Corrosion, Environmental Degradation and Surface Engineering
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Lecture – 31
Life Cycle Impact Assessment

Hello and welcome to the twenty-eighth lecture of the course on corrosion environmental degradation on surface engineering. The topic of this lecture is a life cycle impact assessment, and what do we do in this lecture? We try to figure out any system or product and how it is affecting the environment, society, and economy. There are the three major words economy, society, and environment, and that is why I am showing a kind of worrisome face that it is too difficult to really wrap up this complete topic in one lecture. But the good thing is that there are ISO standards 1400, 14044, and 14040. There are two standards available where there is a systematic manner; everything has been documented. How do we carry out this kind of assessment? Further, we have a number of parameters, and then comparison is also available.

So, we try to figure out whether our product is releasing carbon dioxide (CO_2), how much energy has been released, and what kind of particles are really being released in the environment. Equivalence will come directly from those data comparisons, and there is some sort of software also available that can be utilised for assessing this kind of thing. Now, we will try to explore more, but let me say in a slightly different word, we say the life cycle impact assessment, which many times in a short form we write out LCIA approach is a standardised framework; it has been well documented, and it has been given in a number of standards also, and we will be discussing two standards in this lecture. This is a standardised framework designed to evaluate the entire life cycle of a product, from its extraction as a raw material to its disposal. Such an approach is required, the reason being that we have been talking about sustainability and we know that products should not harm the environment, and our course is also on environmental degradation.

So, this topic is very relevant to our course, and then the question comes: how do I quantify material? How do I quantify energy and resources that are really required during the production, during distribution, during consumption, or may be disposal? Those things are really required. In this case most of the data will come from a manufacturer, and it is again an iterative procedure, not necessary. Then, one go, we can do everything; we can have a number of documents available in literature we can compare. So, we really required how systematically we should take this kind of approach. Then the question also comes: what kind of trash will come out of this product, what kind of emissions will come out, and what are the byproducts. So, those need to be counted to really figure out what the sustainability aspect is related to that product.

Now the trash production emissions, which are really going to affect the air, water, or land, need to be accounted for and energy. Finally, it is getting consumed by the product during manufacturing, during usage, and during disposal; those need to be accounted for. So, these are the important aspects that are really required from a sustainability point of view. So, while we can say LCIA is essential for promoting sustainable development and empowering companies because we are talking about MSMEs and we are talking about very small-scale industries, they need to work on this kind of framework to come up with an evaluation of what kind of product they are developing, whether that is correct or not, and whether they are able to really score high from a sustainability point of view. In the actual case, the case score should be as low as possible because the score is generally counted to show how much it is really affecting the environment.

So, a product that affects the environment the least is more suitable from the emission point of view, from the trash point of view, and from the waste point of view. So, those things are important for us, and we need to consider that. Now, the life cycle assessment of we generally divide in the four steps. What are the four steps? First, there is a goal and scope. Whatever we are studying, what is our goal? Is it a much bigger goal or maybe a shorter goal?

What is meant by inventory analysis? What raw materials will we be using? What type of energy will be required—renewable, non-renewable—or what emissions will be produced? Are we dealing with sulfur oxides (SOx), nitrogen oxides (NOx), carbon dioxide, or other hazardous materials? These aspects need to be evaluated carefully, meaning we must create a balance sheet to track inputs and outputs. This will help us assess the environmental impacts. This is crucial because the process is not straightforward; it involves a complex, iterative approach, symbolized using a double arrow to represent its cyclical nature, rather than a simple, linear relationship. Lastly, interpretation is key. If we don't fully understand the data, our interpretations—and thus our conclusions—will be flawed. However, as I mentioned, there are ISO standards, there are software, and there are very good case studies in literature that those can be utilized. So, one of the case studies is already there; that is what we are going to cover in the present lecture, which was published in 2019 in materials, and then there says assessment of the environmental impact of a car tire throughout is a life cycle. So, the interesting thing in this case study is that tires are very essential, but tire continuously pollute the environment, not only in a direct manner that means they wear out of the leaves a particle in the air; they consume energy; they consume a raw material. So, it is really causing some sort of depletion one way or another, but indirectly also because it can be used for the four wheels; in this case, we are talking about the car tire. Thus, it is a four-wheeler.

So, four-wheeler, when we drive the car, the average is may be 6 litres, and then the 6 kilometre per hour per litre or 8 kilometre per litre. So, those things have also been evaluated in this. So, how can we connect other products or related products with our system that need to be also assessed from an assessment point of view or a life cycle assessment point of view? If I try to describe this, we call it scope, which basically outlines the boundaries and restrictions. What are the restrictions on us, and then we want to analyse in this way because if you define these boundaries very well, then it can be established well, and then may be when we launch a product that can be described easily. Another one is that what is the target population? It is quite possible that the rural population may be the town population or the developed city population; those things are important, and what kind of time frame? Are we talking about 10 years, 200 years, or 1000 years? Those things are also important because, in the long term, everything may turn out to be very harmful, as such, whatever development we are doing.

So, those things are important, and then in which region will this product be more utilized? So, if there are more gains and less harm, then the product will be successful; if it has more harm and fewer advantages, the product will not be successful. So, what we see in this case is scope is defined, and then after that goals, what do we really require as an outcome? Let's assume that our goal is to enhance the process. So, now suppose I have used some manufacturing process and I figure out it requires a lot of energy, as such, and then if there is other technology I am trying to compare the technology with existing technology, I can say the new technology takes less energy.

