use.

For instance, if it is there a material before use is when a customer or the final user is actually using the material or using the product. For example, if it is a car, the car is manufactured by a manufacturer, that is a before use part. And when the consumer is driving the car, that is during use part. And after the use, after the 15 years of the working life of the car, it is sent for dismantling or it is for disposal that is after use. So here as well, during use itself, we can try to work in the directions that whether we are going to have negative zero or positive impact.

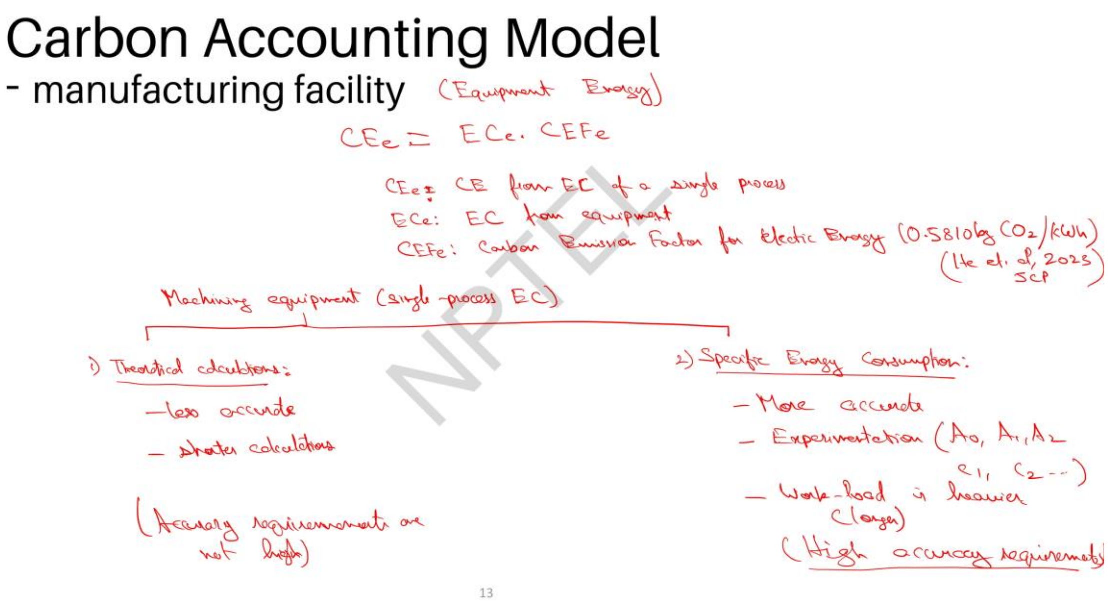
Negative here means you have reduced the material consumption. Zero means no change in the material is there. Positive means when you have increased the material consumption, but this is traded off while reducing the waste later, on the other hand. So, this trade-off is always there. So, here in this lecture, we are focusing on the before use part only,

that is before use also you know the PLM certain parts are there that is product design, then we have process design, then we have production and distribution. So, this is what we are focusing in this lecture. And this is due to energy, carbon emission, due to material consumption, carbon emission, due to waste treatment. These are all indirect treatments that we are talking here. Now here, different types of processes are there which have different types of equipment, types of its material, types of the waste that they produce.

And the realization of a machining process or any assembly process is relatively simple, which is generally completed by one device or operator. And on the other hand, forging and casting processes involve many types of equipment. So, when calculating the carbon fit point for the processes such as forging or casting.

So we will just consider the process flow or the progression of the overall process. But machining segregated different components of machining could be easily calculated and most of the components, most of the products that you see are manufactured by cutting itself, that is machining.

So, we will focus upon machining, then we will move to the casting and forging as a small part in this lecture. So, this slide is focusing on the boundary. That is boundary between the part and the product.



