Carbon Accounting and Sustainable Designs in Product Lifecycle Management

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Week 08

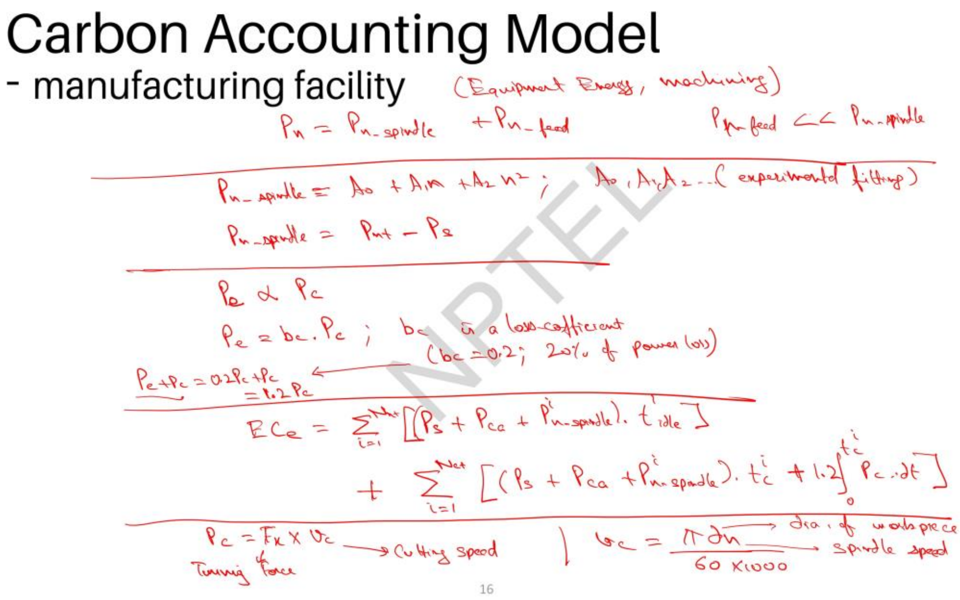
Lecture 38

Carbon Accounting Model (Part-5)

Welcome to the part 4 of lecture series. We were discussing the Carbon Accounting Model in the course 'Carbon Accounting and Sustainable Designs in Product Lifecycle Management'. I am Dr. Amandeep Singh. We have discussed in the last lecture about the cutting power. Cutting power or we will discuss about the carbon emissions due to this cutting power.

We talked about the standby period, the no-load period, and the cutting period with the total cutting period power, where the major power was for the cutting period PC. Now, this power, that is PCT, has five components: PS, PCA, PN, PC, and PE. Here, the standby power and the PCA, which is the machining auxiliary system power, are relatively stable in a working state and can be regarded as constant. The power that will vary majorly would be PN and PC, and PE would be proportional to the varying state of PC. That is, the extra load power would be taken as a proportion of the total cutting power. So, what is PN?

That is, the No - Load Power of drive systems. When we talk about the drive systems, there are two major drives.



That is, PN can be divided into two parts. Power for the no-load system is equal to the power for no-load for the spindle and the power during low load for the feed. And in the demonstration, as you observed, the feed power is only the small motors which are there, which only change the position of the workpiece or the tool in the x, y, and z directions.

$P_{n\text{-spindle}}$ can be approximated as a quadratic function of spindle speed, as shown in Eq.

$$P_{n-spindle} = A_0 + A_1 n + A_2 n^2 \tag{6}$$

The power coefficients A0, A1 and A2 can be obtained by experimental fitting. Under the premise that the feed system and the machining auxiliary system are not running, $P_{n\text{-spindle}}$ can be obtained by subtracting the machine total input power P_{nt} from the standby power P_s when the spindle system is idle, as in Eq.

$$P_{n-spindle} = P_{nt} - P_s \tag{7}$$

The ratio of the extra load loss power P_a to the machine tool cutting power P_c in the cutting state is a constant

(0.15–0.25) , called the extra load loss coefficient ($b_c = 0.2$).

