

SUSTAINABLE MINING AND GEOINFORMATION

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Week – 10

Lecture 49: Life Cycle Analysis

Welcome, students, to today's lecture. This is lecture number forty-nine of our NPTEL course on Sustainable Mining and Geoinformation. In today's lecture, we shall talk about the topic of life cycle analysis (LCA). This lecture and the next lecture will both cover this topic. Today, we will discuss the concept of life cycle analysis in general. In the next class, we will take an example of a mining project so that we can study LCA with reference to the mining project. Today, we will talk about life cycle analysis, or what we call environmental life cycle analysis. So, we will introduce the concept of life cycle analysis. Then, we will discuss the goals of a life cycle analysis study, the steps or phases of the LCA study, life cycle analysis methods, life cycle inventory, life cycle impact analysis, and the utility of undertaking such an LCA study. So, an introduction about the subject: the mining industry plays a vital role in the nation's economy by providing essential raw materials for the manufacturing sector.

CONCEPTS COVERED

- INTRODUCTION
- GOALS OF LCA STUDY
- PHASES OF LCA STUDY
- LCA METHODS
- LCI and LCIA

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INTRODUCTION

- Mining industry plays a vital role in nation's economy by providing essential raw materials for manufacturing sector.
- Mining operations have significant adverse impact on the environment.
- Important to assess the environmental impacts of mining operations and identify ways to mitigate the impacts.
- Environmental analysis in compartment versus product life cycle.
- Life-cycle assessment (LCA) is a widely used environmental impact analysis tool to analyse the effects caused by a product, or process on the environment from beginning to end over its entire life cycle.

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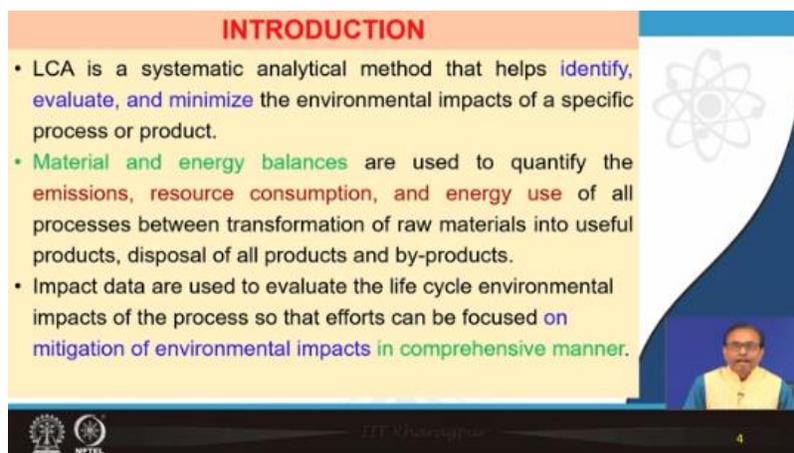
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Now, you all know that mining operations have significant adverse impacts on the environment. So, it is important to assess the environmental impact of mining operations and identify ways to mitigate them. Now, there is an environmental impact. The environmental impact analysis can take place in a compartmental way versus the entire life cycle of the process or the product. So, for example, we can take an example of the mining industry—for instance, iron ore mining. We mine the iron ore, and it is sent to a beneficiation plant, where it is refined or beneficiated. Then, the refined iron ore is sent to the steel plant, where it is processed in a metallurgical smelter, and you produce iron—different types of iron, pig iron, or stainless steel, or whatever it is. Then, that stainless steel or iron goes to a different manufacturing plant where you produce bolts, nuts, things like that. Now, if you see from the stage of mining to the processing plant to your metallurgical plant and then the manufacturing plant, the product is going, and then the product—nuts and bolts—is used in some

application and then it has its life. Then, it is disposed of. So, you can see the product life cycle starts with mining and ends when it is used as a product. After the completion of its useful life, it goes to a disposal site. So, the whole chain from mining to the disposal site is the product life cycle. Actually, when you have to do the environmental analysis, it is better that the environmental impact analysis is not done in a compartmental way but rather covers the entire product life cycle. Then, you will have a comprehensive estimation of the environmental impact, and you should work through the whole chain to mitigate it. That is the correct approach. Having said that, sometimes we do not have control; for example, one company mines the ore, then sends the product to another company—say, a steel plant—and then the steel plant sends the refined steel to a third company, and that third company manufactures some appliance products that go to different users. So, the control is not there throughout the length of the life cycle; that is

why it sometimes becomes very difficult to carry out a full environmental life cycle, what we call cradle to grave. Cradle is where it originates, and grave is the disposal yard. The main concept, when we say life cycle assessment, is from cradle to grave—from the origin to the point of death. Life cycle assessment is a widely used environmental impact analysis tool that analyzes the impact caused by a product or a process on the environment from the beginning to the end of its entire life cycle.