So, it is energy efficient, but takes some sort of it gives more trash or may be give some sort of negative output, then I need to compare with that. So, there should be some benchmark, and that is why the life cycle assessment will provide an overall benchmark. We can compare the two processes with two products, and there may be two different methodologies also. So, those things are important. So, what is our goal and needs to be identified? Another one, as I mentioned very clearly, is that we need to really go ahead with the balancing of invent inventory loads—how much really we are giving and how much it is coming out.

Output may be harmful; it is not only the output that is useful; harmful output will need to be minimised as such. In this case, when we say inventory load, consider the input and output or the process or activity, whichever we are using, by identifying and quantifying the load release in environments. This load can be anything as such. Now here we are talking about the resources in the raw material. If it is a resource as such, then how much energy has been consumed, and as I mentioned, output can be functionality as such, which is really required from a product, but in addition, it can be emission; it can be waste, which really finally requires a disposal, or it may be the kind of some sort of oil that needs to be discarded. Every one year or every six months, that is also waste that needs to be counted, and then those with this kind of output that are harmful to society need to be clubbed in some sort of categories. So, there are many categories now; one is a climate change category; one category is water pollution; resource depletion is another category. So, we need to grip on those things.

So, whatever we collect as an input, we need to put in some sort of group. So, that we can really quantify, and as I mentioned, when we are comparing the two products, two processes, or two methodologies, this kind of comparison will be really very helpful to us. Now coming to the life cycle assessment, how the product process system will affect the environment or the entire life time. Now this is one thing throughout the entire life time of the product, but sometimes we need to also see that even if the product is not there, what will happen because of that after 200 years, or may be after 20 years. So, even after its life, its effect may remain.

These factors must also be considered. What we refer to here is the need to account for the lifetime impact of future loads on the environment. By accurately calculating these impacts, we can predict environmental depletion and develop appropriate policies. Nowadays, products and processes labelled as 'green'—such as green energy or environmentally-friendly manufacturing—are incentivised because they generate fewer emissions. As a result, they are often subject to lower taxation compared to products with higher carbon footprints that contribute more significantly to pollution. For such environmentally harmful products, higher taxes can be imposed as a deterrent. This is a critical point, and to illustrate it in the current lecture, consider the example of fuel efficiency in cars. A small car might offer an average of 20 kilometres per litre of gasoline, whereas a large, luxury car might only manage around 6 kilometres per liter. This comparison highlights the environmental and economic impact of less efficient, high-emission vehicles. So, naturally, I will go ahead with the smaller car for better compared to the bigger car because the average in this case is very high, but we need to really compare with the set parameters, which are already documented. So, this is important, and then which product really should come into a market, and it will be very useful for the market compared to the product, which is really creating more harm to society that should be minimised. As far as possible, those things are important, and then we need to think from a policy point of view. In the Life Cycle Inventory (LCI), I take into account the use of emissions resources, as we are aware that all resources are finite and cannot be replenished indefinitely. So, resource usage is also important for us, then it waste generation whatever it has happened, and then during the entire life cycle, even though I mentioned that sometimes we need to think beyond the life cycle also, and this complete thing will vary from raw material procurement and then finally, to disposal. So, this is what we really required, and then after doing a complete analysis of what we are really looking for, we are trying to identify weak spots.

So, the more and more innovation is possible and manufacturing processes can be improved, materials can be improved instead of 5 years of life as they had with the 10 years of life. What will happen? The raw material consumption will be reduced, and energy consumption will be reduced. So, it is very useful, but what kind of material modifications are really required? This allows us to identify those areas of weakness, and once we take action, we can truly innovate and achieve superior outcomes. Now, if I try to interpret what I mentioned here, So, my interpretation, and that is the fourth step also of this LCA, is that interpretation basically involves a finding, identifying the primary contributing contribution to the environmental impact, and considering uncertainties and limitations of our assessment.

So, what are the uncertainties? I am thinking that this will take around 600 calories of energy, but quite possibly there is some sort of uncertainty in one go. I find 600; in another go, I find 800; and sometime I am finding 300. So, there are a lot of uncertainties that need to be accounted for: do we have good measuring equipment, are we able to quantify things properly? So, these are the important, and further is the limitation. We need to really figure out what the limitations the limitations are or how we are planning to do things, but we do not have those kinds of facilities available. So, those limitations also be accounted for when we are trying to interpret the results from a source. Also another one is that we are able to figure out a weak point or maybe the weak spots, and then we think about the improvement.

An improvement analysis is essential to identify opportunities for reducing environmental impacts. This aligns with the course's objective: to lower energy consumption, enhance waste management, and develop effective strategies that minimize waste generation.

It's also critical that all actions and findings are well-documented. Proper documentation not only ensures transparency but also paves the way for future advancements. If decisions are made without thorough documentation or if interpretations are unclear, the overall results will suffer.

To maintain consistency and reliability, it's important to adhere to established standards, such as ISO 14040 for life cycle assessments, as well as ISO 14044. Following these guidelines will ensure that the processes are carried out with accuracy and accountability.

So, these standards really provide a framework for conducting whole life cycle assessment, and these are important. So, let us first understand what these two standards are. So, these are the literature available for ISO 14040; another one is a 14044. So, this is what we call the ISO; you already know this is an international organisation of standardisation, and then we have many standards, and then whenever we are in the open and then they try to develop a process or product, we need to follow standards. So, these are standards submitted, particularly these two standards. Both of these standards provide guidelines for conducting life cycle assessments.