Therefore, P_a is:

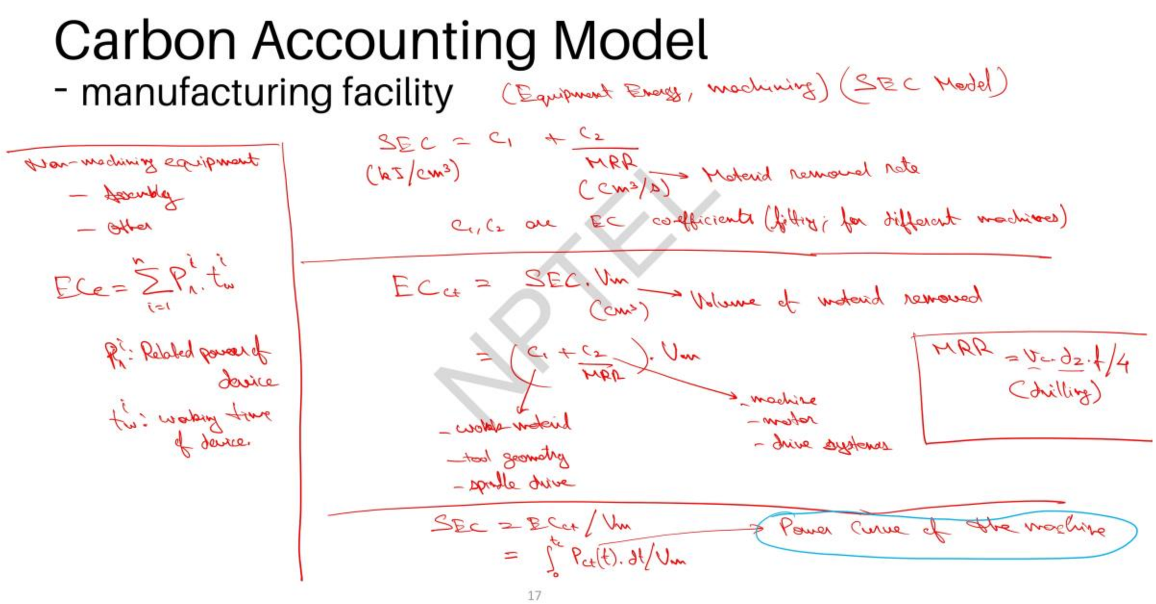
$$P_a = b_c \times P_c \tag{8}$$

The energy consumption of machine tool in processing time EC_e can be converted to:

$$EC_e = EC_{nt} + EC_{ct} = \sum_{i=1}^{N_{nt}} \left[\left(P_s + P_{ca} + P_{n-spindle}^{i}\right) \cdot t_{idle}^{i}\right] + \quad \sum_{i=1}^{N_{ct}} \int_0^{t_c^i} \left(P_s + P_{ca} + P_{n-spindle}^{i} + 1.2P_c\right) dt$$

$$= \sum_{i=1}^{N_{nt}} \left[\left(P_s + P_{ca} + P_{n-spindle}^{i}\right) \cdot t_{idle}^{i}\right] + \sum_{i=1}^{N_{ct}} \left[\left(P_s + P_{ca} + P_{n-spindle}^{i}\right) \cdot t_c^{i} + 1.2 \int_0^{t_c^i} P_c dt\right]$$

P_c is the required power that provides the tooltip to remove the workpiece material.



I will now move on to the next model, which is the Specific Energy Model. Specifically, I will discuss the SEC model.

In the specific energy model, empirical relations are used. The total energy consumption of the cutting state can be calculated using this model. It is verified by experiments on different machines, such as milling machines, grinders, and lathes. The results show a prediction accuracy of more than 90%. Though this is a specific energy model, with a prediction efficiency of more than 90%, it is still used by certain software tools to develop their carbon emission models. Here, Specific Energy Consumption (SEC) is given by:

$$SEC = c_1 + \frac{c_2}{MRR} \tag{13}$$

I will just write down the units here. It is measured in kilojoules per cubic centimeter, representing energy consumption per unit volume. And, C1 and C2 are the characteristic coefficients of machine tool. MRR (Material Removal Rate), measured in units of volume of material per unit of time, that is, cubic centimeters per second C1 and C2, are energy consumption coefficients.

This type of model helps in developing a comprehensive calculation for machine tools or machining processes, serving as a holistic model to measure energy consumption and cutting energy. ECT can be obtained in this way:

$$EC_{ct} = SEC \cdot V_m = (c_1 + c_2/MRR) \cdot V_m \tag{14}$$

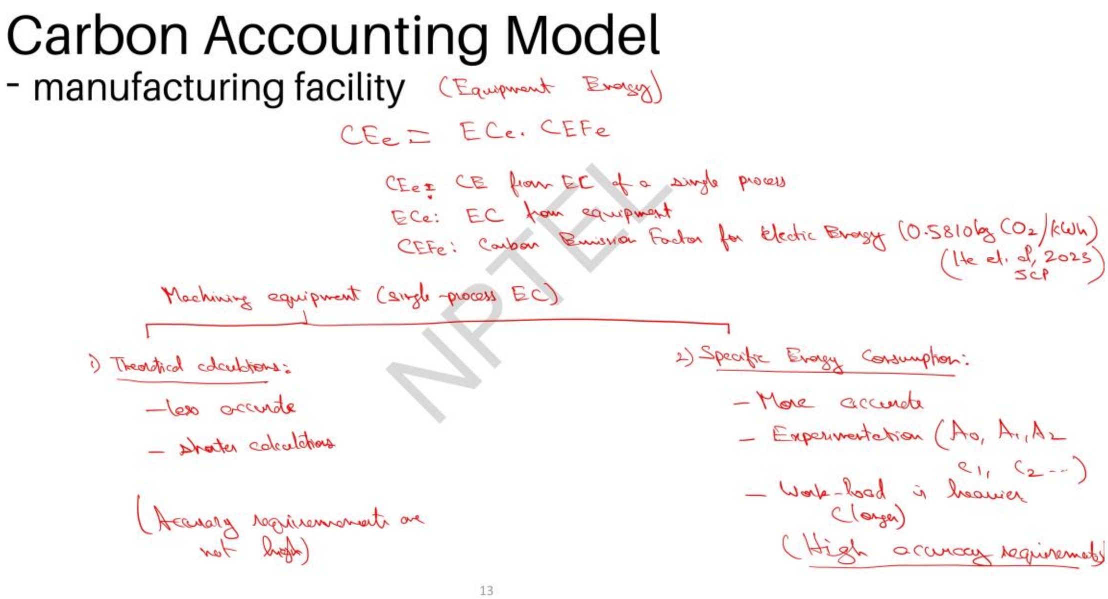
These fitting coefficients, C1 and C2, are different for each case. These are the coefficients used for fitting. And these are for different machines. That is for turning, it would be different; For milling, it would be different; For drilling, it would be a separate coefficient that would be, again taken using experimentation.

Now, the key to predicting energy consumption with this method is: to determine the specific energy consumption model of the machine tool during the cutting stage, where CN is mainly related to the work material properties, which I will refer to as the work material. It is dependent on the work material, tool geometry, spindle drive, and C2.

It is related to MRR, meaning it depends on the material removal rate, which majorly depends on the machine parameters, such as the type of motor, the motor's load, and the drive systems. Cutting force is mainly determined by the shear stress in the shear zone, the work material, cutting depth, feed rate, and all other variables that influence the cutting force. Because energy consumption in cutting is the product of specific energy consumption and volume, specific energy consumption becomes the energy consumption in cutting per unit volume of material removed.

$$SEC = EC_{ct}/V_m = \int_0^{t_c} P_{ct}\left(t\right) dt/V_m \tag{15}$$

This is for drilling. There are different material removal rates for milling because milling involves additional parameters, not just the z-direction. It also moves in the x and y directions. For milling, the material removal rate is different. Here, for drilling, Vc is the cutting speed, dz is the diameter of the drill, and F is the feed rate.



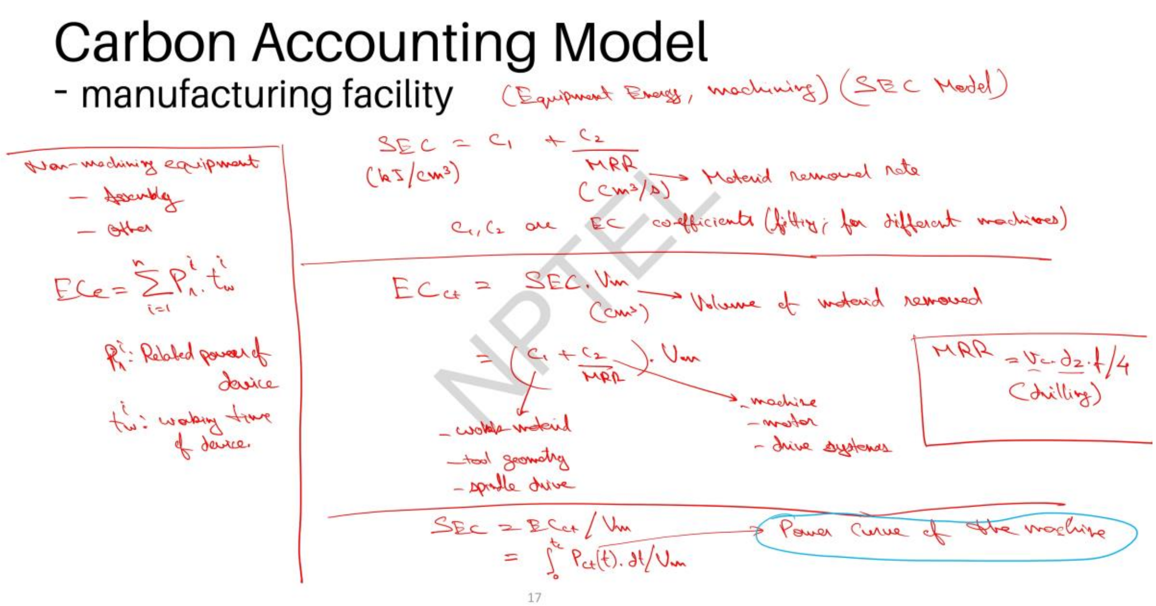
Now, let me return to the slide where I was trying to highlight the differences between the theoretical calculations and the specific energy consumption model.