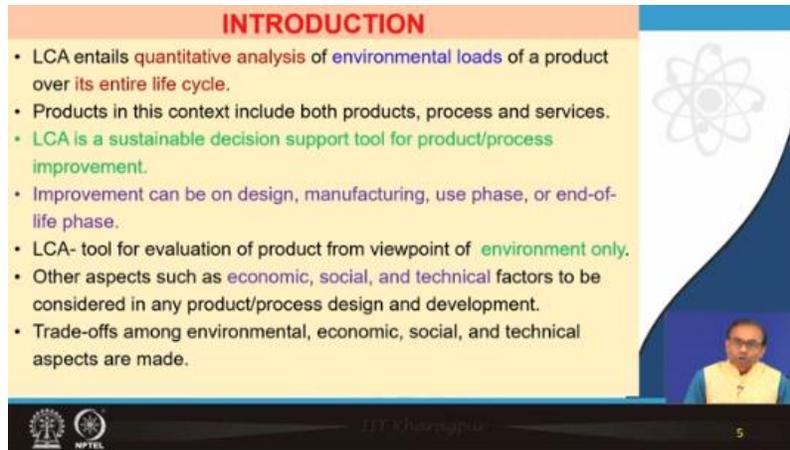
It is a systematic analytical method that helps identify the impact, evaluate the impact, and suggest measures for its mitigation for a particular process or a product. For the analysis, we are using the materials and energy balances that are used to quantify the emission, and quantify the resource consumption, and quantify the energy use of all processes between raw material, from production of raw material to useful product at different stages, and also the use of the product by consumers. Then, after the life of the product is over, it is disposed of at the disposal point. So, through the whole chain, what is the material input, what is the energy input, what is the material output, what is the emission output, waste output? All this quantification we do, then we can identify critical areas, we can identify where maximum impacts are taking place, and how we can suggest modifications to minimise the environmental impact. So, impact data are used to evaluate the life cycle environmental impact of the process so that the efforts can be focused on mitigating environmental impact in a comprehensive manner, not in a compartmental manner, not in an ad hoc manner. So, life cycle analysis entails quantitative analysis of the environmental load of a product over its entire life cycle. Products in this context include both product processes and services.



INTRODUCTION

- LCA is a systematic analytical method that helps **identify, evaluate, and minimize** the environmental impacts of a specific process or product.
- **Material and energy balances** are used to quantify the **emissions, resource consumption, and energy use** of all processes between transformation of raw materials into useful products, disposal of all products and by-products.
- Impact data are used to evaluate the life cycle environmental impacts of the process so that efforts can be focused on **mitigation of environmental impacts in comprehensive manner.**

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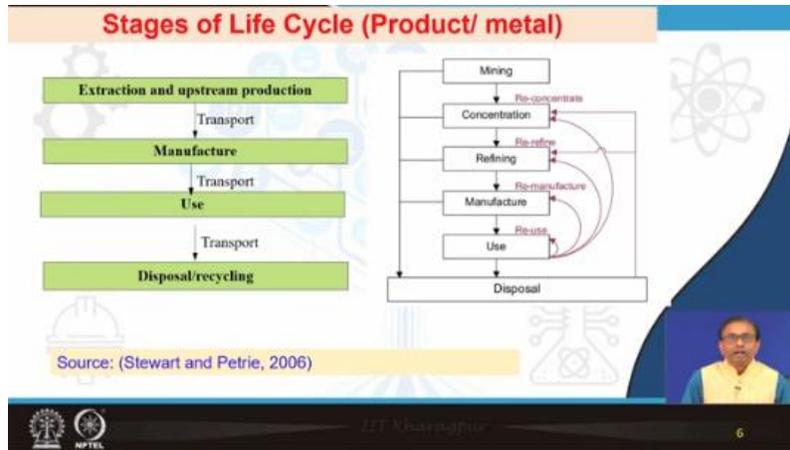
INTRODUCTION

- LCA entails quantitative analysis of environmental loads of a product over its entire life cycle.
- Products in this context include both products, process and services.
- LCA is a sustainable decision support tool for product/process improvement.
- Improvement can be on design, manufacturing, use phase, or end-of-life phase.
- LCA- tool for evaluation of product from viewpoint of environment only.
- Other aspects such as economic, social, and technical factors to be considered in any product/process design and development.
- Trade-offs among environmental, economic, social, and technical aspects are made.