So, whatever the topic on which we are discussing, these two standards are really providing necessary information for those. However, their scopes are slightly different in the focus, and the scopes are slightly different. So, first I am describing ISO 14040; second is ISO 14044. In this case, what we are trying to say is that there is a framework for environmental management. Again, this functionality we are not checking. We are assuming the functionality is better as such, and then how this product is going to really harm the environment—that is what we really need to look into, and we need to seek the necessary information.

ISO 14040 serves as the foundation for life cycle assessment standards, and ISO 14044 builds upon it. ISO 14040 lays out the principles and framework for conducting a life cycle assessment, defining key concepts, terms, and definitions—many of which we've discussed here—with additional examples provided in the standard itself. The process, according to this standard, is divided into four main stages:
1. Objective and scope definition,
2. Inventory analysis,
3. Impact assessment,
4. Interpretation.

These stages guide the entire life cycle assessment, as described in the previous slide. So, now coming to the next one, ISO 14044 is also the environmental management relative and also really goes with the life cycle assessment. However, in this case, detailed requirements are given, and then even guidelines on how to collect the data and how to analyse those data are given. So, this is kind of slightly enhanced. So, this is a standard 14044 that provides more information related to the requirement and then sequentially conducts the life cycle assessment. Not only this, it also assures the quality and credibility of the LCA.

So, we are following all the norms. So, it will be a be a really credible study, and then we should continue with this. This study offers guidance on data acquisition, data quality requirements, and calculation methods. And finally, how to report this data appropriately that has also been mentioned here. So, what we can say is it is a basically implementation standard

ISO 14040 is the fundamental standard, while ISO 14044 provides guidance on how to implement it. These standards are well documented in the literature, so I encourage you to review them for a more detailed analysis. As previously mentioned, there are four stages involved, and one key aspect is data collection. Once we gather the data, it is crucial to categorise it based on environmental impact. We need to consider the various categories of environmental pollution, such as harm to human health, air, water, land, or the broader environment. The collected data should then be allocated to these appropriate categories. Finally, go ahead with some sort of characterisation. We can assign a numerical value from 1 to 100, or alternatively, we can use a scale from 1 to 1000, depending on the specific methods needed for the purpose. And then once that is done, we can calculate the score. Based on a score, we can really say which method is good, or may be what are the weak spots, and where the improvements are really required. Somewhat if you want to really go ahead with a slightly next stage or may be slightly improved.

So, what is a good point in the situation? We have already learnt something like a normalization. All the data that are collected, if you do a normalization, will really be in the 13 parameters that can be easily compared. And then, if we go ahead with some sort of weighting factor, we will also learn about the weighted objective method. We can give a weight one way and then factor in a higher weight compared to the other; it is not necessary all the need to be equated or may be equal weight for each parameter.

So, those things are also required. So, what we are saying is that these are the mandatory elements and these are the optional elements. So, normalisation is an optional way in giving extra weight factors. And then we ensure that the quality of the data is also really reliable, and then we do some sort of mean value and standard deviation—those things we need to be calculated to figure out what the really level of the quality is. Something: if I get a mean value of 1 and a standard deviation of 0.5, then it does not make any sense as such. So, naturally, the quality of the data is not very good, but if I get a value of 5 and a standard deviation of 0.1, the quality is very good. So, those need to be provided completely. So, more and more transparency will provide a better and better life cycle assessment to us. Now, I am trying to write the same thing after organising whatever the organised collection of the input output and potential environmental repercussion assessment should be considered, and then particularly for interrelated components.

How the one parameter is affecting the other parameter, is also considered. Then comes the potential environmental effects we mentioned that we need to really define in different categories. In this case, particularly, resource depletion is one category, ozone depletion is another category, human toxicity is another category, and climate change is another category. So, there are many categories in the literature that really can be used, like for all kinds of products. Not only for the metallurgy, this method is useful for mechanical engineering; it is useful across various disciplines related to education.

When the method is the same for any kind of industry. Now, coming to allocating, particularly input and data, whatever you are collecting to the right category that comes into this, that is what has been shown in this case. Finally, we really need to figure out what the indicators are and then what the benchmarks are. So, like the many times greenhouse gases are given comparison with CO_2 contents. So, CO everything is gain every fact of the greenhouse gas is compared with the CO_2 something like methane (CH_4) has a 4 times more strong if I compare to the CO_2.

So, whatever the one unit load of the CO_2 will be equivalent to, the 0.25 load may be equivalent to the CH4, which is equal to one unit of the CO_2. So, 4 times CH_4 is 4 times stronger, or in fact, much higher compared to the CO_2. So, every time we try to compare with some sort of benchmarking, some sort of indicator is really required. Even energy, whether we want to convert it in kilowatt hours or megajoules, is important because it has some sort of toxicological potential. And then they are basically required to convert all unstructured data to the right framework, which is really required for the appropriate analysis and interpretation.

Now, we try to mention initially that this product life cycle is basically looking at the data and energy of the raw material and energy that will be consumed or may be taken during the extraction of the raw material, and then the production or manufacturing time. So, this is the one where we really required some sort of energy during the usage, and finally, energy may be required during the disposal or whatever recycling is required. Now, we have expressed this in linear terms: extraction, production, manufacturing, and from manufacturing to usage to use to dispose. We are showing in a linear form, but in reality it is highly non-linear, and then if you go with good recycling or reconditioning of procurement, then it can be cyclic also.

So, ideally, cyclic will be the best; once it comes in use, it should run, run, and run without any failure as such. So, it may not be really harmful, that is, ideally, we believe in this manner, but quite possible if the tire is something we are even trying to repair in a proper way, but it causes more and more damage to society, more and more carbon particles, or maybe that is another harmful for the breathing point of view. Therefore, we really need to replace it. So, sometimes the recycling itself may be a problem also. So, we really required this kind of a complete product life cycle assessment to figure out which step is really correct.