So, next slide, I will try to talk about the equipment energy consumption. In equipment energy consumption, we have carbon emissions E that is carbon emissions due to energy consumption for a single process.

$$CEe = ECe \cdot CEFe$$

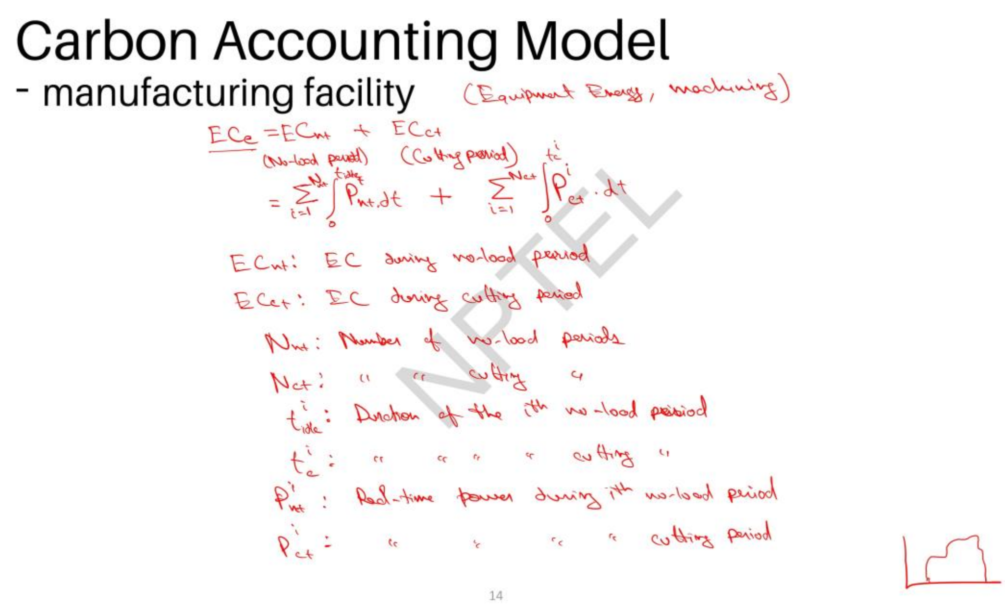
So here ECe you know is the energy consumption from equipment as here I am predominantly talking about the equipment energy in this slide and CEFe is energy and my energy is electric energy. So this is carbon emission factor for electric energy and this is in general 0.5810 kilograms of carbon dioxide per kilowatt hours.

This is from the reference by Hay et al (2023) and from the Journal of Cleaner Production. So, I will put the values from this reference only. When I will try to first focus upon machining equipment that is single process energy consumption. There are two methods.

First method is the theoretical method, theoretical calculations. This is one model. Second model is the specific energy consumption. Vertical model means the rotation of the spindle, the acceleration, the acceleration of the spindle, complicated energy consumption law is there. So, there are machining processes that no load condition is there, load condition is there.

I showed you the power curve in the previous lectures when the system is off and the standby mode is there, then the machining mode is there. All those systems are there in vertical part. Specific energy consumption is when theoretical energy calculation is not directly possible or you wish to find a solution that only takes about the prediction of energy that is specific energy consumption of machine tools cutting operations. The total energy consumption of cutting state can be calculated here where overall total energy is calculated for a specific parts specific Processes, it is sometimes not calculated.

So, specific energy consumption is based upon the material removal rate, it is based upon the cutting volume or other parameters or so. So, there are differences. I will keep this slide, this portion vacant so that later I come to the differences between them. Let me first try to jot down the theoretical calculations for the machining equipment, the single process energy consumption.