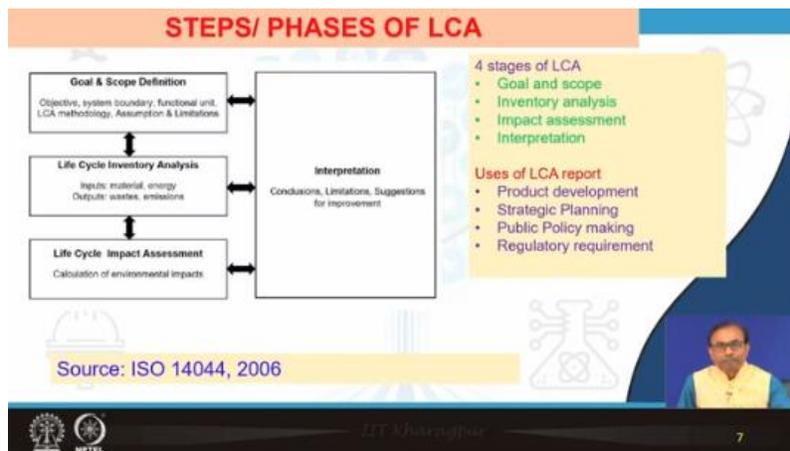
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The objective of carrying out such a study is to suggest improvement in the design stage, in the manufacturing stage, the use phase, or the end-of-life disposal phase, so that the environmental impact will be minimal on the environment. Remember that life cycle analysis is an evaluation of a product or a process from an environmental point of view. But when you execute different projects, the environment is the only consideration. There are other aspects, such as the economic aspect, the social aspect, and technical factors, that are considered during the process design and development. Sometimes we have to make a trade-off in the pursuit of productivity, efficiency, and profit. We may sometimes compromise the environment and other aspects, so although the LCA is only for the environment but remember that it always may not be possible to only look at the environment; that may not be practical, but when you want to calculate the environmental impact, and you want to improve your product from an environmental point of view. LCA is, nevertheless, a very good tool. Now, the stages of the life cycle for any product are represented by two diagrams here. You can see for any product, let us say extraction of the mineral and upstream production, then from the mines, the raw material is transported to the manufacturing point. The product is manufactured in the manufacturing plant.



Then it is transported to the point of use, and after its life is over, the rejected material is transported to the disposal site or the recycling site. So, this is the whole life cycle of any product, any generic product. Now, particularly if you take the example of a metal, you can see mining of minerals or the ore, then it is transported to the concentration plant, where it undergoes some processing. Then the processed or concentrated ore comes to the refinery or the smelter. Again, transportation is taking place. In refining, there is an input of energy and material. There is some impact taking place. Then it is transported to the manufacturing plant. There is input of energy and material, and the environmental impact is there. Then, it is transported to the use point. After the use, it is either going for recycling or it is going for disposal. So, these are the stages of the life cycle, and each stage has some input of material and energy, and there is an output. Output may be a product, a finished product, or waste material (solid waste, liquid waste, effluent, gaseous effluent, or liquid effluent). So, this is the life cycle.



Now, when we want to do the life cycle analysis, we follow the ISO 14044 protocol. There are four stages/phases of life cycle analysis. The first is the goal and scope

definition. The second stage is life cycle inventory analysis. The third stage is life cycle impact assessment, and once the impact is quantified, we are going for the interpretation. How can we suggest improvements to the process or the product so that the environmental impact is minimized, or can we suggest mitigation measures for environmental pollution? Goal and scope of the study: goal, why we are performing the life cycle analysis? Whether there is a policy at the corporate level to identify where the maximum environmental impact is taking place Or whether it is that you want to design a better product, or whether there is a regulatory requirement? So, what is the purpose, and who is the intended audience that should be clear so that we can carry out the study? Now, in the scope of this study, first, you have to define the boundary. As I told the product cycle is very long. So whether it is from the cradle, the origin, to the grave, the disposal point, or within the plant, or within, let us say, the mine.