Naturally, we say recycling and reuse is a very good option, but if recycling itself is consuming a lot of energy, then what do we do? If I am making a new product with one unit of energy and recycling requires two units of energy, naturally I will not go for recycling. This is what we need to evaluate and compare. Now what we are saying in this case is extraction and production. We require raw materials, and those can be gathered using mining. We are aware that the majority of materials are extracted through mining, which may involve drilling into certain formations, particularly vegetation. These raw materials can then be used and further processed, ultimately leading to the production of products.

And then, as I mentioned, the raw materials are turned into the fresh product through the industrial manufacturing process, and this manufacturing process can be categorised in a number of ways. Here we are using the manufacturing as such; it can be forging, it can be anything also, and then another fabrication can be the welding or may be even riveting those kinds of things, and then finally, assembly. So, these are all manufacturing-related. So, in manufacturing, I am using the bigger set, and then these are the subsets of the manufacturing itself, which is basically manufacturing the product, and then we can use various manufacturing processes, and of course, everything needs to be done as per the specification as per the drawings that are being given. Now another point comes over: there will be some sort of waste. Whenever we do manufacturing, there may be chip formation, or some pieces may be broken and need to be recycled. Recycling has been considered, and if it is done efficiently, it can be very beneficial. However, inefficient recycling, where the inputs and outputs aren't thoroughly evaluated, is not truly effective. When done properly, recycling reduces energy losses, raw material usage, and environmental harm, making it worthwhile. Otherwise, the effort is wasted.

In the diagram shown, we highlight that every product's design and development begin with a need or requirement. After this, the product goes into production. The process can include iterations and modifications based on feedback. Once produced, the product fulfils its purpose in use. There is often a feedback loop from customers, leading to continuous improvement. After its lifecycle, the product goes through disposal, sorting, or disassembly. Usable components are retained, and the rest is discarded, completing the post-consumer cycle. Now here we are going for the reuse recycling, and then now the new thing also comes like a repurpose, repurpose is also there in this case. So, the things now everywhere you look at what we are showing that primary resources, which are required, and waste emission everywhere we are showing that primary resources and waste emission. So, these are the inputs and outputs: what are the resources required in terms of material, in terms of energy, and what will be the emissions? As such, we are assuming the functional product will be there, but apart from that, the emissions need to be accounted for. When we go ahead and here the after use it can go for the recycling or it can go for the waste treatment also, and the waste treatment it can be processed and may be completely converted to the other form or it can go for the landfill arrangement.

As far as knowledge is concerned, we try to minimise or almost negligible landfill areas and then waste, and then there should be repurpose, recycle, or reuse as far as possible. However, the data show that is also not justifiable, and then we need to look at either we close the product, or we look into the new technology. When we are not able to recycle, we are not able to repurpose, we are not able to reuse. What is the point of continuing that product? Better we go for the new kind of product, the new kind of technology instead of going for the waste treatment, and then landfill area. So, these are the important for us. So, what we see in this case is that at the end of the useful life of the product, it basically enters the disposal stage.

Line filling is one option; incineration and other waste management procedures people are using, but now in these days, because of sustainability, we do not go ahead with that. Now we give more emphasis on reuse or repurpose, that is, the same thing can be repurposed for some other use. It will be very important, and then coming to the recycling, sometime we go ahead with the disassembly complaint thing, and then we separate and keep the product in us, which may be say 10 percent (10%) failures, and then 90 percent (90%) can be reused though we can go ahead with this kind of thing. So, that is why we are collecting, separating, and processing rejected material. So, that new materials can be generated means after sorting we find only 5 percent (5%) components are bad and 95 percent (95%) elements are right.

So, we are going to again put it back in a cycle. This is what we refer to as a cyclic process. So, preferably, as I say, we are doing many time analyses at the linear process, but an actual is a non-linear process, and then if we can convert in a cyclic manner, that is the best, and that is why the re-enter the cycle means the cyclic process will be the best when the reuse is a cyclic process, repurpose is a cyclic process, even recycling with whatever the modification, discarding a little bit, and may be adding a little bit that will be the better. So, the recycling conserves the resources and reduces environmental impact. So, this should be utilized, but not blindly. We need to do a life cycle assessment, and then we can think about whether those things are correct or not.

If I express it in my other words, we say LCA methodology consists of the four primary steps: goal and scope definition, inventory analysis, impact evaluation, and interpretation. Inventory analysis entails compiling comprehensive data on input and output such as energy consumption, material flow, emission, and debris generation, but in the corrosion, the debris will come out. Where we know that the debris will come out, even the fracture debris will come out. So, those things are required to quantify potential environmental impact inventory data or evaluate it using the impact category, such as some category; something like climate change is one category, human toxicity is another category, and resource depletion is another category. So, we do a categorization. So, that overall comparison turns out to be very good because not every product can be used in the same categories, but if they are well defined, suppose 17 or 20 categories, we can really easily compare products.

So, interpretation concludes the analysis and presentation of the results, including the sensitivity analysis, uncertainty evaluation, and comparison with alternative scenarios of the protocol. There is a sensitivity analysis also required; if I am changing a little bit and then results are very good and favourable, can I really think about that, or maybe there is some one or other parameter with high sensitivity compared to others? Can we go for a deeper understanding of that? So, this is really providing some sort of vertical thinking. Also, if there is something wrong, can we go ahead with the better analysis? Coming to the uncertainty, if we know really the mean value and the standard deviation, or the standard deviation is a very high value, as I given a comparison, the unit mean value may be equal to 1, but the standard deviation is equal to 0.5 naturally, I had to look at what is going wrong and then how do I improve the evaluation method.