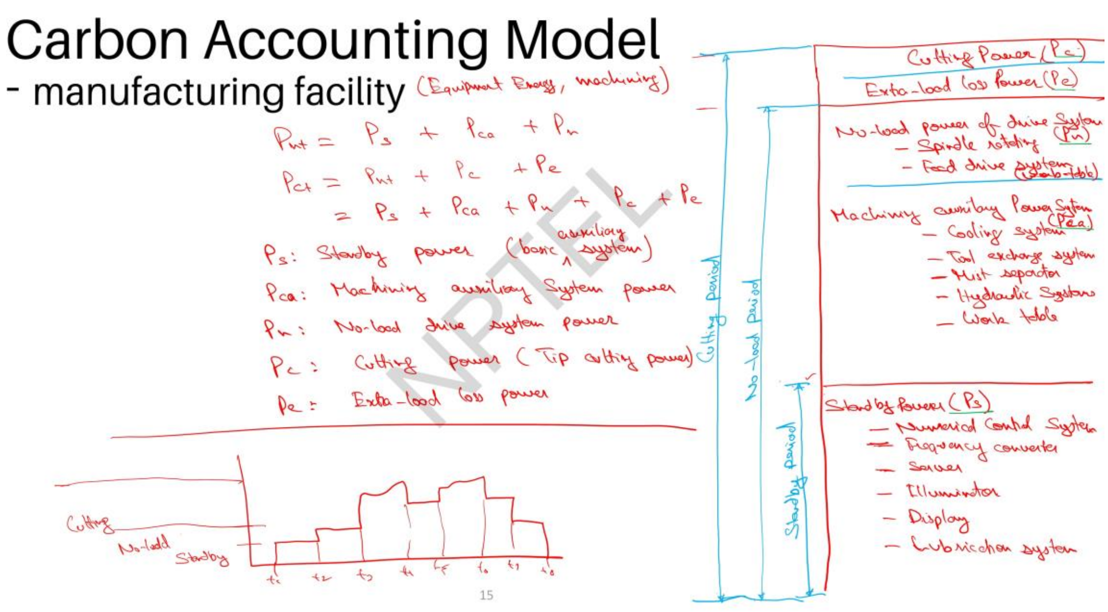


Therefore, the machine energy consumption during the processing time is:

$$EC_e = EC_{nt} + EC_{ct} = \sum_{i=1}^{N_{nt}} \int_0^{t_{idle}^i} P_{nt}^i dt + \sum_{i=1}^{N_{ct}} \int_0^{t_c^i} P_{ct}^i dt \tag{3}$$

Where,

- EC_e *- energy consumption of machine tool in processing time*
- EC_{nt} *- no load energy consumption*
- EC_{ct} *- cutting energy consumption*
- N_{nt} *- no. of no load periods*
- N_{ct} *- no. of cutting periods*
- t^i_{idle} *- the duration of the* i_{th} *no-load period*
- t^i_c *- the duration the* i_{th} *cutting period*
- P^i_{nt} *- the machine real-time power during the* i_{th} *no-load period*
- P^i_{nt}*and* P^i_{ct} *- the machine real-time power during the* i_{th} *cutting period*



Let us try to see that first and then I will show you a figure that how the power flows and then we will go to the laboratory to understand that better that how the power of the spindle and other components is distributed.

The machine tool input power during the no-load period and the cutting period are shown in Fig.

Therefore, the no-load period power P_{nt} and the cutting period power P_{ct} can be expressed as:

$$P_{nt} = P_s + P_{ca} + P_n \tag{4}$$

$$P_{ct} = P_s + P_{ca} + P_n + P_c + P_a \tag{5}$$

Where,

- P_n *– no load power of drive system*
- $P_{n\text{-}spindle}$ *- spindle drive system no-load power*
- $P_{n\text{-}feed}$ *– feed drive system no-load power*
- P_{nt} *- machine total input power*
- P_s *standby power*
- P^i_{nt} *and* P^i_{cT} *-- – the machine real-time power during the* i_{th} *no-load period and the* i_{th} *cutting period*
- A_0*,* A_1 *and* A_2 *– power coefficients*

I have standby power here in which we have the numerical control system, we have the frequency converter We have server of the CNC machine or of the computer that is giving input to the machine. Then we have lights that is illuminator or display or maybe lubrication system or any such auxiliary system where is the basic auxiliary systems. This is my standby power, which is PS, standby. On the top of it, I will now switch on the machine.

From here, I will switch on the machine. So, here it is only standby power. I will just draw this line. And I will switch on my machine here. Then comes the machining auxiliary power system where we have power Ca that is auxiliary in which we have the cooling system and this is for a smaller period.

Only the machine is majorly running at a standby mode when the setup is being made. When the machining actually has to happen, cutting actually has to happen, just a few seconds before the spindle has to be started rotating, the homing of the machine is there, then only these systems comes into play, that is the cooling system, the tool exchange system. That is there is a turret of the tool when the tool exchange is happening and the cutting fluid is also running. That system is also running that comes in the machining auxiliary power system PCA which power is higher or it is added to the power that is a standby power. Then also we have the mist separator.