Goal/ Scope of LCA study

Goal:

- Why perform LCA ? Reason to carry out LCA;
- Intended use.
- List of audience should be provided.

Scope:

Scope of the study includes defining:

- Product system boundary,
- Functional unit,
- Data parameters,
- Target for data quality,
- Impact assessment methods,
- Impact interpretations

So in the mine, we are extracting the mineral or ore, which is going to the beneficiation plant, and then from the beneficiation plant, the mining sphere is over. It is going to another plant. So whether it is from the source of origin to the end of the company gate, cradle to gate, or it is from cradle to grave, that is throughout the entire life cycle when it is disposed of in the disposal site. So, there are cradle to gate, gate to gate, and cradle to grave. This is the system boundary. Functional unit: So, for example, in the case of mining, it can be 1 ton of ore that is produced. How much input, material input, energy input, and how much environmental waste is produced per ton of ore? So, that is a functional unit. Then, data parameter: what kind of environmental quality data do we want to measure and collect, whether it is the air quality, water quality, and where you are collecting the data? Primary data or secondary data? You are generating some data. Data quality is very important. With primary data, you may have more control. With secondary data, the accuracy may not be in your control. Then what are the impact

assessment methods? Then you are predicting the impact from the data. So, what method are you using to predict impact? How accurate is your impact prediction? That is also important, and then once you have predicted the impact, you are interpreting the impact, and as per the interpretation, you are modifying your process, you are modifying your product design, or you want to modify your whole process, so that is the scope.

System boundary: The process is considered within which system? So, cradle to grave or cradle to gate or gate to gate. The diagram of the system boundary is shown here. You can see that there is a flow diagram. Raw material production in the mine. Then you have the production. It is in the manufacturing plant. Then the product is coming to the user's point. It may be society. It may be a plant that is used. The product has a life duration, and after the product's life is over, it will go to the grave or a disposal site, or maybe in between, it can go to recycling, remanufacturing, etc. So you have cradle to gate or cradle to grave or gate to gate, depending upon what kind of unit you are, whether you are a mining unit, whether you are a manufacturing unit, so it all depends. Now, once the system boundary is decided, what is the output function? For example, the mineral or ore is to be smelted in a refinery to produce a metal that is the function, or you are producing an AC. AC will be producing cool air, or you are using the coal. The coal will be used to produce electricity. So, that is the function.

Goal/Scope of LCA

- **System boundary** - processes considered within which system ?
- **Cradle to grave, cradle to gate, gate to gate.**
- **Function** - use of the output product (to be smelted in a refinery to produce metal, to produce cool air, to produce electricity).
- **Functional unit** - This is a measure that allows quantification of the function. For example: tonne of ore, 1 MW of power, 1 unit of AC.
- **Reference flow** - Amount of product that is necessary to fulfill the function (1 tonne of ore)
- **Process Inputs in LCA:** Inputs include **materials, energy (renewable and non-renewable), resources, and organic/inorganic chemicals.**
- **Material and Process Outputs:** **Finished product, by-products, waste generated, effluents (to water, air, soil).**

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Goal/Scope of LCA

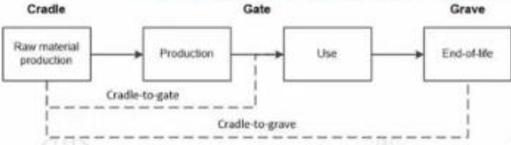
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SYSTEM BOUNDARY

System boundary followed in LCA study could be:
 cradle-to-gate, gate-to-grave, gate-to-gate, or cradle-to-grave.



Source- Samruddha Kokare, J.P. Oliveira, Radu Godina, Life cycle assessment of additive manufacturing processes: A review Journal of Manufacturing Systems, Volume 68, 2023, Pages 536-559, ISSN 0278-6125.