The results of energy consumption quantification based on SEC are more accurate. This means that practical calculations are less accurate. However, the specific energy method is based on experimentation. That is, we need to determine constants like A0, A1, A2, C1, C2, and others. This means developing the model or determining the workload takes more time.

In other words, this model requires more detailed experimentation. However, in the theoretical model, the calculations are shorter. So, the specific energy consumption model takes longer, while the theoretical calculations are much shorter for cutting force. So, this is generally used, where accuracy requirements are not high. So, when accuracy requirements are very high, we use the specific energy model because it is developed through experimentation. For your own facility, you develop the experiments, or the machine tool provider conducts them.

For example, we use the EMCO mill machine. The parameters provided by the manufacturer are specific to that machine. For that machine, specific experiments are conducted in one set of the facility. Another facility, if they have the same machine and parameters, can use the same data. However, these parameters are real-time and accurate, and you can continuously add to the experimentation to refine the results. When high accuracy is required, the specific energy consumption model is used. Now, I will move on to the Non-Machining parameters, which means I will talk about the Assembly Processes.

In terms of assembly, the common product assembly processes include thread connection, welding, key connection, pin connection, and other similar methods that are all part of the assembly. Aside from the assembly, there is energy consumption related to the power for the different systems or working systems that are involved.

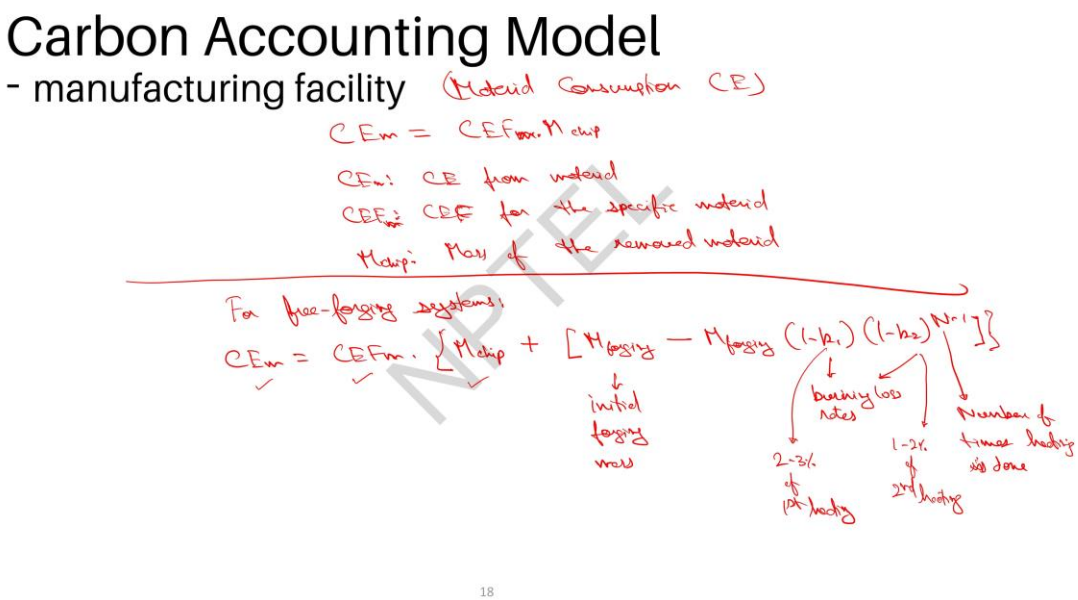


Further, I will focus the next part of my lecture on the non-machining parameters or the non-machining equipment, which could be assembly or any other equipment where machining is not involved. Generally, the energy consumption is equal to the summation of the powers used in these equipment, with the power related to each device, denoted as

$$EC_e = \sum_{i=1}^{n} P_r^i . t_w^i$$

For example, in assembly, we have a handheld router that helps to screw or unscrew, certain spanners and other power tools that are used. For example, you have the air compressor that supplies air to put in, or vacuum out the air for certain places.

So, it depends on the type of power and the equipment that is used. I will express this as PRI, which represents the power related to the device, and t, which is the time for which the device works.