It is if the mist flow is there then hydraulic systems. So, this is then tool exchange system when you say, we also say the work table, if suppose small setup is to be made for the system to run. So, these all come as a power, as an auxiliary power, which is for a machine that is still under no load. No load means actual cutting has not just started. On the top of it, I will draw a small separator here and I will add no load power of drive, no load power of drive system which I have denoted here as Pn.

Here we have majorly the spindle when it has started rotating. And this is only a few seconds before the machine actually starts cutting and the feed drive system. So, this work table, etc. majorly comes here as well. Feed drive till this point. There is no load i will put it here till this point the system is in standby from zero it is standby period and from the standby period till this point still we do not have any load that is from the base zero it is still no load.

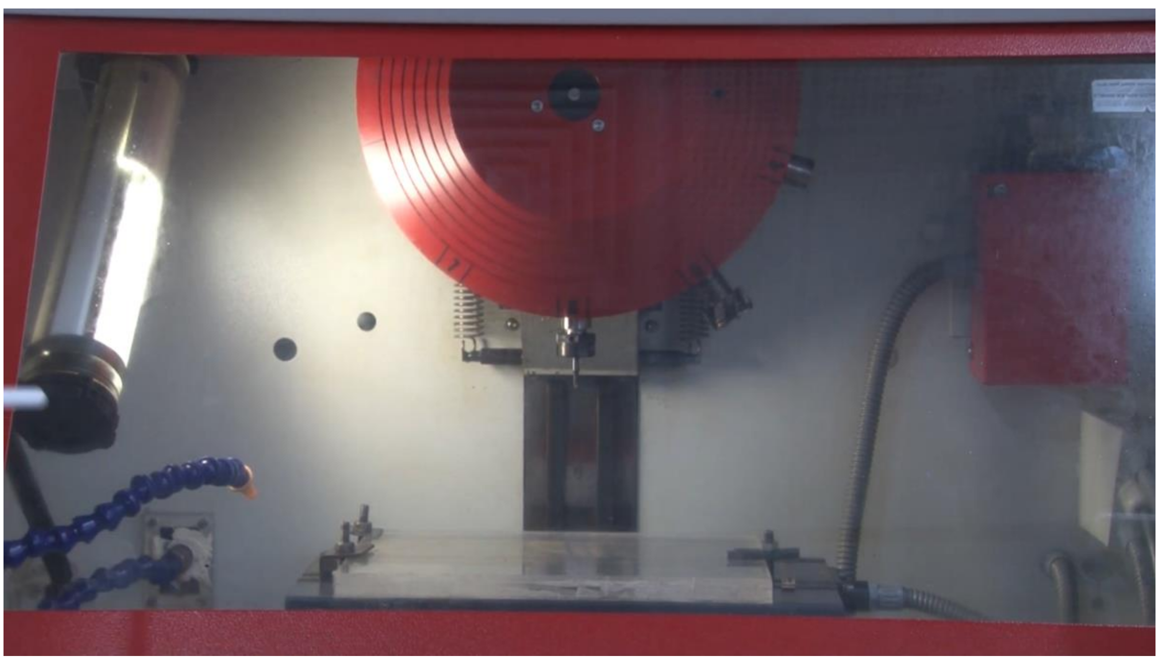
And from here, I will go up till the point when the cutting has actually started, maybe till this point from 0, I will draw a dimension that is the quantum of power which is time or the power during cutting. I will put it as cutting period. So, what is left now? Cutting has not yet started.

Now, finally, you will have a cutting system here. That is, we have two parts in a cutting system. One is the actual cutting, which is the last power when actual cutting is happening. I will put it as cutting power, which is When actual cutting is happening there is always some extra load because cutting might happen for some time, cutting might happen for continuously at a larger power rate.

For example, if it is 1 mm, 2 mm, 3 mm of the holes which you have to do, the depth of the cut is lesser or larger. There is always loss of power and that loss of power is here compensated while putting a parameter that is known as PE, which is the extra load loss power. So, this is making you clear that how the standby period, no load period, cutting period powers are there and this is again associated with the power curves that we drew in the last lectures where it is something like this. If you recall, it was time t1, t2, t3, t4, t5 and so on.