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Now, once you know the function and functional unit, i.e., one ton of ore, one megawatt of power, one unit of AC, or one piece of fan, that is the functional unit and reference flow. So, if you know that one megawatt of power will be produced. So, how much coal is used? So, that is the amount of raw material that is used to produce 1 MW of power; that is the reference flow. For 1 MW of power, how many kg of coal are used? That is the reference flow. So, the amount of product that is necessary to fulfil the function. Now, when you see the processes, at every process, every stage of the life cycle, there are some inputs: material input and energy input. The material could be raw material, steel, iron, or whatever, and renewable and non-renewable energies. Resource input includes water input, chemicals, organic, and inorganic chemicals that are used in the process. These are the material and energy inputs. Similarly, you have the output, material outputs, and other outputs, such as waste output. Outputs are finished product, byproducts, and then waste that is generated, solid, liquid, and gaseous effluents, which are discharged into water, air, and soil. Sometimes within the boundary, because you do not have control of the data or the other process flow diagram, other processes, though they are very important, do

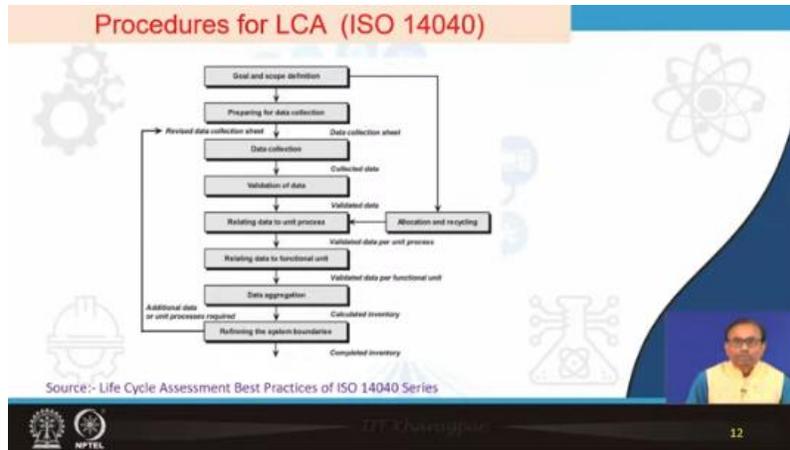
not have their data. That restriction of the data also restricts your system boundary. So, for mining projects, particularly, cradle to gate. The cradle is where the raw material is generated. The gate is actually beyond the gate of the beneficiation plant or the crushing plant. That is the cradle-to-grave. That is the system boundary for mining projects.

SYSTEM BOUNDARY OF LCA

- The system boundary followed in LCA studies for mining are **cradle-to-gate**.
- LCA study in mining comprises of **ore mining, concentration and beneficiation, extraction, smelting, transportation and refining operations**.
- Structure of the system boundary is also dependent on the available datasets, as they are proprietary information.
- **Due to the lack of enough data source, it is hard to assume the end-of-life state of the processed metal.**

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So, for a mining LCA study, it will comprise ore mining, concentration, beneficiation, extraction, smelting, transportation, and refining operations. Now, the procedures of life cycle analysis are as per the ISO 14040 standard. The latest in the ISO 14040 series is 14044 in 2006. So, this is the process flow diagram, goal and scope definition, then prepare the data. What data are to be collected? You prepare that data. Then collect the data, primary or secondary data. Then, the validation of data because the data has quality issues. So, you have to do the normalization, validation. Then, relating data to the unit process. We have defined the functional unit. So, you have to reduce the data to a functional unit. Then you are collecting the input, output, and environmental quality data. Once you have that data, then you aggregate that data and you calculate your environmental impact per unit production or per unit functional unit. Once you have your environmental impact data, you reduce environmental impact to unit function, you suggest the mitigation measures, and then you refine the system so that you get a cleaner product and have a cleaner process. So, data collection, input data, output data, raw material input data, energy input, water input, chemical input, all this data

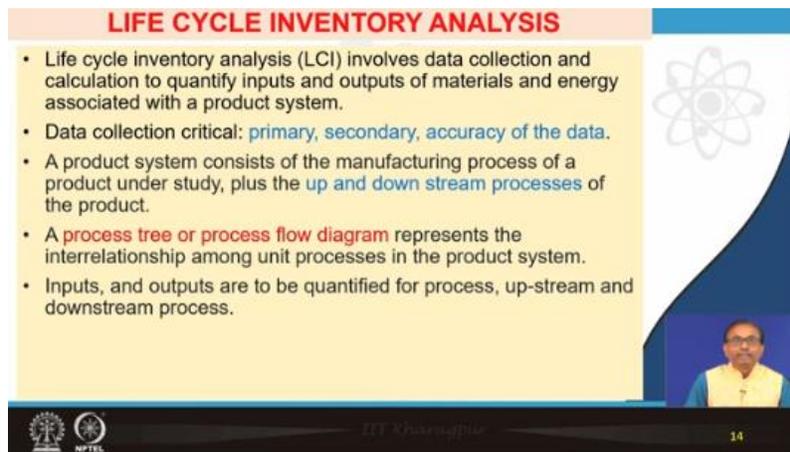


DATA COLLECTION

- Input, output, environmental data to be collected for different process including upstream and downstream process
- Primary data
- Secondary data
- Accuracy of data is very critical
- Data normalization, cleaning may be necessary.