So, these things are important when we go with life cycle assessment, and another LCA can be used for the number of industries. It is not only for manufacturing, or may be construction, or may be energy production, or agriculture. Even though waste management itself is an industry, we can go ahead with the life cycle assessment of the waste management method and the processes also. Life Cycle Assessment (LCA) plays a vital role in supporting eco-design and ecosystem development, as it significantly influences policy formulation. Many policies can be shaped based on LCA findings. For example, if I compare two tires—one that is more cost-effective or cheaper but causes greater environmental damage—I would likely recommend discontinuing that product or advocating for higher taxes on it. So, it will really influence the policies as such, and finally, if we have this sustainability goal or may be eco points available, then we can think about a sustainability certification or may be labelling system. We can use the way we have ISO standards similarly; we can really use some sort of sustainability standard, or may be the labels that this is a good eco system; the product, as such, can be utilized in a better manner. So, those things are important. Another mention is that LCA results really identify the opportunity to improve the product, or, may be, cause more product innovation. It will cause a more sustainable alternative material, which is really required for a society. So, basically, if you look at what is a major issue why we are not very successful in LCA , and of all items is basically data, how do we bring this data, and then how do we really interpret data using the appropriate modelling technique, and then finally, what kind of expert opinion is really required?

So, these things are important to understand: we really require data, we really require good interpretation, and we really require experts because nobody will be an expert in everything. LCA is really multifunctional, and many parameters are there. So, that is why we need to stick to the standards; we need to really follow the guidelines that are available, and for that purpose, I am going to consider one case study where all the standards have been followed and with the addition of the one software, because if you have three or four members, you cannot really evaluate LCA in a complete manner. So, really require some sort of established standards or software that can really provide a good comprehensive evaluation. So, let us take a one-case study that is already available in literature; it was published in 2019, and this is a car tire. The overall weight of the car tire is around 10 kg, and then when you think about the raw material, or may be the inputs, in this input category, we have two things. One is a raw material, another is an energy raw material; not only one material can be a number of materials; then comes what is our scope. Here the scope has been defined only in a few things, even though there is a raw material acquisition, then production, then use and end of the life cycle or recycling, and then, however, there is a possibility of the disposal also.

So, here, however, this paper has given this as a boundary that this is my outline. These are the four steps only we will be going at. So, that means, how the tires are going to get stored—we have not considered what kind of distribution mechanism will be there for tires that are also not there. So, they have already defined that these are the scopes for us, even though, overall, we may require a seven-step or ten-step process, but our analysis is only based on the four steps: raw material acquisition, production usage, and end-of-cycle end-of-life particularly recycling. Now, instead of recycling, if you go for the disposal naturally, it is not been accounted over here. However, we will focus on several aspects of this issue. While we recognise that a functional tire is one form of output, we must also consider other outputs that have not been accounted for. These include atmospheric emissions, waterborne emissions, solid waste, and other harmful gases released into the environment. So, again, they are putting the limits on output; now we are not considering infinity output , as such it will be indirectly also affecting other parameters, but has not been considered for this study. So, they use a number of raw materials; they use synthetic rubber of course; the contribution they are showing is around 24.17 percent (24.17%); the natural rubber they use is around 18.21 percent (18.21%); and carbon black they use is 19 percent (19%). Currently, many individuals are considering the use of graphene as a potential replacement. If you look at the recycled rubber, it is only 0.5 percent (0.5%) weightage. So, they use a tire of the specification, something like a P205, 55, or 60, and then they use three indicators—what is the eco indicator 99?—then another—they use a CED that is a cumulative energy demand, and the last one is an IPCC that is a intergovernmental panel on climate change.

The analysis of the tire utilizes three key parameters: Eco-Indicator 99, Cumulative Energy Demand (CED), and the Intergovernmental Panel on Climate Change (IPCC). These indicators help assess whether a car tire delivers satisfactory results and identify potential areas for improvement, as well as the direction those improvements should take. Now, let's discuss tire specifications. For example, a tire might be labeled as P205/55 R16 or P205/65 R16. The 'P' at the beginning indicates that the tire is designed for passenger vehicles. The number '205' represents the tire width in millimeters.

So, if the tire width in mm is 205 mm, naturally the number is 205. Then next comes the 55, which is a percentage, and the particularly the tire sidewall is a percentage of the width. So, in this case, the width was 205, and 55 percent (55%) of that is a sidewall height that has been mentioned. Then comes R, basically the they are using the radial tire. A radial tire kind of has an internal structure where the layers of the chord are arranged radially from the centre of the tire. So, these are the specifications for the tires. Coming to last 16, which is says the diameter of the wheel in inches.

So, R16 is basically a radial tire with a 16-inch. If I give the full specification, P = 205/55/R16 means that the tire is 205 mm wide, it has a sidewall height of 55 percent of the width, it is a design for a 16-inch diameter wheel, and it has a radial construction. Now coming to the eco indicator 99, what is that eco indicator 99? You say it is a method for assessing the sort of sustainability indicator and then based on the life cycle assessment principles, the eco indicator seeks to quantify potential environmental impact. It really categorises in a number of categories: what are the resource depletion, climate change, ozone depletion, and human toxicity? There are, and in this present case we are considering 11 categories, and it combines, finally, all this course in a single one; that is what we call eco points. So, if Eco points on a higher side, that is a bad product; if Eco points on a lesser side, it is a better product.