We have different times and it was here only the motor was off that is this was standby. This was till this point. It was no load and from here till the end point it is cutting. This is our power curve. This I will show you in a demonstration in a laboratory.

Let us come to the laboratory that is imaginary lab at IIT Kanpur, where I will take you to a CNC setup and we will see how the system when it is standby, the light is there, the auxiliary systems, the basic auxiliary systems are there, display is there, numerical control system is there that is running. And at no low period as well when the cutting is not happening, still system is consuming power. So, let us try to see that in lab and after that we will close the lecture.



Welcome to the laboratory setup. We are in the course Carbon Accounting and Sustainable Designs in Product Lifecycle Management and I am trying to demonstrate you how the power consumption

In the machining varies depending upon the different parts of the machine when they are switched on or switched off and when the actual machining process is there. I showed you the time variability, the way when the motor was off, motor was on, then the processing time, pre-processing time I showed you in the previous weeks. So we are discussing the carbon emissions based upon the energy consumption in machining. And in machining, carbon emissions are proportional to the energy consumption. And how is energy consumption there in a single process?

So this is a typical CNC machine, which is an AMCO concept mill 105. This is a four axis CNC milling machine. In which you can see the setup here. This is our whole machining setup. We have workpiece already set on or it is held on the table here.

And this is a turret in which different tools are there. This is a drill, this is a milling machine and there are lights which are on. So we have different setups here. So this machine is as of now in a standby mode. You can still have some sound coming.

that is some motor is there that is there at the back end which is still running that is we have the lubrication system which is switched on we have a The display system that is also there. This is a monitoring system or the control panel here. We have a display system there on the computer that is switched on. So even when the machine is not running, nothing is happening, nothing productive is there, but still energy consumption is there.

We have the server of the system there. At the back, we have the cooling system, the server that is also switched on. Frequency converter, nubel control system, all of them are working in a standby mode itself. So when we shut the door of the machine, now machine will work in this mode itself because it is for the safety of the operator who is working on the machine. The machine would not work unless the door is shut.

And now the coolant system could be switched on. It would be switched on when the machine would run. And I would run the machine in 2-3 modes. That is first I will do one small milling operation with 1 mm of depth. Then with 2 mm of depth, then I will try to do a taper.

From 1 to 2 mm, how do we go about? You will see the difference in the sounds. The sound intensity, that is sound if it is like, these different sounds is giving me the power or the load that is there taken by the motor. This is proportional to the energy consumption.

Now this is the second level of the power consumption pre-processing when this is a coolant system.

This blue pipe that you could see is a coolant system. That has now started delivering the coolant. That is now switched on. Now you can see the sound is coming little high. So this is the second level when the energy PCA is there.

That is the power of the auxiliary system that is now started operating. So, the hydraulic system has started operating. The mist system will start operating. The exchanging knives, cooling system that will start operating. Those all will start working here.

Then we will come to the actual process when actual machining happens, what is the power consumption. And similarly, I will also show you now after the machining, after the laboratory demonstration here, the curve that how the power consumption goes. So let us now try to run the machine. So now let me show you some sounds of the auxiliary systems. Now machine, though it is in standby mode, I will move the table now.

This table is being moved. Is it operator who is moving the table? You see the sound. This is turret is being moved, table is moved. Each of them is having associated sound for the turret.

This is the sound of the motors which are controlling them. This is also energy consumptions. So, which comes into machining auxiliary system power. That is PCA that we call this. Now, let me rotate the tool.

this is slow speed rotating less energy consumption little lesser like let me now increase the speed at little higher speed or may be much higher speed the rotation speed you will observe and you will also observe the sound coming here it will be heavier that is high energy consumption this is high energy consumption now the rpm of the machine is 1200 here This is sound coming. These are all the systems which are one coming but still the cutting period is not there. That is we are still in a period when spindle drive system is working. This is stable is my feed drive system from X in X and Y direction.

Z direction is the territory in Z up and O. This is all feed system. It is also working. So this is my no load power of drive system. Now let me start cutting. In cutting there will be cutting power that is tip cutting power PC and we will also have extra load loss power because extra load is good we will be applying for cutting.