Now, I will focus on material consumption and carbon emissions. In material consumption, the carbon emissions due to the material are simply the carbon emission factor for the material times the mass of the material that is removed, which I will denote as M chip. So, this represents the carbon emission from raw material consumption, which is primarily caused by machining — that is, due to the equipment we discussed in the previous slides. The material that is removed during machining or operations also has a carbon emission associated with it.

So, here, CEM represents the Carbon Emission from the material, and CEF M is the Carbon Emission factor for the specific material. M chip is the mass of the removed material. But this is true for almost all types of machining. And for free forging systems, I will explain what we have here.

$$CE_m = CEF_m \cdot \left\{ M_{chip} + \left[M_{forging} - M_{forging}(1-k_1)(1-k_2)^{N-1} \right] \right\} \tag{21}$$

Where,

CE_m - carbon material emission

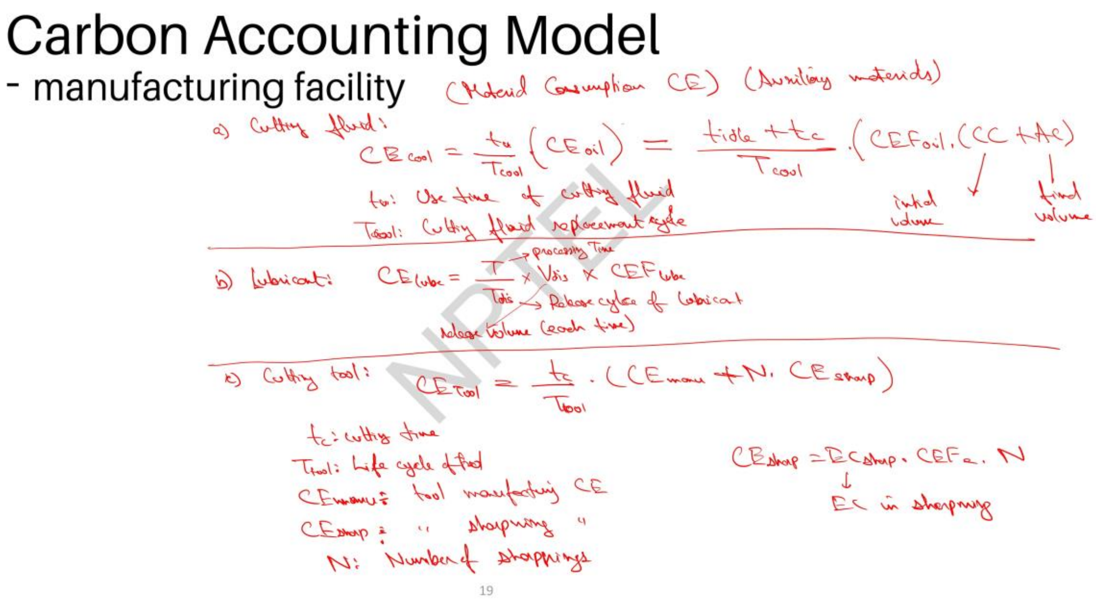
CEF_m – carbon emission factor for raw material production

$M_{forging}$ – initial forging mass.

k_1 – burning loss rate of the first heated metal (2–3%)

k_2 - burn rate of metal per heating from the second time (1.5–2.0%)

N – number of heating



Similarly, I can have a carbon emission model for material and auxiliary materials. In auxiliary materials, we can talk about cutting fluid, lubricants, and cutting tools. In casting, we will also discuss auxiliary materials, and in assembly, auxiliary materials would also be included.

So, what are the auxiliary material carbon emission when we talk about the cutting fluid? Cutting fluid is mainly of two kinds: water-based and oil-based. So, here I will state that

$$CE_{cool} = \frac{t_u}{T_{cool}} \cdot CE_{oil} = \frac{t_{idle} + t_c}{T_{cool}} \cdot CEF_{oil} \cdot (CC + AC) \qquad (23)$$

Where,

CEF_{oil} – carbon emission factor for the production of mineral oil (2.853kgCO2/L);

t_u – use time of cutting fluid (s)

T_{cool} - cutting fluid replacement cycle (s)

CC and AC – initial and additional volume of mineral oil (L), respectively.