So, we can compare the two separate products based on eco points. Another one was the CED, which is the cumulative energy demand. It really evaluates how much quantity of energy is really required. This represents the total amount of energy needed throughout the entire life cycle of the product, process, and service. This is particularly important when discussing tires—specifically, the energy required to manufacture a tire, the energy needed for the tire to operate on the road, and the energy necessary for its disposal. So, everything will come in a CED. So, that is why the comprehensive evaluation of the energy input at a various phases, including extraction of the raw material, production, transportation, usage, and finally, disposal, all these categories need to be accounted for in this case. And then another thing is that it also considered direct as well as indirect energy consumption. So, electricity is a kind of direct consumption in this case of fossil fuel, which is really required for the usage purpose or some other renewable energy sources. Now, here if we know the manufacturing itself is taking huge energy, and then can we really work on to reduce the energy consumption? That is the kind of time when we really document everything and then we know this portion is major and we need to be reduced.

So, it basically gives a good brainstorming session, and then we can think about how to really reduce energy input for the manufacturing, how to reduce energy input for the usage, or when the vehicle runs such that an increase in efficiency really will help us. So, energy inputs are typically expressed in this case in megajoules (MJ) or kilowatt hours (kW h). So, there are giving two units. So, that we can compare various options.

In this case, the energy input is presented in megajoules (MJ) or kilowatt-hours (kWh). It is essential that this information is documented clearly and made accessible to everyone. Transparent and well-structured documentation is crucial. This should include all calculations performed, the assumptions made, the sources of data, the basis for the data used, and the mathematical methods employed.

The Eco-Indicator 99, the Cumulative Energy Demand (CED), and the Intergovernmental Panel on Climate Change (IPCC), established in 1988, are important sources of information in this context. These frameworks play a vital role in scientific assessments and reports, particularly regarding climate change, its impacts, and potential mitigation and adaptation strategies.

So, lot of information can come from these sources. When we delve into the IPCC, we find a wealth of information. However, our primary concern was the source of these data and the socioeconomic effects they may have. Fortunately, the IPCC provides these answers. So, the primary object of the IPCC is to apprise and synthesise the most recent scientific findings. Every year, they try to look at data and then try to improve it. So, with scientific, technical, and socioeconomic data, I have had a lot of problems: how do I quantify, how do I come up with socioeconomic effects, and socioeconomic data that can come from this? Ensuring a thorough and objective evaluation of the current state also of knowledge.

This is important: such documentation and reports are crucial because they are grounded in exhaustive reviews of scientific literature. This isn't just a matter of compiling data; it involves meticulous literature reviews and insights from thousands of experts in the field. The conclusions are not based on the opinions of a select few but rather reflect a broad consensus among many experts. These reports serve as valuable benchmarks against which we can compare new developments and assess how existing scores have been established.

In this case study, three primary aspects have been thoroughly incorporated. Now, let’s examine the data provided. The researchers collected this information over the course of one year, from 2015 to 2016. For example, they reported that 1.928 kg of synthetic rubber was utilized, alongside natural rubber and carbon black. They also noted that approximately 36.112 liters of water were required. The energy needed to fabricate one tire was around 828.896 megajoules (MJ), which can be roughly rounded to 829 MJ. Finally, when discarding the tire, the final weight is about 40 kg; however, in the context of recycling, this weight may not be necessary.

Another assumption now is that we really required some assumption that everything needed to be documented well. So, what they use in that manufacturing process generates something like a 10 kg wheel, but they generate around 0.5 kg of trash as such, and then on average they consume 3000 litres for the life cycle of a 50000 km. That means, when the car is running for the 50000 km, every tire consumes roughly 750 litres.

For example, a car with four wheels requires a 3000-litre fuel capacity. So, on average, each tire required 750 litres of petrol or maybe gas, whichever is in the vehicle they are using. So, in this case, the assumption is basically a traveler distance of 50000 km, which means that after 50000 km, this tire will not be in use; either it should be recycled, or maybe it should be discarded or go for disposal, and then sometime the 50000 km is not mentioned, then the life is a 5-year life cycle. Then, as I mentioned earlier, they have not considered the storage; they have not considered the distribution.

The data regarding these aspects is completely absent, as no thorough checks were conducted and other relevant factors were overlooked. Regarding the disposal side, if tires are not efficiently recycled, alternative methods must be considered. In reality, tire recycling is often not efficient; it tends to be both labour-intensive and energy-intensive.

So, to go for the disposal, they use some sort of burning and try to recover the 40 percent (40%) of energy back, or they go ahead with some sort of shredding, then it goes for the 38 percent (38%) of the energy back. Now, when they go for the burning, they require points, maybe 0.06 kilogrammes of fuel and then 0.06 megajoules (MJ) of electricity per tire to put in a fire, and then they can get 40 percent (40%) energy back. However, when they go for the shredding, they do it in two stages. The first is a 16 by 16 mm particle size.

They consume roughly 7.4 megajoules (MJ) of electricity and 1.5 kg of water per litre of water, and some sort of oil for the shredding. They go for the next stage, where they really require another 5.13 megajoules (MJ) of energy to reduce a particle size to less than 0.7 mm. However, if they want to go for some sort of pyrolysis process, they require roughly 2.68 to 3.46 kilowatt hours per tire, which is not very high. So, depending on the finally, what is the real aim? Are we going for pyrolysis? Are we going for burning directly in a boiler, kind of wherever they really require furnaces, and they can burn the tire directly, or they go for the shredding? Of course, emissions will be different in each case.