or environmental output, environmental emission data to be collected for different processes, including upstream and downstream processes. So, we have primary data, secondary data, accuracy of data is very critical, data normalization, data cleaning, etc., may be necessary. Because unless you have the accurate data, your impact prediction will not be very accurate, and you will have a misleading interpretation. Once you have that, then life cycle inventory analysis will consist of data collection with respect to the input, material input, energy input, water input, chemical input, and output products. What is the product data? What is the environmental data? A process tree or process flow diagram may be necessary so that you can collect the data process-wise for each process. What is the input, and what is the output data? You will understand the flow of the material, and you will understand the flow of the sequence of the environmental load. The environmental impact in the life cycle analysis is called environmental load. So, you have to calculate the environmental load for each process for a functional unit. Once you have the life cycle inventory data, you have to do the life cycle impact analysis using a prediction model. Once you do the life cycle impact analysis for the upstream process

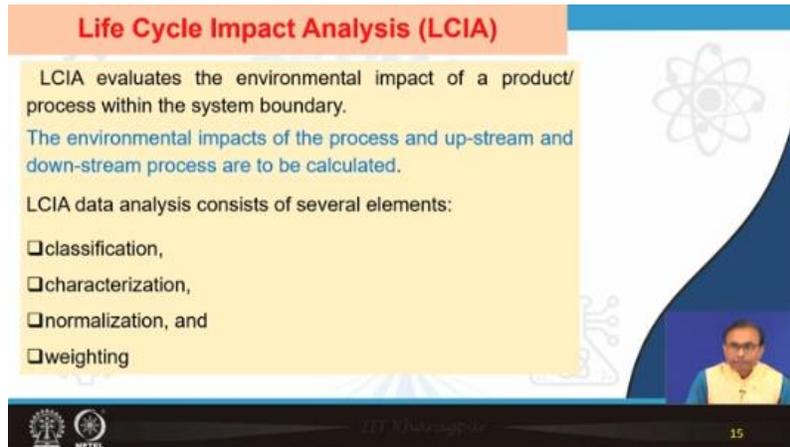
and downstream process, following the process tree diagram, then you will have several data points.



LIFE CYCLE INVENTORY ANALYSIS

- Life cycle inventory analysis (LCI) involves data collection and calculation to quantify inputs and outputs of materials and energy associated with a product system.
- Data collection critical: **primary, secondary, accuracy of the data.**
- A product system consists of the manufacturing process of a product under study, plus the **up and down stream processes** of the product.
- A **process tree or process flow diagram** represents the interrelationship among unit processes in the product system.
- Inputs, and outputs are to be quantified for process, up-stream and downstream process.

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Life Cycle Impact Analysis (LCIA)

LCIA evaluates the environmental impact of a product/process within the system boundary.

The environmental impacts of the process and up-stream and down-stream process are to be calculated.

LCIA data analysis consists of several elements:

- classification,
- characterization,
- normalization, and
- weighting

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That data needs to be classified, characterized, normalized, weighted, and aggregated, and they have to be reduced to per unit function, per functional unit, per process; they have to be reduced. Now, when we do the impact analysis, particularly now, there are different impact categories we have to consider. This is as per the ISO 14000 series standard. There are so many impact categories we have to consider, and the impact prediction will be along these impact categories. So, what are the common impact categories that are considered for the LCIA? They are abiotic and biotic resource depletion, depletion of natural resources, physical resources, and biological resources, global warming potential, depletion of ozone, photochemical oxidant formation or ozone or smog formation, acidification, eutrophication, human toxicity, toxicity to humans, toxicity to plants, ecotoxicity, toxicity to the ecosystem, solid waste, hazardous and radioactive waste generation, and the effluent that is produced. So, all these are the impact categories on which your impact prediction will be done. Now, because this life

cycle analysis is a data-intensive analysis. So, data quality is very, very important. So, once we collect the data, the uncertainty and sensitivity analysis are critical to ensure confidence in the data that has been collected, data that will be used because on this data we will be using empirical equations and some predictive models to predict the impact.