Similarly, I have a model for the lubricant. For the lubricant, the model is simple:

$$CE_{lube} = \frac{T}{T_{dis}} \times V_{dis} \times CEF_{lube} \qquad (24)$$

Where,

- *T – processing time*
- T_{dis} *- release cycle of the lubricating oil*
- V_{dis} *– release volume of the lubricant each time*
- CEF_{lube} *– carbon emission factor for the production of lubricating oil (2.853kgCO2/L)..*

$$CE_{tool} = \frac{t_c}{T_{tool}} \cdot (CE_{man} + N \cdot CE_{sharp}) \qquad (25)$$

- Where,
- t_c *– cutting time*
- T_{tool} *- is the life cycle of the tool*
- CE_{manu} *– tool manufacturing carbon emissions*
- CEF_{manu} *– carbon emission factor for the production of cutting tool*

- M_{tool} - *mass of cutting tool*

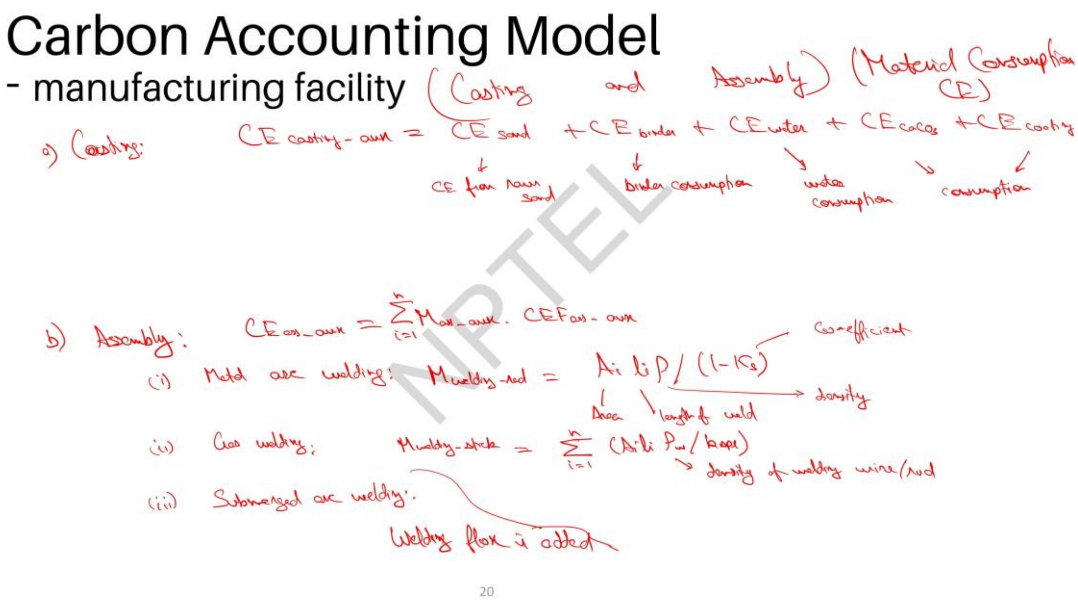
The carbon emissions of the grinding tool at one time are: $CE_{sharp} = E_{sharp} \cdot CEF_e . N$

Where,

N – number of sharpening

E_{sharp} – *energy consumption of sharpening tool at one time*

CEF_e – *electric carbon energy emission factor*



Now, I will talk about the auxiliary materials that is Casting and Assembly. Though these are two very separate processes, I'd like to put the relationships in a single slide. The auxiliary materials required for sand casting processes mainly include molding materials, such as molding sand, coarse sand, calcium carbonate, various coatings, and so on.

Certain physical and chemical methods are used to recover the sand. The molding sand is prepared again by adding binders or additives when the sand is heated. However, there is still some loss of sand during the process. When discussing waste materials and emissions, we consider the loss of sand and other materials in casting, as well as water wastage, sand wastage, and similar issues. These contribute to the overall environmental impact of the casting process.

Let me now first talk about the material consumption carbon emissions. So,

$$CE_{casting\_aux} = CE_{sand} + CE_{binder} + CE_{water} + CE_{CaCO_3} + CE_{coating}$$

- *CE_{sand} - carbon emission from raw sand consumption*
- *CE_{binder} - carbon emission from, binder consumption*
- *CE_{water} - carbon emission from water consumption*
- *CE_{CaCO3} - carbon emissions from limestone consumption*
- *$CE_{coating}$ - carbon emissions from coating consumption*

In assembly, there are certain ways. There are Permanent Joints and Temporary Joints. For permanent joints, there could be rivets, including permanent rivets, and welding is also one of the processes used for permanent assembly. For the temporary assembly, screwing, unscrewing is generally used. For permanent joints, there could be rivets, including permanent rivets. Welding is also one of the processes used for permanent assembly.

$$CE_{ass\_aux} = \sum_{i=1}^{n} M_{ass\_aux,i} \cdot CEF_{ass\_aux,i} \quad (27)$$

Let me talk about different welding processes. First, let me talk about the shielded metal arc welding. Then, I will talk about the gas welding and we will also talk about the submerged arc welding.