In any case we consider, it is crucial to define the scope and boundaries of the assessment—what we aim to achieve and our specific objectives—since emissions will vary accordingly. Additionally, as per ISO 14044 standards, it’s important to allocate data accurately for each case. In the 2019 case study, the authors assume that the manufacturers adhered to all regulatory norms and maintained full transparency throughout the process.

So, they haven't followed this system 14044, but if you want, you can go ahead. However, they collected the data using the directly manufactured data, but they did a data validation. How did they do data validation? To validate, they use an energy equation, they use a mass balancing equation, and then they try to do auditing so that not a single piece of data is missing anything; it is not a mismatch or loss at all. So, if this balance gives proper results, then we do not have to worry, and then, as we say, the energy audit and the mass audit conservation are really important, and finally, they can aggregate those data. Then what we say is that this aggregated data is more fully useful for us, and we can really go ahead with a better man. Now, what is the next stage? To basically look at the contribution and then whatever the data that are coming out, what kind of pipe products will come out, and then either we do performance analysis on that, or we use some sort of software and the software already knows that, what kind of and the byproducts will come out, or maybe what will be the emissions as such.

So, they use SimaPro software as such, which they feel is well-known software for life cycle evaluation, and then basically to investigate the environmental effect related to the automotive tires. So, this software is available even though you can try it; it is initially free, and then what kind of changes can be made, then whatever the product we are trying to make. So, they say the SimaPro is a powerful solution for those who want sustainable changes. So, environmental protection to avoid environmental degradation we really require sustainability in the product. So, they have developed this on some sort of algorithm; they have incorporated all those algorithms in this, and then they give a good decision; that is what they are claiming, and then they say that will provide to another; we say the LCA approach provides insight, so that you go for the better and better decision, empowering better choice, and reduce environmental footprints, which is really the goal of this.

So, this is the one software available. When we go for the life cycle assessment, this kind of software can be utilized; it will really provide some results, and then if the industry can buy it, it can be used for the card's purpose for some time. Now, coming to the overall data, the scores, which really required, as we say, the eco indicator 99 can provide some sort of data to us, and then they have 11 categories. They divide those 11 categories in 3 categories , and what are those 3 main categories? one is human health, then is ecological quality, and the last one is resource depletion. So, these are the 3 categories they divide everything. This is the one indicator we use over the CED, where the energy balance will be coming, and finally, the IPCC, where we have very rich data and scientific and expert opinions are also available. So, we can compare easily. So, in this case, for human health, we required some sort of respiratory-related or carcinogenic impact that was related to human health.

However, they also added a climate change ozone lower depletion and ionising radiation in the one, and then they now correct, then they express one parameter that is a DALY that is a disability-adjusted life years to overall impact. What will be the impact on human health? So, DALY is a parameter or factor, or maybe the number that is related to human health. Now coming to the ecosystem, so whatever the emissions that are coming out from manufacturing usage of the system, product, or component that are really causing some sort of harm to society. So, we need to really figure out how it is affecting and causing harm to the ecosystem. Now it is if it is causing a biodiversity loss because, in these days, that is a very important term that nothing should impact the biodiversity. If there is a loss of biodiversity or a negative impact on ecosystem health, it must be accounted for. One key parameter used for this is the 'potentially affected fraction,' which provides information about the proportion of species exposed to hazardous or dangerous compounds. So, it can be zero also if the product is good and then it is not really harming; however, we know that tire is causing some sort of harm to society, and that is how the PEF will be counted. Another one is the acidification or eutrophication of fication damage, which can be counted with something like a PDF that is a potentially disappeared fraction. In this case, basically the vanishing of the items is one causing harm to the species and another one, which causes a complete removal of those species from environments. So, these two factors are utilized for that purpose. The last one is a natural resource depletion. We know that we have restricted or limited natural resources; of course, this may change from one source to another.

So, a natural resources category indicates a surplus energy value in megajoules (MJ). So, whatever is left will be given in megajoules (MJ), and as this energy is consumed, the remaining natural resources will only use up to this megajoule (MJ). After perhaps a year, this megajoule (MJ) will decrease for another year. So, it can be used for long-term planning this method. So, these three indicators are accounted for with an eco indicator 99. Now these are the data; they have given, in this case, the life cycle inventory in the extraction of minerals then they actually wherever the process is done, that will be causing some sort of land acquisition or may be usage. This kind of material generates anaerobic azeos and then ammonia; they utilise some sort of pressurise or heavy metals, CO_2 and then HCFC; those things are also common VOCs and then pH, and then coming to the effects of this.

Then we say that extraction of the resources may have some sort of impact on vascular plant acidification; that is why we use our PDF parameter. toxic stress, PF parameters, and climate change, of course; this is directly related to the damage to human health, as well as ozone level depletion, ionisation, respiratory effects, and carcinogens. So, these are the factors, and then the IPCC, which is basically inter governmental panel on climate change, provides the quantitative assessment of a greenhouse impact and gas impacts, and then they give in terms of CO_2. So, basically, the parameter is a global warming potential, and then what is the real contribution of each gas towards this kind of score, that is, a GWP score as such, and then IPC gives values in terms of 20 years, 100 years, and 500 years. So, that is a basically long-term plan, and then we want a sustainable world, and in a sustainable world, those parameters are very important. And then, as I mentioned, the eco point and eco indicator points are important. In this case, we need to convert whether 140 points, 150 points, 160 points, or maybe 50 points will be more important and better for the overall results.