Life Cycle Impact Analysis – Classification

Common **impact categories** considered in LCIA are:

- Abiotic and biotic resource depletion
- Global warming
- Ozone depletion
- Photochemical oxidant formation (Ozone) or smog formation
- Acidification
- Eutrophication
- Human toxicity
- Ecotoxicity
- Solid waste, hazardous and radioactive waste

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Uncertainty and sensitivity analysis

Data Analysis

- Uncertainty and sensitivity Analysis are critical to ensure confidence in their data, impacts and results enabling **informed decision-making**.
- Most common method for **quantitative uncertainty analysis** is stochastic modeling, particularly Monte Carlo simulation.
- **Monte Carlo simulation is the most preferred method.**

Final Results
Calculation of environmental load per functional unit, per unit process.

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If my data quality is not accurate, my impact will also be inaccurate. So, the result that I will be giving will also be misleading. So, for informed decision-making, for accurate decision-making, sensitivity analysis or uncertainty analysis is mandatory for the life cycle analysis. The most common method of quantitative uncertainty analysis is using stochastic modeling. Particularly in most of the life cycle analysis, inventory analysis, or life cycle environmental analysis, the Monte Carlo simulation method is the most preferred method that has been used in the life cycle analysis. Now, once your impact analysis is done, you are finally providing a result to different stakeholders, to the corporate, to your product design team. And the final result is in terms of the calculation of environmental load per unit process and the calculation of environmental load per functionality. You can say air pollution per ton of ore, water pollution per ton of ore, or

you can say air pollution by the drilling operation, air pollution by the blasting operation, and air pollution by the crushing operation. So, per process or per functionality, you have to use both. So, the environmental impact data that has come has to be segregated in terms of per unit process, in terms of per functional unit. So, this is the ultimate output that we are calculating within the system boundary. How much environmental impact is taking place? How much air pollution is taking place? How much water pollution is taking place?

USE OF LCA STUDY

- Cleaner Product development by change in product design;
- Change in process
- Strategic Planning
- To comply with regulatory requirement
- Public Policy making

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What is the impact of climate change? How much CO₂ is generated? How much ozone depletion is taking place? Now, per ton of coal produced, for example, how much CO₂ is generated? Per unit operations per blasting involving 1000 tons of coal, how much CO₂ is generated? etc. Ultimately, our environmental output will be in terms of per functional unit. Now, once we determine the environmental degradation, the environmental impact per unit ton or per functional unit, we have also done a process flow diagram. Now, we can identify which process has had the maximum impact. Once we identify that, then we will think about it, we will do some process modification, some design modification, so that the environmental mitigation measures are taken in those processes, so as to reduce the environmental impact per functional unit. So, the use of an LCA study will help to develop cleaner product development by making suitable modifications in the product design. Cleaner process by a change in the process flow diagram, or a change in the process. Then, strategic planning for corporations at a corporate level can use the LCA.

For strategic planning, because they want to use this study so that their product design will change, their process will change, and then their environmental impact will be reduced. This study may be useful for other purposes, such as when they are applying for a loan from a funding agency. They will say that they have a cleaner process, so they

should get some preference from the funding agency. Or to comply with regulatory requirements: sometimes the government or some statutory offices will require that you conduct a life cycle analysis to identify your environmental impact and how to reduce it. Public policy making: When the government develops mineral policy, steel policy, aluminum policy, energy policy, or environmental policy, it may want to know which process contributes to environmental degradation. For example, which sector contributes more to climate change, so they can advise those sectors that their sector is more responsible for contributing to climate change, so they should take measures to identify ways of reducing its effects. They may have to conduct this life cycle analysis, identify shortcomings in their process or product design, and then take mitigation measures to develop a cleaner process or product design, resulting in a cleaner product.

SUMMARY

- What is LCA?
- Terms used in LCA
- Stages of LCA
- Methods of LCA
- LCI and LCIA.
- Data sensitivity

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To summarize, in today's class, we have defined what LCA is, the terms used for LCA, its stages and phases, methods of LCA, and the utilization of the LCA study. These are the references you can go through to get a detailed idea. This is the end of today's class, and I thank you for your patience. In the next class, we will provide an example of how life cycle analysis is used in the mining or mineral industry, possibly as a case study. We will discuss how LCA has been applied to the mineral, mining, or coal industry. Thank you very much.

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