We will also see how does that happen. Yes, the cutting it is coming down. This is a end ball mill cutter and the workpiece is acrylic. As I also told based upon the workpiece type the carbon emission for material is accordingly. So this is acrylic, transparent acrylic plate of 20 mm thickness.

This is just a drilling. This is now processing. It is cutting is happening. This is now very hard material. It is high speed steel.

Tool is cutting my very soft material that is acrylic. That is why very heavy sound is not coming. Had it been mild steel the sound would be high for cutting. It is moving in other direction, y direction. Here now, the cutting speed is there.

It is now little, the depth is not very heavy. The depth should be around maybe 2 mm, 3 mm maximum. So let me now increase the depth. More depth, then we will do cutting so that the sound comes. Depth.

Now you see, the sound is coming. If I increase the feed rate here, the table feed rate, more sound would come. And this is a coolant system. Coolant system has to be there in the machining part itself. So now I have put the coolant system.

I did not put the coolant system because I wish you to see this scrap or the scrap is coming out because coolant will also flush off this scrap now. So this is cutting fluid that is being applied. Cutting fluid or coolant whatever we call it. This is also cleaning of this scrap. But now the machining is still happening.

Now the machining is going. You see the sound. You hear the sound. The machining is happening in this direction. But this is now actual cutting that is happening in the machining.

So this is acrylic material. That is why the sound is not that heavy. And the coolant has two purposes. One is to splash off or to clean off the scrap. That is the chips.

And number two, second point is the cooling material. cooling of the system so that the internal or residual stresses are not developed much when we are machining something this is how cutting is happening all right now we can stop the machine you will again see when we stop the machining the tool will come up Now, we have stopped the machining. The spindle is stopped. But still, the initial standby system is still running.

You can see the light is switched on. The illuminator is there. The server is there. The display is also on. The frequency converter, numerical control system, all of them are running at the back end.

Lubrication of the machining is there. So, some of the systems in the standby are still running. And now comes the setup cost. Setup cost or setup energy. When we are changing the work piece or we are changing the tool here, the tool change in the turret itself in automatic system in the turret itself one tool is there.

Second tool could come, it can keep changing the different kinds of a tool and this can hold up to 10 tools. I can show you how the turret rotates, they always change the tool, so this is our setup tool could be changed and to change the plate that is the work piece we have to again open the door. The change has to happen but still machine would be running in standby in standby also energy would be there. This is turret, second tool, third tool. It does not have any tool at point number 7.

So I will now come to point number, it was previously using tool number 6. It has come to tool 8, tool 9, tool has to be little clean. So you can see the metal scrap there at tool 9. So each evening the machine is cleaned. So when this tool 9 was used in the morning, so you can see the scrap, that was a metal scrap.

So that was being used. So these are all systems in a single process, single process or in a machining system which consume energy and energy consumption varies according to the power consumption levels. That is when the machine is actually in process or the machine is waiting for the workpiece to be changed, for the tool to be changed, still energy consumption is there. This is for a single process. So from this process, process one, process two, process three, adding to make it a production line.

And this makes it a total product energy consumption and proportional carbon emission. And these overall products, whatever parts are there, taking them all together makes our facility efficient. Energy consumption and a proportional carbon emission accordingly. And then there is distribution, then there are auxiliary systems, then there are transfer to the whole cellular. So all those parts are there in the carbon accounting.

So let me move to the quantitative models which I am discussing to quantify this energy to find the carbon emissions based upon the energy used at different levels of the machining. This was a laboratory demonstration where I demonstrated how the power consumption varies based upon the sound of the system where it was running, the number of motors which were there and the power consumption in a way it is there in this illustration when the cutting power is the highest power which is having no load period, standby period in it and final cutting is happening here, the cutting power. from this point to this point. It is final cutting that is happening. I will take this further in the next part of the lecture series on the carbon accounting model.

We will try to discuss in the theoretical modeling of the equipment in the machining. Then I will go to the specific energy model. Then we will talk about further about material consumption, about waste treatment and other carbon emission systems.

Thank you.