However, as also mentioned, we need to really look at that the data that we are providing, what is a standard deviation with that, are of very good quality. So, let us take an example. In this case, they have given the and then the score from 1 to 5, and then they have used the word uncertainty index. They say that the uncertainty index is basically estimating some results and measuring. So, when and if there is a difference between this. So, estimated results and equivalent measured values, whatever the difference that will give a uncertainty the lesser difference, naturally uncertainty is the lesser side; uncertainty is more that really the difference is more on a higher side, and that happens whenever we go further dQI lesser.

So, dQI less is nearly providing more uncertainty compared to that. So, instead of the uncertainty, they went with the dQI value, and then this dQI was basically defined on two parameters, indicating minimum value 1 and maximum value 5. A higher dQI score shows higher data quality improving greater trusty workness, or, may be, the truth of this while minor variation. So, in this case, only a minor variation is here. So, they are assuming 10 percent (10%) deviation is minor; it is obvious that, as such, we cannot estimate everything very accurately. So, 10 percent (10%) variation is tolerable, while coming the 50 percent (50%) is very bad; we should not go to this side. If we are able to keep high dQI, that is very good for overall, and then the life cycle assessment.

They then evaluated the overall environmental impact based on a 1,000-point scale. For the entire study, they used SimaPro software to generate histograms, presenting the data in a clear format. Initially, they provided the information in a single table, as shown here. These are more like a deterministic value; they are not going to change, while now they go for this kind of software; they provide the minimum value, and they provide the maximum value, and these values are different. Now when you use software, you need to provide data, and there may be a number of data points that you are using. So, in this case, they use 1000 points to give data, and then based on that data, the Sima program generates a histogram, which will be shown in the next slide for the different categories. What are the different in the back categories? So, this software itself provides a number of categories as such based on whatever the raw materials or products we are using are given.

Now here, what is the difference? When we were using that time, the water quantity was only 32 or 36 litres, while in this case we are using 40 liters. So, the data have been changed to some extent when we are going for more and more detail analysis. Now coming to this slide, they have 11 categories: the carcinogenic is one category, respiratory effects are another one, then organic and inorganic, climate change, radiation, ozone layer depletion, exoticity, acidification, land use, minerals, and fossils. Now what they are using is that most of the environmental impacts are happening at the production level. So, carcinogenic is happening only in the production level, radiation is happening only in the production level, ozone layer depletion is also happening in the production level, and naturally, land usage is also in the production level.

When combining these categories, the overall environmental impact during the usage phase is found to be around 141 points. In comparison, the points associated with production and processing are relatively low, and the recycling phase contributes minimally to the total impact. So, in this situation, recycling is a better option as such, but recycling is very cost-efficient and cost-intensive and then needs to be made more efficient for purpose. So, this is what they have changed; this is the third stage of life cycle assessment, and then they did a grouping in different categories overall; they divided into 11 impact categories, and then they found that when the tire is on usage, the maximum impact is happening because of the fossil fuel. So, even though car engines are required for fossil fuels, tires are also related to that; if we make tires efficient, which consume less energy naturally, it will be for the better. Therefore, it is clear that in this situation, fossil fuels are contributing at their maximum level and should be minimized, with recycling being another important consideration. Even though it is a very good point, it may be almost 0 points, but we do not use that kind of recycling of the tire very efficiently. Using that method or technology is not really efficient in this; we require better and better technology to come up with a recycling.

To summarise the lecture, we explored how life cycle assessment (LCA) can be used to identify the environmental impacts of a product, specifically focussing on an automobile tire based on literature. We found that tire usage has a significant cumulative impact, reaching approximately 141 points, with the majority of the effect attributed to the usage phase.

The main impact categories are:

- Fossil fuel consumption, contributing around 66%,
- Respiratory inorganics, contributing 22%,
- Climate change, contributing 9%.

Fossil fuel consumption, while indirect, is a significant factor. However, respiratory inorganics, such as sulfur dioxide (SO_2) and nitrogen dioxide (NO_2), are particularly important from a health perspective. Carbon dioxide (CO_2) is counted under the climate change category, while sulphur oxides (SO_x) and nitrogen oxides (NO_x) fall under the respiratory inorganics category.

So, we need to minimise. If we do not worry about fossil fuel, we say it is an indirect one. We need to think about the sulphur dioxide (SO_2) minimisation. The nitrogen dioxide (NO_2) minimisation may not be only the production, even the usage time, and that it is happening because of the tires indirectly. So, those things are important. Another one we say is that life cycle,, mostly this manufacturing itself is energy intensive, and usage is also energy intensive. So, that should be minimize If we do the work on that brainstorming and try to optimise the performance of the tire, we can really reduce this energy consumption. Energy recycling as such technique has a limited influence on minimising the negative impacts of tires, the reason being we do not have a energy efficient recycling technique and require the two-stage recycling and shading, and furthermore, we require more processing on that.

The eco index for the manufacturing, usage, and recycling of automobile tires was measured at around 153 points, with a standard deviation of 37.2. This high standard deviation indicates significant variation, highlighting the need for improved tools to reduce the environmental impact of tires.
To achieve this, we need more energy-efficient recycling systems, as well as measures to reduce energy consumption during both the manufacturing and use phases. Manufacturing alone accounts for around 20% of the total energy consumption. Additionally, reducing energy use during vehicle operation is crucial, which is why fuel-efficient vehicles, particularly smaller ones, are preferable. These more efficient vehicles should be subject to lower taxation compared to larger, less fuel-efficient vehicles.

So, these are the comparisons, and then when we say which product is causing more harm to society, that should be accounted for appropriately. So, this is a very good tool to compare the different materials, different products, and different processes and then come up with the right results, and it really gives a really good initiation for the new innovation. So, thank you for attending this lecture. I hope this lecture will be useful to you. Thank you.