For metal arc welding, the mass and carbon emission factor need to be calculated. The carbon emission factor for the specific material can be obtained from journals or handbooks. The mass of the welding rod is

$$M_{welding\_rod} = \sum_{i=1}^{n} [A_i l_i \rho / (1 - K_s)] \quad (28)$$

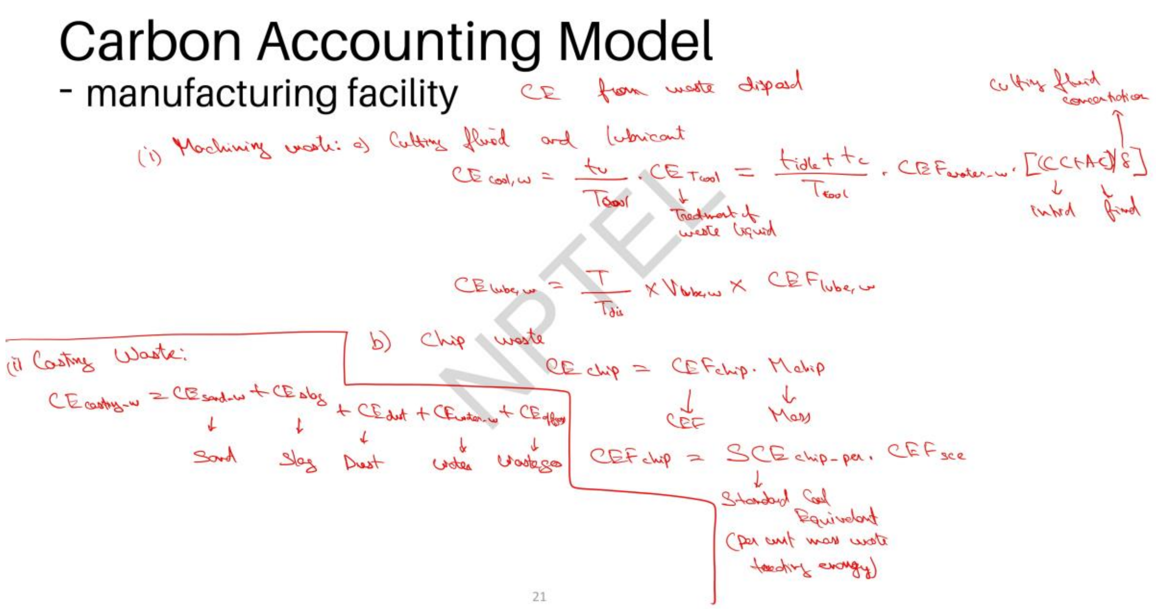
Where,

- *n – number of welds*
- *K_s – electrode loss coefficient*

This is for metal arc welding in general. For gas welding, there is a welding stick. For that, the mass for the stick is

$$M_{welding\_stick} = \sum_{i=1}^{n}(A_i l_i \rho_w / k_{spl}) \tag{29}$$

Now, one of the important parts is carbon emissions from waste disposal. After waste disposal, I will close my model on carbon accounting. This is also one of the important factors. We talked about the energy. As I said, in sustainable designs, it is energy, material and, waste treatment. Carbon emissions from the energy that is consumed in the equipment and due to material, there are carbon emissions.



Now, we will talk about the carbon emission due to waste and I will close my model. This is one of the models or very few of the models that I am discussing here. The multiple models used in developing software solutions provide direct calculations. There is certain processing that happens in between. That processing is, these algorithms or models which are there.

So, carbon emission from waste disposal, when I talk about, I will try to now segregate this into three parts. That is the machining waste, forging waste and casting waste. In machining waste, the waste produced includes waste liquid, waste chips, cutting fluid, and lubrication waste. So these kinds of waste are there. So, let me first talk about the waste generated from cutting fluid and lubricant

First is cutting fluid and lubricant. The carbon emission due to cooling is represented as

$$CE_{cool,w} = \frac{t_u}{T_{cool}} \cdot CE_{Tcool} = \frac{t_{idle} + t_c}{T_{cool}} \cdot CEF_{water\_w} \cdot \left[(CC + AC) / \delta \right] \qquad (32)$$

Where,

- *$CE_{T\,cool}$ - carbon emission from waste liquid treatment*
- *CEF_{water_w} - carbon emission factor of wastewater treatment*
- *δ - cutting fluid concentration.*

Similarly, we have a model for the lubricant. That is, carbon emission. The carbon emission due to the wastage of the lubricant is

$$CE_{lube,w} = \frac{T}{T_{dis}} \times V_{lube,w} \times CEF_{lube,w} \qquad (33)$$

Where,

- *$CEF_{lube,w}$ - carbon emission factor of waste lubricating oil treatment*
- *$V_{lube,w}$ - volume of waste lubricating oil*

Other than the cutting fluid in machining waste, I have the chip waste. The carbon emission due to chips or scrap produced is

$$CE_{chip} = CEF_{chip} \cdot M_{chip} \qquad (34)$$

Where,

- CEF_{chip} - *carbon emission factor of waste chips treatment*
- M_{chip} - *mass of waste chips*

The treatment energy consumption of different waste chips is different. The corresponding carbon emission factor can be calculated as:

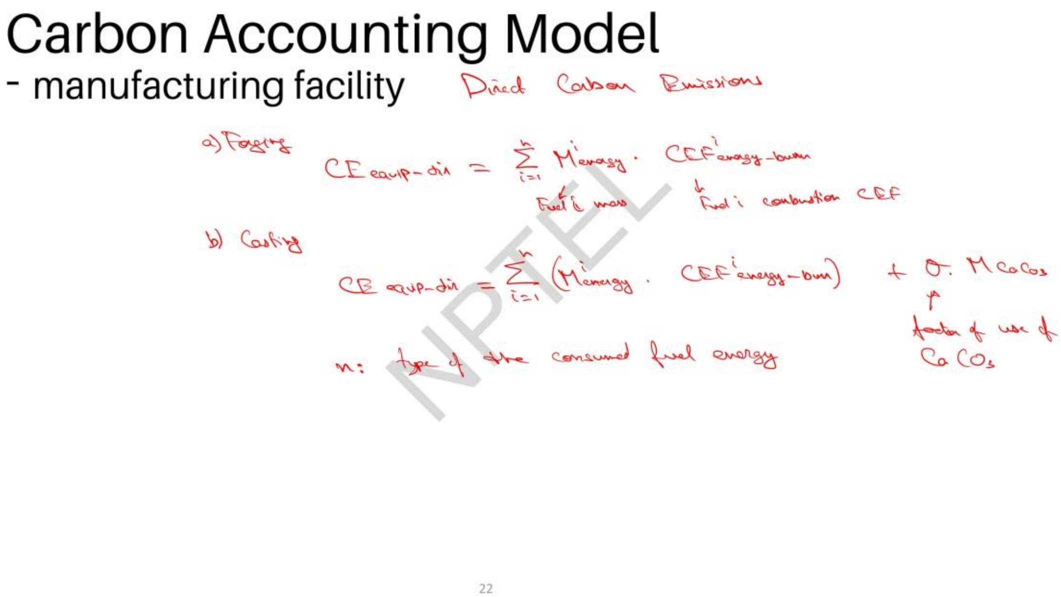
$$CEF_{chip} = SCE_{chip\_per} \cdot CEF_{sce} \tag{35}$$

Where,

- SCE_{chip_per} - *standard coal equivalent of unit mass waste treating energy consumption (kg ce/kg)*
- CEF_{sce} - *is the carbon emission factor of standard coal combustion.*

Similarly, the forging waste or casting waste could be calculated. Casting waste is very similar to, as we discussed, the casting material. So, casting auxiliary material includes sand, binder, water, calcium carbonate and coating. So, if I put casting waste here, let's say, this is first waste, I am discussing and, casting is the second waste. In the casting waste, like the casting auxiliary material waste, I will take it as CE (Carbon Emission) due to waste.

$$CE_{casting\_w} = CE_{sand\_w} + CE_{slag} + CE_{dust} + CE_{water\_w} + CE_{offgas} \tag{36}$$



Carbon emissions which are direct, what are those in casting and forging? So, I will now put the models for the carbon emissions in forging and casting. Which were direct. Also, this is there in welding as well. So, for forging, what is the direct carbon emission?

$$CE_{equip\_dir} = \sum_{i=1}^{n} \left(M_{energy}^{i} \cdot CEF_{energy\_burn}^{i} \right) \tag{42}$$

$$CE_{equip\_dir} = \left[\sum_{i=1}^{n} \left(M_{energy}^{i} \cdot CEF_{energy\_burn}^{i} \right) \right] + \theta \cdot M_{CaCO_3} \tag{43}$$

And, this is how different models are there. So, this was a detailed, layer-by-layer modeling, a quantitative approach for carbon accounting of a manufacturing facility, workshop, or plant.

We talked about the part layer, product layer, and equipment layer, all functioning within the umbrella of the facility. These relationships do not need to be remembered. It is important to understand how the different factors are calculated and integrated into our software system.

We then develop our own program to have the model ready. In the next week, I will provide a brief introduction to ESG, and then I will discuss SLM (Service Lifecycle

Management) and ALM (Application Lifecycle Management). Afterward, I will conclude my part of the course.

Thank you.